EXPERIMENTS WITH SUBSURFACE IRRIGATION AND DRAINAGE ON A SANDY SOIL IN QUEBEC

by

NISAR AHMED MEMON

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Department of Agricultural Engineering
McGill University, Montreal, Quebec,
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Nisar Ahmed Memon

ABSTRACT

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EXPERIMENTS WITH SUBSURFACE IRRIGATION ON A SANDY SOIL IN QUEBEC

Field experiments were conducted on St-Samuel sandy loam soil in 1982 and 1983, with eight replicates of irrigated and non-irrigated maize plots. Soil moisture regime, root density and maize yields were determined to demonstrate the effect of subsurface irrigation and drainage systems.

Laboratory experiments were conducted on large and small undisturbed soil cores to determine pertinent soil properties, relating drainable volume and steady upward flux to water table depth.

A water balance model was developed and used with a stress-day-index to predict water table depth, excessive and deficit soil moisture conditions and effects on corn yield. Economic analyses were made to identify subsurface irrigation/drainage designs which optimize the profit for a corn crop.

A simple method based on first and second order moments was proposed to determine the effects of parameter uncertainty in the relationship of steady upward flux vs water table depth on subsurface irrigation/drainage design parameters.

Based on the above information, a realistic subsurface irrigation/drainage design was proposed and operational recommendations were made for an example field.

RESUME

PhD NISAR AHMED MEMON GENIE RURAL

ESSAIS D'UN SYSTEME D'IRRIGATION SOUTERRAIN UN SOL SABLONNEUX

Des essais furent effectués sur un loam sablonneux en 1982 et 1983 sur 8 parcelles irriguées et 8 autres non-irriguées. Le taux d'humidité du sol, la densité des racines et le rendement du mais furent déterminer afin de démontrer l'influence de l'irrigation et du drainage souterrain. Des expériences de laboratoire furent effectuées sur de petits et de gros échantillons de sol intacts pour déterminer les propriétés pertinentes du sol en reliant le volume drainable et le régime permanent ascendant à la profondeur de la nappe phréatique.

Un modèle du bilan hydrique fut développé et utilisé avec un index de contraintes journalières afin de prédire la profondeur de la nappe phréatique, les conditions d'humidité du sol ayant un bilan hydrique déficitaire ou excessif sur le rendement du mais. Des analyses économiques furent effectuées afin d'identifier les systêmes d'irrigation et de drainage souterrain optimisant le profit d'une culture de mais.

Une méthode simple basée sur les moments de premier et de

second degré fût proposé pour déterminer l'effet de l'incertitude des paramètres sur le lien entre le régime permanent ascendant, la profondeur de la nappe phréatique et le système d'irrigation/ drainage souterrain utilisé. Un design réaliste d'un système de drainage/irrigation souterrain et les recommendations quant au mode d'opération basées sur les paramètres décrits précédemment furent proposées.

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CONTRIBUTIONS TO KNOWLEDGE

Much research work has been conducted on subsurface drainage but, only a few studies were found in the literature dealing with subsurface irrigation. The conclusions drawn from such studies have often been qualitative, particularly those concerned with design criteria. Ideally, design criteria should involve two very distinct considerations. The first of these is the physical consequence of subsurface irrigation/drainage design on soil-water-plant interrelationships. The second aspect is to determine an optimum subsurface irrigation/drainage system from an economic point of view. There is a lack of knowledge with respect to these aspects of subsurface irrigation/drainage system designs.

The work reported in this thesis is an attempt to investigate soil water regime and crop yield in assessing the prospects for subsurface irrigation on sandy loam soil. The work also attempts to provide methodology to identify economically optimum subsurface irrigation/drainage systems. It suggests guidelines and recommendations for design and operation of such systems. Finally, it proposes a simple method for analyzing uncertainty due to soil parameters in subsurface irrigation/drainage system designs.

This thesis contributes to knowledge on aspects of subsurface irrigation/drainage in the respects indicated below:

1. The first practical field scale subsurface irrigation experiment in Quebec has been carried out. It has been shown that subsurface irrigation can be achieved more efficiently and economically than any other method of irrigation in flat sandy loam soil.

2. The effects of subsurface irrigation and drainage on the variation of soil moisture regime above the water table has been clearly demonstrated, see Tables 6.3 and 6.4.

3. The effects of subsurface irrigation and drainage have been quantified in terms of available water in the root zone. It has been shown that the available water in subsurface irrigation plots was twice as much than that of non-irrigated plots, see Figures 6.1 and 6.2.

4. A close agreement between pressure head at 30 cm depth and water table above the 100 cm depth has been found, this indicates that the capillary connection between the water table and bottom of the root zone is continuous and that an upward flux equal to, or greater than, the evapotranspiration demand is occuring, see Figures 6.3 and 6.4.

5. A method to establish the relationship between steady upward flux and water table depth has been proposed as an aid for making decisions about the optimum water table depth for the design and operation of subsurface irrigation systems, see Figure 6.5.

6. It has been found, using the above method, that the pressure head distribution above the water table agrees well with the observed pressure head distribution. The results of 4 above, with the height of capillary rise of water bieng about 100 cm, with the evapotranspiration demand at 4.5 mm/day, has been confirmed.

7. It has been found from the field experiments that the yields of maize increased very significantly due to subsurface irrigation and were almost double than those of non-irrigated plots, see Tables 6.8 and 6.9.

8. A functional relationship has been found between volume of soil drained and the water table depth which has been used in the prediction of the water table depth, see Equation (6.3) and Figure 6.6.

9. A simple water balance model for water table depth, AE/PE ratio and amount of subsurface irrigation volume predictions has been developed and used, incorporating the

results of 5 and 8 above.

10. A stress-day-index concept has been used in conjunction with 9 above for prediction of drought stress and wet stress to evaluate the effect on maize yield, see Equations (4.3) and (4.6).

11. The applicability of a water balance model for subsurface irrigation/drainage design work has been justified by comparing predicted water table depths to those of observed values, see Figures 6.7 and 6.8.

12. Crop models, using the results of 10 above, have been proposed to compute the reduction in maize yields due to the effects of drought and wet conditions, see Equations (4.4) and (4.7).

13. The applicability of crop models in conjunction with the water balance model has been demonstrated by comparing predicted maize yield to that of observed maize yield obtained from two years of field experiments, see Table 6.12.

14. The results of 12 above have been used in combination with drain spacings and the range of saturated hydraulic conductivity values to optimize maize yield, see Figures 6.9 and 6.10.

15. Simple economical analyses, using the results of 12 and 14 above have been used to compute profits for given maize production costs, installation costs, selected interest rates, amortization period and range of maize prices, see Table 6.17.

16. The procedure of 15 above corresponding to drain laterals and the range of saturated hydraulic conductivity values has been used to optimize profit for subsurface irrigation/drainage designs, see Figures 6.11, 6.12 and 6.13.

17. A 90% confidence bound has been defined to demonstrate the risk due to variation in saturated hydraulic conductivity on the optimization of profits with respect to subsurface irrigation/drainage design spacing.

18. The results of 16 above indicate that the drain spacing required to maximize the profit is insensitive to interest rate and corn price, but is sensitive to saturated hydraulic conductivity.

19. A simple method has been demonstrated to analyze the effects of uncertainty due to soil parameters on subsurface irrigation/drainage system designs, see Chapter VII.

In addition to the above contributions, this thesis also provides guidelines and recommendations for design and operation of subsurface irrigation/drainage systems as dicussed in chapter VIII. A detailed example is given for St.Samuel sandy loam soil. Graphs are presented to show a realistic design.

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LIST OF SYMBOLS AND ABBREVIATIONS

a,b,c	Constants.
A	Area, m^2.
AE	Actual evapotranspiration, mm.
C.V	Coefficient of variation, percent.
CSd	Crop susceptibility factor for soil moisture deficit, (dimensionless).
CSw	Crop susceptibility factor for wet conditions, (dimensionless).
d	Depth of the impermeable layer below the drain, m
d_e	Equivalent depth, m.
DD	Depth of the drain pipe, m.
DWT	Design water table depth, m.
e	Evapotranspiration rate, mm/day.
E_p	Pump efficiency, percent.
f	Drainable porosity, percent.
h	Water table depth at midspacing, m.
h_1	The height of water table above the impermeable layer at the drain, m.
ha	Hectare.
hp	Horsepower.
h_L	Head loss, m.
$h_{L,conv}$	Head loss due to convergence, m.
$h_{L,tot}$	Total head loss, m.
h_o	Height of the water table above the drain, m.
k	Unsaturated hydraulic conductivity, cm/s.
k_s	Saturated hydraulic conductivity, m/day.

KW	Power.
m	Height of the water table above the drain at midspacing (also called deflection or pressure head), m.
m_o	Initial height of the water table at midspacing, m.
MFLP	Matric flux potential, m^2/s.
n	Manning's roughness coefficient.
PE	Potential evapotranspiration, mm.
q	Drainage coefficient, mm/day.
q_u	Upward flux, mm/day.
Q	Flow rate, m^3/day.
Q_{ET}	Water requirement for plant use, m^3/day
Q_c	Total water capacity, m^3/day
Q_t	Total seepage loss, m^3/day
re	Effective radius of drain, m.
R	Hydraulic radius, m.
s	Distance, m.
s_e	Slope of the energy grade line, m/m.
S.D	Standard deviation, m.
SDd	Stress day factor, (dimensionless).
SDI_d	Stress day index due to soil moisture deficit, (dimensionless).
SDI_w	Stress day index due to wet conditions, (dimensionless).
SDw	Stress day factor due to wet conditions, (dimensionless).
t	Time, day.
var	Variance.
V	Velocity, m/s.

V_d	Drainable pore volume, mm.
W	Drain spacing, m.
x_i	Water table depth on ith. day, m.
y	The height of the water table above the drain at midspacing, m.
y_1	The height of the water table above the impermeable layer at midspacing at $t=t_1$, m.
y_o	The height of the water table above the impermeable layer at midspacing at t=0, m.
YR	Relative yield, (dimensionless).
YR_d	Relative yield that would be obtained if only soil moisture deficit occurs, (dimensionless).
YR_w	Relative yield that would be obtained if only wet stress occurs, (dimensionless).
α	Alpha.
θ_s	Soil moisture content at saturation, percent.
θ_w	Soil moisture content at permenant wilting point, percent.

I INTRODUCTION

The world population is growing fast and is heading toward 6 billion by the end of the twentieth century (Wortman, 1976). The world wide rate of increase of food production must keep pace with the rate of population growth or widespread malnutrition, as famine, can be expected.

Land and water use are the essential elements on which the food production is based. Development and utilization of land and water constitute the foundation on which to sustain and increase crop production.

Soil moisture is one of the main natural elements of plant growth and should be balanced according to the needs of the plant. The availability of moisture for plants is controlled by rainfall, irrigation and drainage. Therefore, irrigation and drainage systems must be designed to provide sufficient moisture conditions for maximum agricultural production.

Drainage involves removal of excess surface water and lowering of the water table by means of ditches and subsurface drains to provide sufficient aeration in the root zone in a humid climate and control of salinity in soils in irrigated semi-arid areas.

In some humid areas where water surplus and water deficit occur, drainage alone may not be able to provide suitable moisture conditions for plant growth. Supplementary irrigation is needed to provide water during periods of drought to achieve adequate plant growth.

It is believed that subsurface irrigation can be used in conjunction with subsurface drainage systems to provide supplemental irrigation in drought periods with low cost and labour requirements.

Prior to 1974 in the St-Lawrence lowlands, only a small portion of subsurface drain installations have been made in sandy soils because of the lack of suitable envelopes to prevent sand from entering the drain pipes. With the advent of suitable envelope materials the installation of subsurface drains in sandy soils has increased rapidly.

The general practice in drainage design has been to install drains of the same depths in sandy soils as in clay soils. The subsurface drains have ranged in depth from 1.4 m to 0.9 m since this has given satisfactory results in clay soils and has allowed for long laterals with existing topography to reduce the length of drains required per hectare. The result for the medium and coarse sandy soils has been excessive drainage when the water table dropped to depths greater than 0.8 m, owing to their higher hydraulic conductivity and higher drainable porosity. Rashid- Noah (1981) reported that 30% of the soil volume was drained when the water table depth was at 1.2 m. This drained volume is considered to be excessive compared to the 15% air volume required for healthy development of crop roots. Especially in dry periods, the soils will lack moisture and result in physiological drought which reduces plant growth. Similar observations for these soils were reported by Miller et al., (1973).

In order to prevent excessive drainage and physiological drought, subsurface irrigation systems can be used. Subsurface irrigation is the cheapest form of irrigation system because the water distribution is provided by the drainage pipes. It can often be operated by installing water table control chambers and pumping water in, to raise the water table in the field. This method of irrigation is recommended in relatively flat land areas where alternate intervals of water surplus and water deficits occur.

Climatically, the province of Quebec may be suitable for subsurface irrigation because there is excess precipitation in winter and early spring, and often a shortage of rainfall in summer. In winter and early spring the water table can be lowered by subsurface drainage and in summer the water table can be raised for optimum crop production by adding water to the drain pipes.

Thus, the design of subsurface irrigation must meet the two main requirements, that is the system must be capable of removing all the excess water after periods of heavy rainfall, and supply the evapotranspirational demand during dry periods. Probably this is the most critical requirement for designing combined drainage and subsurface irrigation systems.

At present, Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec, has not established any design criteria. It is generally felt by various experts that theories for movement of water through soils under saturated and unsaturated flow conditions should be able to and be used with proper boundary conditions to design combined irrigation and drainage systems.

Various theoretical procedures are available ranging from steady state to non-steady state theories for the design of subsurface irrigation/drainage systems. Steady state theory (Hooghoudt's method) is preferred by the drainage designers because of its simplicity and the fact that it appears to give reasonable results when compared to non-steady state theory. However, these theories provide solutions for specific values of variables such as a steady rainfall rate or desired rate of water table fall. Since in reality the factors such as rainfall and evaporation cause the water table to fluctuate, the basis for a good design should be the prevention of undesirable patterns of water table fluctuations and the resulting effects on crop growth.

This can be done if the effect of water table and soil moisture content profiles on crop yield is known. There are some models available such as those of Hiler (c.f Hardjoamidjojo et al., 1982) and Shaw (1978) which do consider the effect of water table and soil moisture content on crop yield.

With the advent of computers, it is possible to make the many calculations needed to predict the water table depth and the variation of soil moisture content in the root zone with respect to time. This has given rise to the water balance approach which is sufficiently flexible to enable one to consider soil-water-plant parameters for the design of subsurface irrigation/drainage designs on a sound economic basis.

There are at least 30,000 hectares of sandy soils in the south- west region of Québec. The climate pattern of this region is such that 3 out of 5 years are dry years resulting in considerable crop losses (Lake and Broughton, 1969). Because of this, the capital investment required for a drainage system alone may not be justified. This situation, therefore, demands that rational guidelines be established to ensure maximum economic return for the design of subsurface irrigation/drainage systems.

The calculations for the spacing between subsurface irrigation laterals depend on soil parameters, such as hydraulic conductivity, profile depth and the water table depth which should be maintained during the growing season. The optimum water table depth depends again on the unsaturated flow properties of the soil, rooting depth and climatological factors. Thus, the design of subsurface irrigation includes consideration of both saturated and unsaturated flow properties of the soil. These properties are subjected to variability due to the complex nature of soil and water characteristics. Subsurface irrigation/drainage design is often done on a deterministic basis, using approximate values of uncertain soil water parameters. Therefore, the uncertainty in soil water parameters would result in uncertainty in the performance of the drainage and irrigation systems and hence, risks.

Given the problems encountered in the design of subsurface irrigation/drainage systems, a series of experiments were conducted to determine the feasibility of subsurface irrigation in Richelieu county, Quebec. The experiments described in this thesis are the first field scale subsurface irrigation experiments in Quebec. In recent years subsurface irrigation has begun to be used on a field scale in North and South Carolina and Florida in the U.S.A. Some of the results from our experiments in Richelieu county were used in the water balance model to obtain optimum subsurface irrigation/drainage designs.

II OBJECTIVES

The objectives of this study were selected as follows :

1. To layout the field experiment with two treatments, that is, irrigated and non-irrigated with 8 replicates and study the effects of subsurface irrigation on crop yield.

2. To define the optimum water table depth to meet the evapotranspirational demand by capillary rise using soil properties obtained from laboratory and field experiments.

3. To conduct a field experiment to observe water table depths in non-irrigated and subsurface irrigated plots of maize in order to evaluate the soil moisture regime above the water table.

4. To observe the soil moisture tension and moisture content of the soil profile in non-irrigated and subsurface irrigated plots of maize to investigate the upward flow from the water table to the plant roots.

5. To make economic analyses to show the maximum additional benefits obtained due to installation of subsurface irrigation with different design alternatives.

6. To examine the effects of uncertainty in saturated and unsaturated soil properties on subsurface irrigation designs.

7. To recommend guidelines for designing combined subsurface drainage and subsurface irrigation systems for sandy soils.

2.1 Scope

The results of this study will indicate the feasibility of a subsurface irrigation system and its effect on yield of maize. The study is restricted to the sandy soils of southern Quebec, Canada.

III REVIEW OF LITERATURE

3.1 Subsurface Irrigation/Drainage Theory

Subsurface irrigation , sometimes referred to as subirrigation , is the reverse of subsurface drainage. Therefore, steady and non-steady theory developed for drainage can be conveniently employed in subsurface irrigation with some minor changes in the initial conditions and boundary conditions. Whenever, drainage theory is the topic of discussion, subirrigation theory will be implicitly considered in it.

3.1.1. Steady state theory

A steady state is said to exist when a system -its boundaries and the flow rates along these boundaries- does not change with time. These boundaries and the flow rates of a system are time invariant.

Solutions to Laplaces' equation for hydraulic potential in problems of groundwater flow in drained lands provide a rational basis for the design of subsurface drainage installations.

The first elliptic equation for drainage was derived by Colding (1872) (c.f. van Schilfgaarde, 1957), assuming horizontal flow in the saturated region.

This analysis resulted in a drainage equation with the maximum water table height proportional to the square root of the rainfall rate. However, the principal limitation of the ellipse equation when used for tube drainage was that convergence of the stream lines near the drain is ignored.

Hooghoudt (1940) presented a refinement in the drainage equation using the Dupuit-Forchheimer (D.F.) theory. The D.F. theory assumes that the hydraulic gradient at any point is equal to the slope of the water table above that point. This implies that water flows horizontally because all the equipotentials are vertical planes. This is an erroneous picture of actual flow paths of water near the drain where flow paths are quite curved.

His analysis did take into account for the first time the effects of radial flow near the drains and the nearly horizontal flow at greater distance from the drains. His approximate equation may be expressed as (see Figure A-1, appendix A)

$$W^2=4k_s/q \; (2dm + m^2) \qquad ....(3.1)$$

Where W is the drain spacing, k_s is the saturated hydraulic conductivity of the soil, m is the height of the water table above the centre line of the drain at a point midway between the drains, d is the depth of impermeable layer below the drain and q is the drainage coefficient.

Considering Figure A-1, Appendix A, a steady state equation for subsurface irrigation can be derived using Hooghoudt's analysis. In this case the drainage coefficient, q, is replaced by the evapotranspiration rate, e, and subjected to boundary conditions for subsurface irrigation, i.e.

$$y = h_o + d \text{ at } x = 0 \quad \text{and } y = Y + d \text{ at } x = W/2$$

The resulting equation may be expressed as:

$$W^2 = 4k_s/e \; (2mh_o + 2md - m^2) \qquad \text{....(3.2)}$$

Where m is the deflection at a point midway between the drain which is equal to h_o-Y ; h_o is the height of water table above the drain at the drain and Y is the water table height above the drain midway between the drains. The derivations of equations 3.1 and 3.2 are shown in appendix A.

The convergence of seepage lines near the drains can be accounted for by substituting an equivalent depth, d_e, for d, as suggested by Hooghoudt. He provided charts for determining d_e or a function of depth to the impermeable layer and spacing between drains.

Moody (1966) examined Hooghoudt's solutions and presented the following equations from which d_e can be computed

For $0<d/W<0.3$

$$d_e = d/(1+d/W)\ \{8/\pi \ln(d/r_e) - \alpha\} \qquad ....(3.3)$$

in which

$$\alpha = 3.55 - 1.6d/W + 2(d/W)^2$$

for $d/W > 0.3$

$$d_e = W\pi/8\ \{\ln(W/r_e) - 1.15\} \qquad ....(3.4)$$

in which r_e = effective drain tube radius.

Kirkham (1958) avoided the simplifying assumptions of D.F. theory and made an analysis using potential theory. Kirkham's solution not only provides an estimate of drain spacing but also the distribution of pressure head in the flow zone.

These solutions are also more accurate than Hooghoudt's due to exact mathematical procedures but also, they are much more complicated. Wesseling (1964) indicates that

Hooghoudt's formula did not vary more than about 5% from those of potential theory.

During the last few decades and even today certain physical and mathematical assumptions have generally to be made in the derivation of drainage equations, leading to different mathematical forms for the same drainage situation. The drainage engineer is thus faced with a number of different design equations that claim to give reasonably satisfactory drain spacings, without any guide to their applicability. Kirkham (1966) reviewed steady state drainage theories for parallel drain lines and commented on the need for various equations to be compared for computing numerical values for the same drainage geometry. In more recent times, Lovel and Young (1984) made a comprehensive examination and compared the ten steady state equations for installation of parallel cylindrical drains laid above a horizontal impermeable layer. Based on several drainage equations reviewed, Hooghoudt's equation (3.1) was found to give results within the known solution obtained from hydrograph analysis.

From the above discussion, it appears that even though Hooghoudt's steady state equation is an approximate physical theory, it generally gives the results within the permissible error. Thus, it can be used with reasonable confidence for drain design purposes.

3.1.2. Non-steady state theory

Many drainage engineers have stated that the formulas which describe the water table in equilibrium with rainfall and irrigation water do not conform to the situation in the field when the water table is fluctuating. These fluctuating water tables are called transient or non-steady state as opposed to steady state in which the hydraulic head does not vary with time. Non-steady state problems, although far more difficult to solve than steady state problems, are of greater interest than the latter, in that, steady state conditions will seldom if ever be reached in the field.

The solution of non-steady state flow problems have been based on the assumption that there exists a distinct, single valued drainable porosity (or specific yield) representing the total fraction of the soil volume which is stored or drained from the soil profile with the rise or fall of the water table. Childs (1960) has pointed out that this assumption is in serious conflict with reality, where the volume of water drained or stored depends upon the increase or decrease in tension in the pore water.

There are two types of theories applied to the solutions of the drainage problems in non-steady state condition. One is the potential theory from which Laplace's equation is derived. Since this equation is time invariant, its application to non-steady state requires that the time variable be introduced by means of the boundary condition. Another theory that has been widely used for non-steady state is Dupuit-Forchheimer theory. Both of these theories can be used to study the rise and fall from a known initial condition in the presence or absence of precipitation (van Schilfgaarde, 1970).

Numerous methods have been presented for describing rise or fall of the water table. In general these methods require D.F. assumptions which give rise to a non-linear partial differential equation (P.D.E.), sometimes referred to as the Boussinesq equation. Because this non-linear P.D.E. is difficult to solve it is frequently linearized (Polubarinova-Kochina, 1962). Several investigators such as Glover (Dumm, 1954); Werner, 1957; Maasland, 1959; Terzidis, 1968; linearized the Boussinesq equation in many ways and solved it by analytical methods.

Analytical solutions were made by Boussinesq and subsequently by Glover (Dumm, 1964) when the drains rest on the impermeable layer. When the drains do not rest on the impermeable layer then the analytical solution using the Boussinesq equation breaks down. One may then resort to linearization and then solve the equation. However, van Schilfgaarde (1963) found an analytical solution of this equation. The solution thus obtained still fails one of the boundary conditions. This shortcoming can be alleviated by considering the drawdown process as a sequence of small steps (van Schilfgaarde, 1964).

An entirely different and simple approach to derive an equation for falling and rising water table conditions was proposed by Bouwer and van Schilfgaarde (1963). Their method uses the combination of steady state and water balance equations in which they assumed uniform flux for the rise or fall of the water table. This assumption has limited validity because the water table rise or fall varies with distance from the drain. They introduced a correction factor C in their resulting equation. The factor C is defined as the ratio of the average flux between drains to the flux midway between drains. This factor varies from 0.8 to 1.0.

3.1.3. Rise of water table

During irrigation, the water level is maintained at a constant elevation in the control chamber at the outlet. Subsequently, subirrigation is continued by raising the water level at the mid-spacing to an optimum depth which is sufficient to meet ET demands to the root zone. The time required to raise the water table to a depth sufficient to provide ET demands depends on the initial water table depth, initial moisture content of the profile, ET rate at that time, drain depth and drain spacing. The length of time required to raise the water table to a predetermined depth will be more for the deeper water tables than for the shallower ones. How deep the water table could be, depends on the management practices and instrumentation. In the design of a subsurface irrigation system, this aspect must not be ignored otherwise crop loss may occur during the length of time required to raise the water table.

Skaggs et al., (1972) have conducted subsurface irrigation experiments for various drain spacings and measured water table movement at the mid-spacing. They found that the time to raise the water table increased as the drain spacing increased.

While steady capillary rise is an important phenomenon in subsurface irrigation design, the transient process (rise of water table) is also important. Approximate methods for predicting water table rise for both initially horizontal and draining profiles have been presented by Skaggs (1973).

A similar approach to that of Bouwer and van Schilfgaarde (1963) discussed in section 3.1.2. can be used to determine the time to raise the water table to a predetermined depth. If the water table is assumed to rise without any change of shape, the flux per unit area of water table is uniform between drains. Therefore, steady state subsurface irrigation equation 3.2, which also assumes uniform flux can be used to predict a rise of water table at the mid-spacing

$$dy/dt = e/f \qquad \text{....(3.5)}$$

where y is the height of water table midway between the drains above the centre of the drain, e stands for evapotranspiration rate and f is the drainable porosity.

Solving equation (3.5) for e and substituting equation (3.2) and integrating between t_o, y_o and t, y yields,

$$t-t_o = fW^2/\{8k_s(d+h_o)\}.\ln[\{(h_o+2d+y)/(h_o-y)\}/\{(h_o+2d+y_o)/(h_o-y_o)\}] \qquad \text{....(3.6)}$$

In reality it is not possible that the water table rises uniformly without change of shape. Skaggs et al., (1972) observed in the field experiment that the water table was not rising after the initiation of irrigation. It remained stationary for a long time even after the water table over the drain reached at the maximum height. Bouwer and van Schilfgaarde (1963) treated a similar situation for a drainage case by introducing a correction factor 'C', then equation (3.5) may be expressed as:

$$e = fC\ dy/dt \qquad \text{....(3.7)}$$

Where 'C' is defined as the ratio of the average upward flux to the flux midway between the drains. Because the upward flux at the mid point is zero, the factor 'C' is undefined for the initial period of subsurface irrigation (Skaggs et al., 1972). Thus equation (3.6) is valid only for the period when water table is rising upward.

Skaggs (1973) has obtained a numerical solution of the Boussinesq equation for subsurface irrigation boundary conditions. He presented non-dimensional solutions in graphical form for various evaporation rates. These solutions can be used to calculate the time to raise the water table at various evaporation rates. The drawback in this equation is, that it does not consider the unsaturated flow.

However, efforts have been made in solving Richard's equation for both saturated and unsaturated conditions and compared with solutions of the Boussinesq equation (Skaggs and Tang, 1976). In their analysis it was observed that both solutions were not different from each other when variable drainable porosity was used in the Boussinesq equation.

The solutions of combined saturated and unsaturated flow are too complicated and are far beyond the practical application. Moreover, these methods require effective values of soil properties which are difficult to obtain due to field variability. Therefore, there is little to be gained with the complicated solutions compared to using the simpler and approximate methods.

3.2. Subsurface Irrigation/Drainage Systems

Subsurface drainage and subsurface irrigation systems can perform both drainage and irrigation functions dependent on the prevailing climatic conditions. In wet conditions, the water table is lowered by subsurface drainage in order to prevent crop damage due to excessive soil water. In dry periods, the water table is raised by pumping water into the water table control chambers to supply water to the growing crops. If the system is properly designed, both drainage and irrigation may increase the production and maximize net returns. Moreover, subsurface irrigation systems have many advantages compared to other types of irrigation systems.

1. The initial cost of subsurface irrigation systems is very low, because most of the cost is attributed to the drainage system.

2. The energy costs for subsurface irrigation are smaller than for most other irrigation systems.

3. Subsurface irrigation has lower labour requirements than other irrigation systems.

4. High crop yields are possible.

Subsurface irrigation is practiced in some parts of the Netherlands (Kalisvaart, 1958) and United States (Renfro, 1955). However such systems have not yet been used to their full potential because they are difficult to design. The design procedure for drainage is more established than for subsurface irrigation in terms of spacing and depth of subsurface pipes. The critical factor in the subsurface irrigation mode is to raise the water table from the initial water table depth. The response time to raise the water table increases as the water table depth increases. For example, placing the drain pipes at 2 m depth in sandy soils would have probable water table depth of about 1.6 m early in the growing season. Raising the water table from 1.6 m to a depth of 0.6 m would require more time than if the drains are placed at a depth of 1.2 m.

Fox et al., (1956) pointed out the advantages and disadvantages of subsurface irrigation systems. They stated that subsurface irrigation holds promise, and if properly designed and operated, might be the best method available. They presented a simple procedure for determining ditch spacings required to maintain desired water table elevations. Fok et al., (1971) analysed the water distribution pattern around subsurface drainage pipes to determine the spacing, depth and required discharge using algebraic manipulations. However, the above studies did not include field experimental evaluations.

Skaggs (1979) discussed the important water movement factors for the design of subsurface irrigation systems and characterized subsurface irrigation under steady state and transient conditions. The transient state was based on the Boussinesq equation which was solved numerically under subsurface irrigation boundary conditions. The results from the field (Skaggs, 1979) for different drain spacing of 75, 30 and 15 m were compared to the numerical solution (Skaggs, 1973). A fair agreement between observed and calculated values of water table movement was found. Bouwer (1959) and, Swell and van Schilfgaarde (1963) presented methods to solve the governing differential equations for unsaturated steady state flow under subsurface irrigation boundary conditions. However, both solutions encounter the relationship between k and h, which are generally difficult to obtain for many soils.

There is a lack of established criteria for subsurface irrigation using subsurface drainage systems. The practice is not widely established. However, the critical factor affecting subsurface irrigation is to raise the water table to a height where the roots can get sufficient water during peak transpiration periods. Ultimately this depends on the spacing, depth of drain, soil water properties and initial water table height. With regard to the spacings for subsurface irrigation pipes, Kriz and Skaggs (1973) showed that sufficient water can be supplied to the root zone of the crop on Lumbee sandy loam with a 17 m drain spacing. The results of Skaggs et al., (1972) showed that 7.5 m and 15 m drain spacings have supplied enough water to the root zone, but a 30 m drain spacing was not able to supply enough water to the root zone on Fallsington fine sandy loam soil. A 30 m drain spacing was needed for good subsurface drainage in wet periods on this soil. This indicates that both subsurface drainage and subsurface irrigation systems should be considered in the design for a successful operation.

3.2.1. Upward flow from the water table

In subsurface irrigation design the water is supplied through the control structure into the drain tube to raise the water level in the soil to a height such that water can be transmitted by capillary rise to the effective root zone at steady rates. The water table is kept constant at that height throughout the growing season to meet the demands of evapotranspiration.

Moore (1939) was probably the first person to investigate the upward flow in soil cores by introducing water at the base of the column (imbibition) and allowing evaporation at the top of the column. He concluded that coarser soils supported higher evaporation rates at greater depths to the water table.

Upward flow from water table to the root zone is in the unsaturated zone. Therefore unsaturated flow properties of the soil are of much interest in subsurface irrigation design. Gardner (1958) analysed the steady upward flow from soils with shallow water table depths. He solved the governing equation with the functional relationship between unsaturated hydraulic conductivity and pressure head, k=f(h). Gardner presented a simplified expression for steady upward flux in terms of water table depth. The results of laboratory experiments supported the relationship between upward flux and water table depth (Gardner and Fireman, 1958).

Willis (1960) has obtained the relationship between upward flux and water table depth solving the steady state flow for layered soil. While Parlange and Aylor (1972) have solved the governing equation for transient flow.

For steady unsaturated flow, the upward flux is constant everywhere and the governing equation may be written as:

$$d/dz\ [k(h)\ dh/dz - k(h)] = 0 \qquad ....(\ 3.8\ )$$

where h is the soil water pressure head, z is measured downward from the surface and k(h) is the unsaturated hydraulic conductivity function. Numerical methods can be used to solve equation (3.8) for water table depth at a given steady upward flux. The upper boundary in this case may be taken as the bottom of the root zone. The lower boundary is usually taken as the water table depth where pressure head h equals to zero.

There are several other ways of estimating the relationship between upward flux and water table depth in the absence of k(h) and Θ(h) relationships. Empirical equations can be used to calculate the functional relationship of k(h) and Θ(h), selecting parameters based on soil texture. Anat et al., (1965) derived the governing equation by assuming the Brooks and Corey (1964) form of hydraulic conductivity function. A similar equation for maximum upward flux was derived by Raats and Gardner (1974).

Another approach for determining maximum upward flux may be obtained by using the concept of matric flux potential (MFLP) discussed by Shaykewich and Stroosnijder (1977). The MFLP ($m^2\ s^{-1}$) may be defined as:

$$MFLP(h) = \int_{h_o}^{h} k(h)dh \qquad ....(3.9)$$

Equation (3.9) can be integrated between some lower limit of pressure head, h_o, at which the moisture content is Θ_o and allowable pressure head, h, at which the water content is Θ. For steady state flow,

$$q = k(h)\left(\frac{dh}{dz}\right) - k(h) \qquad \text{....(3.10)}$$

If one assumes a steady state situation between two points in the soil at some finite distance $z_2 - z_1$ equals to Δz, to approximate equation (3.10).

$$q_u = -k(h) + 1/\Delta z \int_{h_o}^{h} k(h)\,dh \qquad \text{....(3.11)}$$

Using the MFLP concept

$$q_u + \overline{k}(h) = 1/\Delta z \;[\mathrm{MFLP}(h) - \mathrm{MFLP}(h_o)] \qquad \text{....(3.12)}$$

The procedure to get maximum upward flux involves the calculation of MFLP at different suction heads, until the limiting, h_{max} is reached. Then maximum upward flux is calculated using equation (3.12). Shaykewhich and Stroosnijder (1977) showed that MFLP is a more exact method in simulating water movement than other methods up to date because it combines both parameters controlling water flow (hydraulic conductivity and hydraulic head) into a single parameter.

Above methods for developing a relationship require that unsaturated hydraulic conductivity function, k(h) must be obtained as previously explained.

It is generally difficult to determine unsaturated hydraulic conductivity, k(h). The next alternative is to determine k(h) from soil moisture characteristics of the soil. These characteristics are relatively easier to determine than the k(h) function.

A number of prediction methods have been proposed and were reviewed by Bouwer and Jackson (1974). Recently Mualem (1976) proposed a model to predict k(h) based on θ(h) curve. His model is based on closed-form analytical expressions and has been extended and described in detail by van Genuchten (1980). Among the most frequently used methods are those predicted by Millington and Quirk (1961) and Marshall (1958). Experimental evaluation of these methods shows that when a matching factor is used to force the calculated and measured conductivities to agree at a given water content, usually saturation, reasonable results are obtained (Hillel, 1980). When the matching factor is based on the saturated hydraulic conductivity, both the Millington and Quirk and Marshall equations can be written in the following form (Jackson, 1972).

$$k(\theta_i) = k_s(\theta_i/\theta_s)^p \frac{\sum_{j=i}^{m} (2j+1-2i)/h_j^2}{\sum_{j=1}^{m}(2j-1)/h_j^2} \quad \text{....(3.13)}$$

Where $k(\theta_i)$ is the calculated conductivity at water content θ_i, k_s is the saturated hydraulic conductivity, θ_s is the saturated water content, m is the number of water content increments equally divided on the soil moisture characteristic curve (usually between 10 and 20 is adequate) and i and j are indices. The exponent, p, is a constant originally given the value of 4/3 in the Millington and Quirk formulation and 0 for Marshall. A p value of 1 had been found to give better results (Jackson, 1972). The pressure head h_i is taken in the middle of each increment where θ_i has the largest value for each water content increment. In other words, h_i is taken between θ_i and θ_{i+1}. The hypothetical plot of θ versus h is shown in Figure 3.1 which illustrates this procedure.

3.3. Optimizing Subsurface Irrigation/Drainage Designs

The design requirements express the agricultural function of the subsurface irrigation/drainage system interms that can be used as input information to maximize the economic returns from the farm enterprise. Therefore the design requirement should express the optimum drain spacing by which increase in profits can be a maximum due to installation of subsurface irrigation. This criteria of

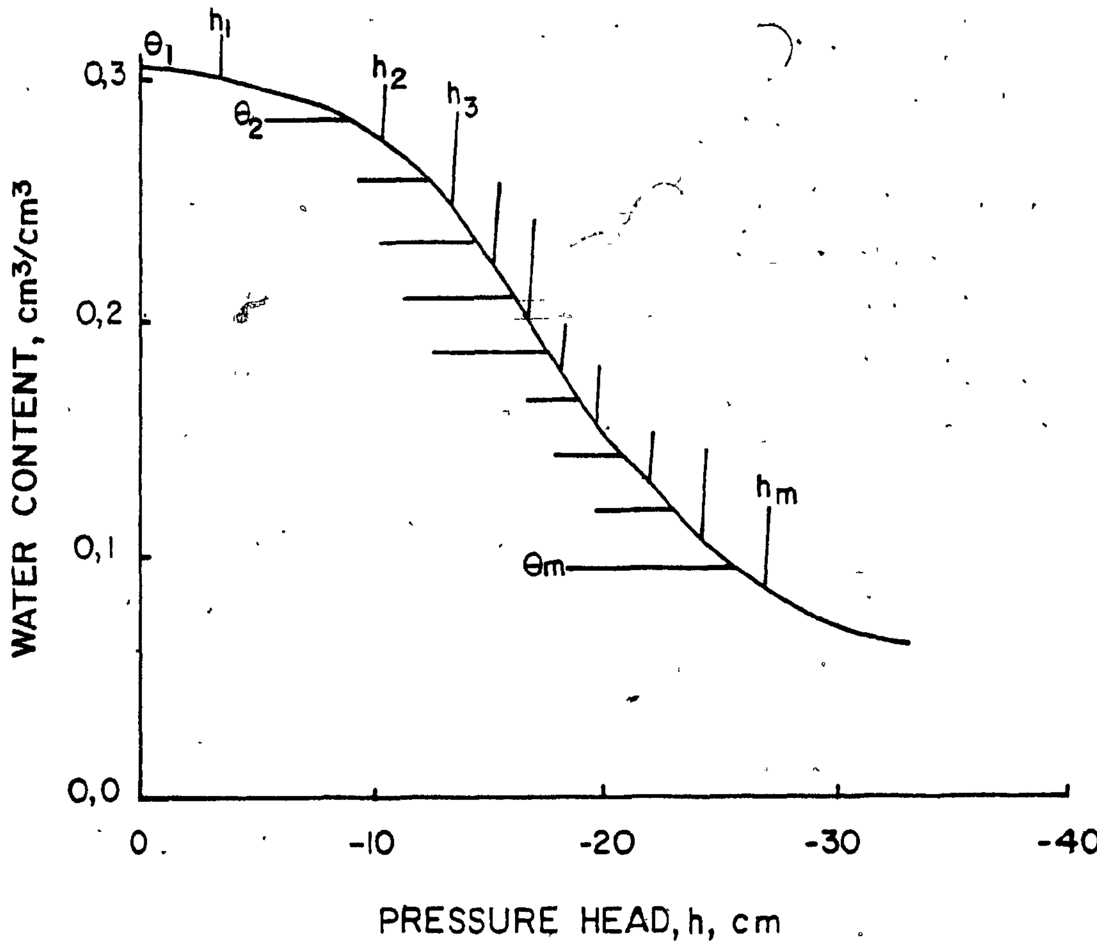

Figure 3.1. Hypothetical water content-pressure head curve showing equal water content increments and correspondig pressure heads used to calculate the unsaturated hydraulic conductivity.

designing subsurface irrigation can be obtained from a water balance approach and agricultural production functions.

The basic idea in the water balance approach is to compute the changes in soil moisture in response to the input of precipitation and outputs of evapotranspiration, drain outflow and deep seepage. Mathematical book-keeping equations are used to balance the input and output for some specific time intervals.

Optimal design of subsurface irrigation/drainage systems has received less attention in the literature. There are very few studies such as Bhattacharya, (1977); Skaggs,(1978); Skaggs and Nassehzadeh-Tabrizi, (1982) and Durnford et al., (1982) have optimized the drainage system on the net benefit approach. However the author did not find any study in the literature in which optimization of subsurface irrigation was considered with respect to increase in revenue.

Bhattacharya (1977) used the water balance and an integrated economic model to compute the losses and associated probabilities and the average annual loss for corn. The design criteria was based on an average net revenue increase due to the installation of subsurface drainage.

Skaggs (1978) developed a DRAINMOD for the design and evaluation of multi-component water management systems to establish design parameters from which subsurface drainage, subirrigation and sprinkler irrigation systems can be designed. The design of the optimum system was based on water management system objectives such as working day, SEW_{30} and dry days. He did not consider the agriculture production function for the evaluation of a water management system. Skaggs and Nassehzadeh-Tabrizi (1982) integrated the crop model with DRAINMOD for optimization of drainage system design.

Earlier studies by Wiser et al., (1974), optimized the design of a subsurface drainage system. He considered the optimum design in the sense that it maximized the amount by which the system benefits exceeded the system cost.

All the above studies dealt with the design of subsurface drainage systems. However, subsurface irrigation is becoming popular in the humid areas having alternating periods of water surplus and deficit. It should be mentioned that either too much or too little water is detrimental for crop growth. Considering the increase in drainage installation cost, crop production cost and farm land prices, there is no alternative but to search for better and more efficient water management systems.

The aims of subsurface irrigation/drainage in humid regions are to provide an adequate water supply when dry conditions occur during the growing season in order to avoid drought stress on the crop and to remove excess water that accumulates during the wet periods in the growing season in order to avoid the effects of excessive soil moisture on the crop. Minimizing these two conditions would result in an optimum design of subsurface irrigation/drainage systems.

3.3.1. Effect of soil moisture deficit on crop yield

As the reservoir of water in the soil is depleted, plant dehydration increases such that physiological activity in the plant is affected. Thus, the development of water deficits in the plant is described together with their effect on physiological and morphological processes. Soil moisture is essential to maintain turgidity, meet transpiration requirements and serves as an important constituent of plant cells. Soil moisture deficit usually accompanies high temperatures from the reduced cooling effect due to reduced evaporation of water caused by stomatal closure. Glover (1959) found that the stomata of corn plants exposed to severe drought over periods of one week or more never seem to be fully open. This indicates that stomata are severely damaged by long periods of drought which will cause subsequent reductions in yield even if soil water levels become adequate following the drought (Waldren, 1983).

The development of crop water use simulation models is fairly recent. However, there exists today a large number of crop and soil water balance models varying widely in sophistication and use. Some models have been developed primarly to estimate the water consumption for use in scheduling crop irrigation. Other models such as those developed by Ritchie (1977) and Arkin et al., (1976) can be used for irrigation scheduling but are also used to estimate plant yield by relating water stress at various growth stages in the plant's life cycle to dry matter or grain yield.

Yield response to soil moisture stress is important in developing strategies for irrigation management and provide economic evaluation. Indeed, this relationship is quite complex and is related to many other factors such as fertility status, critical growth stages, lodging, disease, insects and climate. Many of the functions used are statistical in nature. These functions are developed by Morey et al., (1980), Musick and Dusek (1980), Hillel and Guron (1973) and deWit (1958).

Other models incorporated many factors such as CO_2 availability, photosynthesis rate and complete climatic conditions to predict yields. The work of Childs et al., (1977) and Duncan et al., (1971) are the examples of these models. Again other models used the dynamic approach. An example of such an approach is Burt and Stauber (1971) and Morgan et al., (1980). The former used five 10-day periods. The latter authors used daily available soil moisture to obtain a relationship with corn yield response using previous information on dry matter accumulation in the plant when the water is not limiting. Although these models are accurate, the requirements for numerous inputs limited their applicability.

Daily predictions of evapotranspiration from soil moisture budgets can be combined with plant growth models which include the stress day concept developed by Hiler (1969) and used by Hiler and Clark (1971), Hanks et al., (1969), Sudar et al., (1979) and Shaw (1978). Each of these models exhibited reasonable accuracy. Shaw's model was based on extensive research in Iowa, (USA) and uses the crop susceptibility factor for corn, developed for 5- day intervals relative to silking (Shaw, 1976) during 90 days growing period. While Hanks (1974) divided the growing season into 5 periods and used a crop susceptibility factor during those five periods. The SPAW model developed by Sudar et al., (1979) is similar to Shaw's model. SPAW model, however, did not consider the adjustment of the root distribution as it is incorporated in Shaw's model.

3.3.2. Effect of excessive soil moisture on crop yield

Crop production is not only reduced by deficient soil moisture conditions but it is affected by excessive soil moisture condition as well. It is well recognized that excessive soil moisture condition affects aeration (poor gaseous exchange), influences heat properties of the soil and reduces the nitrogen by denitrification. Excessive soil moisture can cause flooding conditions which tend to reduce transpiration, photosynthesis, moisture and nutrient uptake. The end result is that the crop yields are drastically reduced.

In order to design an efficient subsurface irrigation/drainage system which ensures a suitable soil environment for maximizing production, the relationships between crop yields and excess soil water are required (Morey et al., 1975).

Some earlier studies reported by Wesseling (1974) related soil properties such as aeration or thermal conductivity to crop growth. These properties are difficult to determine. Therefore, water table depth was used as an indicator of crop growth. Although the water table depth does not have direct influence on crop growth, it indirectly determines the prevailing moisture conditions, water supply, aeration and thermal properties of soil.

In most of the studies optimum water table depth is defined for each soil type and crop specie (see table 2.2 given by Wesseling, 1974). A more important relationship for humid regions is the effect of intermittent flooding and high water table depths.

Sieben (1964) studied the effect of fluctuating water tables on yield. He took a 30 cm water table depth below the soil surface as a critical level and computed so called SEW_{30} values from,

$$SEW_{30} = \sum_{i=1}^{n} (30 - x_i) \qquad \text{....(3.14)}$$

Where x_i represent daily water table depths below the soil surface on ith day during the growing period (full year) and n is the number of days in the growing period. For this computation only x_i values less than 30 cm from the soil surface are summed over a growing period. Nibler and Brooks (1975) used this concept and found significant correlation with SEW_{30} values and yields.

Hiler (1969) advanced the stress day index (SDI) method to characterize the effects of water stress on crop yields. The concept provides a quantitative means for determining the degree of stress imposed on the crop during the growing period. The concept is applicable for characterization of both irrigation and drainage requirements (i.e. excessive and deficient soil water). The SDI is determined by multiplying the crop susceptibility factor (dependent upon variety and stage of development of the given crop) and SD (stress day) factor (measure of the degree of stress caused by excessive soil water conditions). In this concept, SDI is inversly related to the crop yield. This means that minimizing the SDI value would maximize the crop yield.

The crop susceptibility factors for excessive soil water conditions were estimated by Hiler (c.f. Hardjoamidjojo et al., 1982) for corn. The growing period of 80 days until maturity of the corn was divided into three growth stages and crop susceptibility values were determined experimentally.

Hardjoamidjojo et al., (1982) used this concept and characterized the effect of soil water on corn yields. They developed a regression model which was tested with the data of two other localities. A good agreement was found despite the differences and variations in the experimental conditions among them. Furthermore, they claimed that the SDI-yield model can be used for all the conditions.

Skaggs and Nassehzadeh-Tabrizi (1982) used an SDI-yield model for North Carolina conditions and found reasonable agreement. Further, they used this model to optimize the drainage system for a corn crop.

3.4. Crop Performance

Experience with subsurface irrigation described in the literature has shown some encouraging results in terms of crop performance. In Texas, Zetzch (1964) has shown that cotton yielded more in subsurface irrigation plots than in furrow irrigation plots and the former required 42% less water. Buch and Kneebone (1965) reported 340 Kg increase in cotton yield with subsurface irrigation over the non-irrigated plots.

In some places controlled drainage is used to conserve moisture for plant use. In such a system, prolonged drought conditions may cause the water table to drawdown to a depth such that no more water can be supplied to the root zone by capillarity. The plants could be stressed as long as the drought continues. Doty et al. (1975) have experienced this condition in which they found that controlled drainage has given better yields than the drained field, but due to the drought period the growth of the plant was still retarded. If water was pumped into the system this would have been more beneficial at the time of drought.

In subsurface irrigation, the capillarity from the water table to the root zone plays an important role in supplying the evapotranspirational demand. Therefore the water table should be controlled to an optimum depth where plants can receive water through capillarity. The relationship between water table and silage yield of corn was investigated by Doty et al., (1975). They found that the silage corn yield increased by 500 Kg/ha for each additional day the water table was maintained at less than 1 m from the surface in sandy coastal plains soil. While Follet et al., (1974) have reported the yields were maximum in plots over a water table, 60 to 90 cm below the soil surface. Williamson and Kriz (1970), Wesseling (1974) and Doty et al., (1979) reviewed literature on the response of agricultural crops to different water table depths.

Recently, Doering et al., (1982) found that optimum yields of corn and sugar beets were obtained at a water table depth of 1m on sandy soils in North Dakota, USA.

Obviously descrepancies exist regarding optimum water table depth for maximum crop production. However, it is difficult to transfer the results from one location to another. Optimum water table depth depends on the climatical conditions, crop species and soil physical conditions.

For maximum crop production, it is recommended to supply enough water for evapotranspirational requirements and maintain the root zone with approximately 15% air volume.

3.5 Uncertainty Approach To Subsurface Irrigation/Drainage Design

Conventional subsurface irrigation/drainage designs are based on consideration of saturated flow properties of soils. Efficient design of a subsurface irrigation/drainage system requires the characterization of both unsaturated and saturated flow. Rigorous treatment of combined saturated-unsaturated flow has been followed by Rubin (1968) and Watson (1974). It involves numerical solutions of Richard's equation for appropriate boundary conditions and effective values of soil properties. While this approach is adaptable to most boundary conditions of interest, numerical solutions are often difficult to obtain (Tang and Skaggs, 1977). It is also difficult and expensive to obtain effective soil properties. It is frequently argued that the variability of soil parameters prohibit the use of more vigorous treatment of exact methods which are not worth their cost.

Different techniques ranging from purely analytical (Bakr et al., 1978) to fully numerical (Freeze, 1975) have been employed in analysing initial-boundary value problems of groundwater flow.

The uncertainties occur either because of inadequate or inaccurate field measurements or because of natural causes such as those associated with drying and wetting of the soil profile due to recharge from natural precipitation and to discharge through evapotranspiration.

Spatial variations of soil parameters such as hydraulic conductivity and infiltration even in uniform land areas manifest large variations. Nielsen et al., (1973) conducted an experiment on 150 hectares of land to evaluate the magnitude of spatial variation on a soil considered generally uniform relative to most cultural practices. Their results showed larger spatial variation in unsaturated hydraulic conductivity than the other parameters such as steady infiltration rate, particle size distribution and bulk density. The cause of variation may probably be a range of textural differences within horizons which is not generally covered in a mapping unit when soil series are mapped on smaller scales. The variation in soil parameters manifest uncertainty in the design and therefore, the risk.

The traditional approach to the design of subsurface irrigation/drainage flow is deterministic. If a property has been measured at a few locations, its distribution in space is determined by some kind of smooth interpolation, and then the flow problem is solved by using the appropriate differential equation. This approach is open to criticism for two reasons : first, the variables of interest do not vary in a regular manner on space. Second, in practice the measurements are generally scarce i.e. only a few points, and values at other points are subjected to uncertainty.

Also the deterministic models are derived from basic assumptions to keep the analysis tractable. There can often be uncertainty due to such assumptions. Therefore, deterministic models should be modified to account for various uncertainties. To overcome these difficulties stochastic modelling has been used with increasing frequency in the last few years. It has become quite common to regard flow variables as random variables characterized by probabilistic distributions rather than by some deterministic values.

A Stochastic model offers, in a sense, a direct approach to determine the random effects on soil parameters. A stochastic analysis generates equiprobable input traces, with each trace having similar statistical properties. The probability distributions of system response are used for design and operation decision making.

van Schilfgaarde (1965) used the steady state equation obtained by Kirkham based on potential theory to develop a relationship between water table and intermittant rainfall.

He studied the risk of failure of a drainage system due to the uncertainty in rainfall by running a drainage model with a long historical record. Extensions have been made to this approach by Young and Ligon (1972), Foroud (1974), Chieng (1975) and Skaggs (1978).

Various approaches are available to treat the effects of uncertainty on groundwater flow. Two main approaches have been followed so far. One is the geostatistical approach applied by Russo (1983) in the design of trickle irrigation systems in a heterogeneous soil. The second line is that of groundwater modelling by stochastic differential equations applied by Freeze, (1975); Sagar, (1978); Bakr et al., (1978); Dagan (1979) and Smith and Freeze (1979).

The main difference between the two aforementioned approaches is that the geostatistical methods take into account measured values as given and fixed and allow for random fluctuation at other points of the formation. In contrast, stochastic modelling assume that the hydraulic properties have some statistical structures and that they fluctuate everywhere according to the corresponding probability density functions.

The stochastic differential-equation models of groundwater flow can be divided into two main groups : Full distribution analysis and first and second moment analysis. In full distribution analysis a complete specification of the probabilistic properties of all stochastic inputs and parameters of a flow system is obtained and is used to yield completely the probability distribution of the resulting flow. The two most important full distribution techniques are the method of derived distributions and Monte Carlo simulation. An example of derived distribution analysis is Eagleson's (1978) recent evaluation of infiltration due to stochastic precipitation events and Sagar and Kisiel's (1972) examination of parameter uncertainty for aquifer pump tests. The Monte Carlo simulation has been applied to the investigation of the effects of spatial variability of physical properties of flow through porous media by several authors, including Warren and Price, (1961); Freeze ,(1975) and Smith and Freeze, (1979). The flaw in the Monte Carlo simulation is that the results obtained are never in the closed analytical form that a derived distribution strives for and therefore, are not readily transferable to a new situation (Dettinger and Wilson, 1981).

In contrast, the first and second moment methods assume that the information about the random variable (or function) are sufficient to characterize a mean representing the central or expected tendency and the variance and covariance representing the amount of scattering around the mean. An example of a random variable or function fulfilling this assumption is one which is normally distributed. The only restriction or limitation of this method is that the coefficient of variation must be small.

Dettinger and Wilson (1981) underscoring the advantages of first and second order analysis over the Monte Carlo technique stated that "the numerous simulations required by the Monte Carlo technique can lead to an enormous computational burden when an aquifer requires detailed modelling and has complicated boundary conditions, heterogenous parameters, and two or three dimensional flow. The computational burden will generally place serious limitations, raised both by economics and expediency, on the accuracy with which estimates of probabilistic parameters can be obtained. Since the accuracy of Monte Carlo experiments is an increasing function of the number of simulations carried out. Because of these limitations on the use of other methods of analysis, first and second order analysis of numerical models are a natural choice and can generally be made with an accuracy consistent with the accuracy of the numerical model itself".

In addition to the above advantages, Benjamin and Cornell (1970) suggested that in many situations it is not possible to predict the exact value because of the very nature of the random variable (or function). However, the mean, variance and covariance are often sufficient on which to base engineering decisions.

Prasher (1982) has employed the first and second moment method to study the effects of parameters uncertainty in subsurface drainage design. He estimated the risk (standard deviation) considering the drainage parameters in the design of a drainage system.

To design an optimum water table sufficient to provide water supply to the root zone, unsaturated flow characteristics, root density and above ground environment are considered. A method for subsurface irrigation design that includes uncertainty due to unsaturated and saturated flow parameters has not yet been developed.

In view of the above facts, the first and second moments method is used to evaluate the uncertainty in the design of a subsurface irrigation system which includes the uncertainty in the unsaturated and saturated flow parameters. This approach can be applied readily. It gives the necessary information regarding the parametric uncertainty than other methods which are impractical to incorporate in day-to-day designs.

The technique for the analysis of uncertainty will be discussed in chapter VII.

IV THEORETICAL CONSIDERATION

4.1 Model Specification And Development

In a humid area, surface and subsurface drainage systems are necessary to lower the water table in order to provide trafficable conditions for seed bed preparation and planting in the spring and for harvesting in the fall. The prevailing drainage design practice has been to install deep drains to minimize the length of drains per hectare. The result is that, sandy soils drain excessively owing to their higher drainable porosity at the higher water tensions, achieved from the water table associated with deep drains, as compared to shallow drains. When rainfall does not occur regularly, crop production is reduced because of water stress during the growing season. It is possible to avoid excessive drainage by putting a water level control chamber on the subsurface drain collector pipes to prevent the water table from dropping to the level of the subsurface drains. This allows plants to extract more water from the soil profile. It is expected that this system will not provide assistance during long dry spells when drainage water is not available. The next alternative is subsurface irrigation in which a control chamber is placed at the outlet and water is pumped into the control chamber to maintain a constant water level elevation, so as to keep the water table at a more or less steady state in the field.

Some advantages of subsurface irrigation are obvious because the same system is integrated to perform dainage in spring and fall and provide irrigation in summer months with addition of little cost. But the difficulty is its design to ensure proper functioning in both drainage and irrigation modes. The design procedures are not established as those in subsurface drainage design.

The method adopted in this chapter is to develop a water balance model to analyze the effect of subsurface irrigation/drainage systems on soil water conditions and to predict their effects on annual average corn yields. The methodology is an attempt to provide an economical optimum subsurface irrigation/drainage system on sandy soils. An optimal subsurface irrigation/drainage system is defined as one which provides the maximum economic benefits.

In modelling the physical system, a soil column which extends from the impermeable layer to the surface, is located midway between adjacent drains and is assumed to be homogeneous. The soil column is divided into two zones, a dry zone and wet zone (Skaggs, 1978). The depth of the dry zone is a function of the effective root depth during the growing season. The wet zone depth extends from the water table up to the root zone and possibly to the surface of the soil. It is assumed that separate soil water distributions in two zones will adequately describe the physical process of the entire soil column from the surface to the impermeable layer.

The available moisture capacity (AWC) of a dry zone which is assumed to have a maximum depth equal to the rooting zone depth and is defined as the moisture held between the saturated moisture content, Θ_s, and the permanent wilting point, Θ_w. It is assumed that the plant roots extract water down to some lower limit (permanent wilting point).

The water content distribution in the wet zone is assumed to be that of a soil profile which has achieved drained to equilibrium. This assumption is consistent with the theoretical study of Skaggs and Tang (1976), who have shown that, except for the region close to the drains, the pressure head distribution above the water table during drainage may be assumed nearly hydrostatic for many field scale drainage sytems.

From the initially saturated soil column, moisture depletion takes place due to AE and drain outflow (q), and the depth of the wet zone increases. Drain outflow continues as long as the water table is above the drains or the drain overflow level. AE continues to deplete moisture from the wet zone as long as upward movement of water is sufficient to meet ET demands. When upward movement of water determined as a function of water table depth is not sufficient to supply ET demands, the rest of the water is removed from the root zone storage creating a dry zone. When the dry depth becomes equal to the root depth then AE is set equal to the upward water movement.

In determining soil moisture distribution in the dry zone, It is assumed that the AE is equal to PE when available moisture of the dry zone is between Θ_s and Θ_{50} (50% of the available moisture capacity) (Figure 4.1). When available moisture is below Θ_{50} but larger than Θ_w, it is assumed that the AE decreases linearly with available moisture. This assumption is consistent with that of Feddes and Zaradny, (1977). In the event of rainfall, the dry zone has to be filled first until its capacity is reached and then till the wet zone is filled. Any excess after that is considered to be surface runoff.

Since the water balance model predicts water table depth, it requires a method by which it calculates this depth. The method used here requires that there be a relationship between irrigation/drainage volume and water table depth. This relationship determines how far the water table falls or rises when a given amount of water is removed or added. The volume of water drained at various water table levels can be measured directly from large cores or can be calculated from water retention characteristic curves.

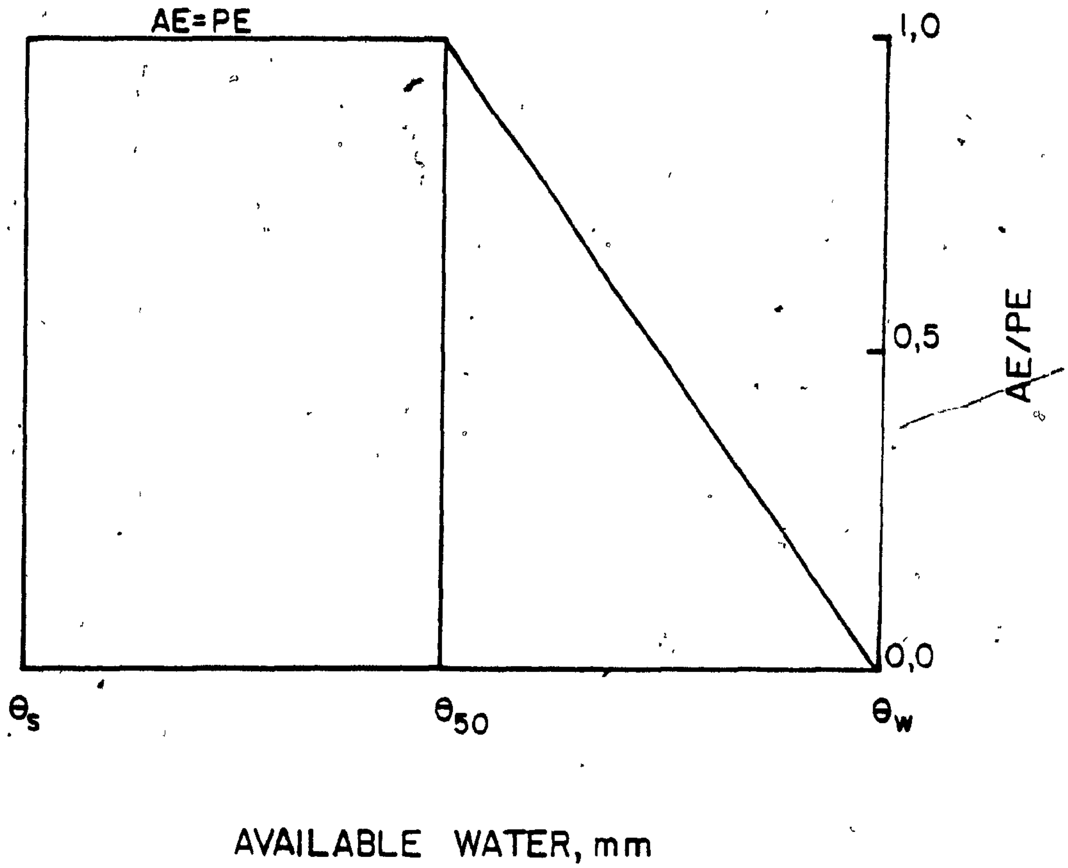

Figure 4.1. Moisture depletion curve.

Drainage volume (sometimes called the water yield) can be calculated from the water retention characteristic curve. In this method, it is assumed that the water content distribution at any time is the same as that of a profile drained to equilibrium. Then the volume drained (V_d) per unit area, when the water table drops from the surface to depth (Y_1), may be expressed as:

$$V_d = \int_0^{Y_1} (\theta_s(y) - \theta(y))\, dy \qquad \text{....(4.1)}$$

Where $\theta_s(y)$ is the saturated soil water content prior to drainage and $\theta(y)$ is the equilibrium water content which is obtained from the soil moisture characteristic curve for a water table depth of Y_1. By numerically integrating equation (4.1), V_d can be calculated for any depth Y. This method can be adopted for multilayered soils in which a separate soil moisture characteristic curve is required for each layer as input.

In calculating the water table depth a soil moisture balance is done for each zone. When upward movement of water, determined as a function of water table depth, does not satisfy ET demands then the remaining water requirement is removed from the root zone creating a dry zone. The depth of the wet zone may continue to increase due to drainage and to some upward water movement. The dry zone depth will also increase simultaneously until the moisture content reaches the permanent wilting point. The water table depth will be calculated as the sum of the depths of the wet zone and the dry zone.

The effective rooting depth with time will be used in the model and can be approximated from the experimental results in the literature. Mengel and Barber, (1974) have reported root distribution of corn in a silt loam soil which was drained with drains placed 1m deep and 20 m apart. The data of Mengel and Barber are plotted in Figure 4.2 for root depth versus time. Skaggs, (1978) suggested that the effective rooting depth time relationship should not be based on the maximum depth of root penetration, but should be based on the 60% curve of Figure 4.2 which gave good results, as far as Skaggs' DRAINMOD model performance is concerned . An approach similar to that of Skaggs will be followed here to test the model performance. Since the model starts simulation from March 31, when fallow conditions prevail, an effective root depth of 4 cm is assumed. This assumption is consistent due to the fact that evaporation takes place within the soil.4 to 5 cm below the soil surface (Goodwin et al., 1982). The values of root depth versus time will be given in tabular form, whereas the values which are not in the table will be interpolated.

The maximum upward flux and water table depth relationship will be calculated by using equation (3.12). The method of

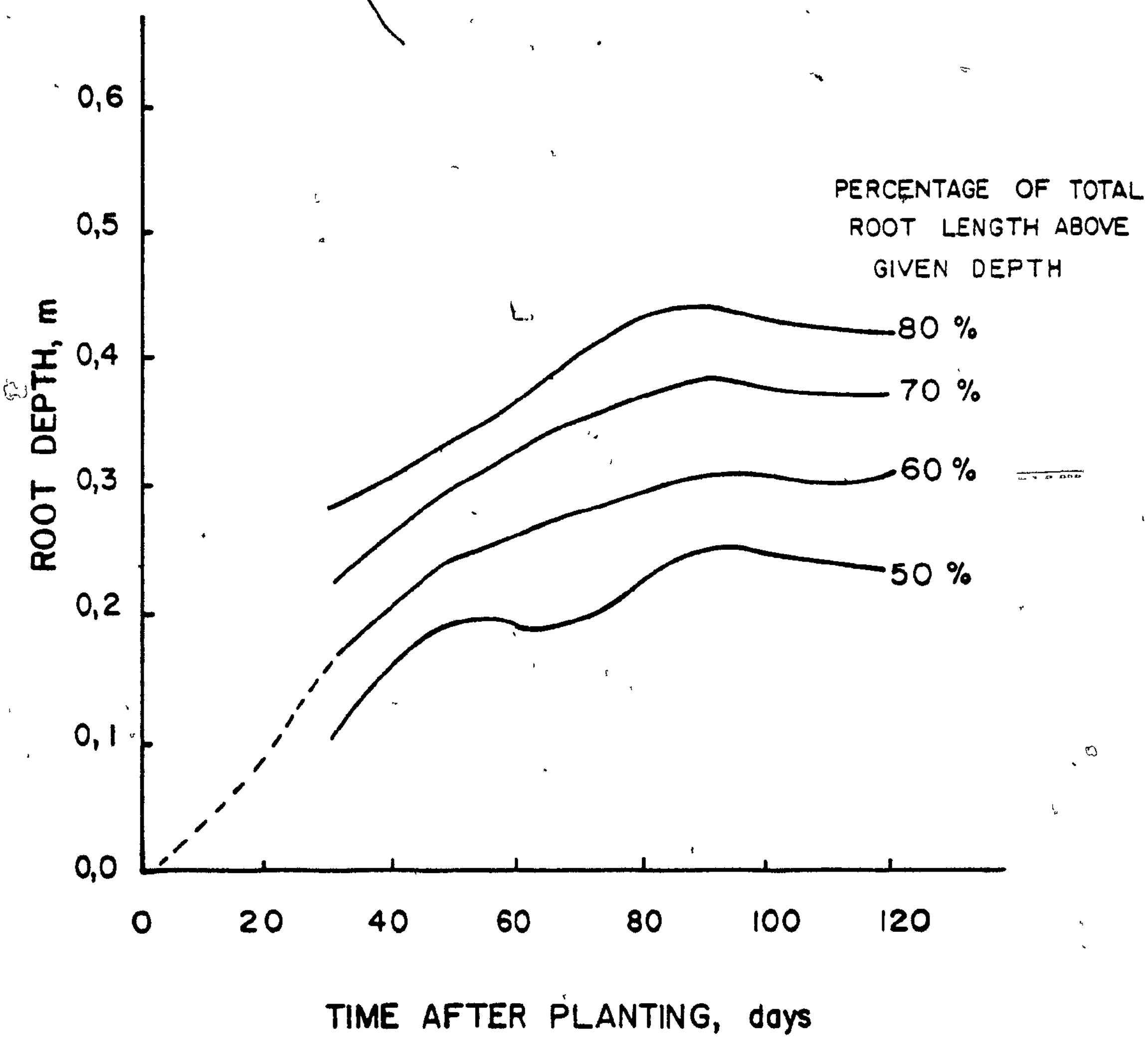

Figure 4.2. Relationship between root depth and time after planting for corn for 50, 60, 70 and 80 percnt of the total root length exists above given depth (After Mengel and Barber, 1974).

determining this relationship will be discussed in Chapter VI.

The drainage aspect of the model is based on Hooghoudt's equation (3.1). Figure A.1 (Appendix A) is a schematic diagram of a subsurface drainage system. Note from this Figure that DWT is the design water table depth and DD is the depth of the drain. DWT in the model can be assigned a suitable value depending on the type of crops grown and their root zone depths. It appears from the the literature (Chieng, 1975; Foroud, 1974; Luthin, 1980; Bhattacharya, 1977) that 40 to 50 cm is widely used range for DWT. Thus in the present study a value of 40 cm will be used. It is assumed that if the drainage rate calculated from equation (3.1) is greater than the drainage coefficient (which is 10 mm/day for the Quebec region), then the drainage rate is equal to the drainage coefficient (Chieng, 1975), otherwise the drainage rate follows Hooghoudt's equation. This assumption is consistent with the fact that the sizes of the drain tubes are choosen to provide a design capacity, which is called drainage coefficient.

Another component of the water balance model is subsurface irrigation. When subsurface irrigation is used the water level in the control chamber is raised to a given elevation to provide a certain head , h_0 , (Figure A.1) so that the water table in the field can be raised. A weir is set in the control chamber so that, if the water table in the field is higher than the water level in the control chamber, drainage will occur and the additional water will spill over the weir and leave the system. When the water table in the field is lower than the water level in the control chamber, water will move out of the chamber at a rate given by equation (3.2) raising the water table in the field or supplying ET demands. Subsurface irrigation will be started just after planting by closing the outlet valve provided in the control chamber. The volume of subsurface irrigation water and the water table depth during subsurface irrigation will be predicted for different drain spacings.

The moisture balance will be calculated on a day-to-day basis using daily values of rainfall and PE. The simulation output includes daily values for water table depth and AE for both subsurface irrigation and subsurface drainage systems. This information will be used in separate crop models of maize yield response for excessive and deficient soil moisture conditions in order to estimate maize yields in subsurface irrigation and drainage systems. The following sections deal with the conceptualization of crop models.

4.1.1 Yield reduction due to soil moisture deficit

The effect of soil moisture deficit on crop yield has been the subject of much research work in the past (Hanks, 1974;

Musick and Dusek, 1980; Robins and Domingo, 1953; Shaw, 1974). It is common knowledge that soil moisture deficit inhibits plant growth, thus reducing yields.

Generally corn plant development is divided into five stages: (1) planting to emergence, (2)emergence to tasseling, (3)tasseling to silking, (4)silking to maturity, (5) dry down period. The importance of each stage has been reviewed by Shaw, 1978 and Salter and Goode, 1967 . They concluded that tasseling to maturity is a critical stage where plants are more sensitive to shortage of water than at other stages of development. Therefore, the impact of daily soil moisture deficit must be weighed by a crop susceptibility factor which is dependent on the stage of plant growth. Shaw, (1974) developed a crop susceptibility factor for corn based on extensive research in Iowa (USA) and given in Table 4.1. Recently Skaggs and Nessehzadeh-Tabrizi, (1982) used this approach in optimizing a drainage design system for corn.

Shaw, (1978) developed a corn response model for deficient soil moisture conditions which is based on stress day index (SDI). SDI is a measure of the intensity and duration of crop deficit. Mathematically, the SDI can be expressed as:

$$SDI_d = \sum_{i=1}^{N} CSd_i * SDd_i \qquad \ldots (4.2)$$

TABLE 4.1: Crop susceptibility factors for maize due to deficient soil moisture conditions with respect to silking (after Shaw, 1974).

Period*	CSd	Period	CSd
Before 8	0.50	After 1	2.00
7	0.50	2	1.30
6	1.00	3	1.30
5	1.00	4	1.30
4	1.00	5	1.30
3	1.00	6	1.30
2	1.75	7	1.20
1	2.00	8	1.00
		9	0.50

*Each period consists of 5-days.
Before and After are the periods with respect to silking.

TABLE 4.2: Crop susceptibility factors for maize due to excessive soil moisture conditions. (after Hiller, c.f Hardjoamidjojo et al., 1982).

Growth stage	Days after planting	CSw
I	0 - 42	0.51
II	43 - 80	0.33
III	81 - 120	0.02

where SDI_d = Stress day index due to soil moisture deficit

CSd_i = Crop susceptibility factor due to soil moisture deficit for the ith growing period

SDd_i = Stress day factor due to soil moisture deficit for the ith growing period

N = Number of periods in the growing season.

The stress day factor, SDd_i is defined as:

$$SDd_i = \sum_{j=1}^{n_i}(1.0 - AE_j/PE_j) \qquad ...(4.3)$$

Where AE_j = Actual evapotranspiration for jth day in growing period

PE_j = Potential evapotranspiration for jth day in the growing period.

n_i = Number of days in the ith growing period.

Finally Shaw's model for deficient soil moisture can be expressed in normalized form as:

$$YR_d = 100 - 1.22\ SDI_d \qquad ...(4.4)$$

Where YR_d = Relative yield due to soil moisture deficit.

Note that from Table 4.1 the CSd values are given for each period relative to the silking stage. Each period consists of 5 days. The stress day factor for the season will be calculated by equation (4.3). Whenever the stress day factor for two or more consecutive 5-day periods was 4.5, or greater, Shaw multiplied the SDI for those periods by an additional factor of 1.5. This was necessary to explain the greatly reduced yields found under severe stress periods of more than a few days duration (Shaw, 1976).

4.1.2 Yield reduction due to wet conditions

The same stress day index approach can be used for wet stress conditions and its effect on corn yields. Stress day in this case can be found by summing the excess water table fluctuations above a critical depth of 30 cm as used by Wesseling, (1974):

$$SDw_i = \sum_{i=1}^{n}(30 - X_i) \qquad \ldots(4.5)$$

Where X_i = Daily water table depths below the soil surface during growing season.

n = Number of days in growing season.

Stress day index for excessively wet condition may be expressed as:

$$SDI_w = \sum_{i=1}^{N} CS_{wi} * SD_{wi} \qquad \ldots(4.6)$$

where SDI_w = Stress day index for wet conditions.

CS_{wi} = Crop susceptibility factor for each growth stage.

N = Number of days in growth stage

Crop susceptibility factors for corn at different growth stages developed by Hiler (1980) (c.f Hardjoamidjojo et al., 1982) are presented in Table 4.2

The model for predicting corn yield response to excessive soil water conditions was obtained in studies of Hardjoamidjojo et al., (1982) and it may be expressed as:

$$YRw = 100 , \quad \text{for } SDI_w \leq 8$$
$$YRw = 103 - 0.42\, SDI_w, \text{ for } 8 < SDI_w < 245 \quad \ldots (4.7)$$
$$YRw = 0 , \quad \text{for } SDI_w \geq 245$$

Then the general crop response model can be expressed as:

$$YR = YR_d \cdot YR_w \quad \ldots (4.8)$$

Where YR is the relative yield, $YR = Y/Y_p$, $YR_w = Y_w/Y_p$ and $YR_d = Y_d/Y_p$; Y_p is the potential (base) yield that would be obtained in the absence of soil water stress conditions; Y_w is the yield that would be obtained if only wet stress occurs; Y_d is the yield that would be obtained if only soil moisture deficit occurs; and Y is the yield of a given year.

V MATERIALS AND METHODS

A field experiment with subsurface irrigation was conducted in the 1982-1983 growing seasons on the farm of Mr. L. Charbonneau, St. Louis Parish, Richelieu county, Quebec. The experiment was laid out with 8 replicates; that is there were 8 plots which received subsurface irrigation and 8 plots which received no irrigation.

In the 1982 summer, there were problems with equipment breakdown and poor subsurface irrigation response on some of the plots. Supply of irrigation water was limited. It was only possible to irrigate for 16 days (Figure B.1, Appendix B), whereas in 1983, there was partial supply of water for 26 days and full supply of water for 16 days (Figure B.2). The water moved from the subsurface drain pipes through the soil satisfactorily on two of the plots in 1982. This indicated that subsurface irrigation was possible in this region and that significant yield increase could be expected in seasons which had significant dry spells.

Improvements were made to the subsurface irrigation system in 1982 and 1983. The experiment was repeated in the 1983 growing season.

In 1983, a dam was built 1 km downstream in the municipal ditch, to create a reservoir to supply the field with irrigation water. The dam consisted of a removable steel frame anchored to a concrete base. Wooden planks were used to hold the water behind the dam.

Unfortunately the reservoir was not large enough and did not receive sufficient inflow to supply the complete water needs of the extremely dry summer. A well was drilled 55 m deep in late August, 1983 about 1.5 km to the west of the experimental field and water was pumped to the control chambers via a 10 cm diameter non-perforated corrugated plastic pipe burried in the ground.

5.1. Field Site

The experimental field is located approximately half way between Sainte-Victoire and Saint-Louis in Richelieu County about 1.5 km north of Rang Prescott. This is about 24 km south of the city of Sorel and about 120 km north east of Macdonald College. The area of the field is about 10 hectares. The location of the field is shown in Figure B.3.

5.2. History

The soil is primarily a St. Samuel sandy loam. A soil survey, conducted by Rashid-Noah (1981), showed that this soil consists of a dark brown fine sandy loam top soil layer of 15 to 20 cm thickness underlain by an olive pale medium sand down to a depth of about 1.6 meters. The soil is clay from 1.6 meters down to bedrock at a depth of about 30 meters. The clay is relatively impermeable. The water table is almost always above the top of the clay layer.

Corrugated polyethylene subsurface drains were installed in 1972, with a spacing of about 30 meters between laterals. Grain corn has been grown as the major crop since 1967. The subsurface drainage system was modified by the addition of non-perforated branch mainlines and four water table control chambers as indicated in Figure 5.1.

When installing these new branch mains in June 1982, it was observed that some of the subsurface drains were partially filled with sand. When the drain tubes were installed in 1972, a filter fabric was placed over the top of the pipe but no filter fabric was placed under the bottom of the corrugated plastic drain pipe. One lateral drain was found to be completely blocked with fine sand. It was replaced by a new corrugated plastic drain tube enrobed with a knitted polyester drain envelope.

During the subsurface irrigation in 1982, the water table responded satisfactorily in the plot which had the new drain lateral added and in one other plot, (A-2 and A-4, Figure 5.1). The water table did not rise properly in the other six

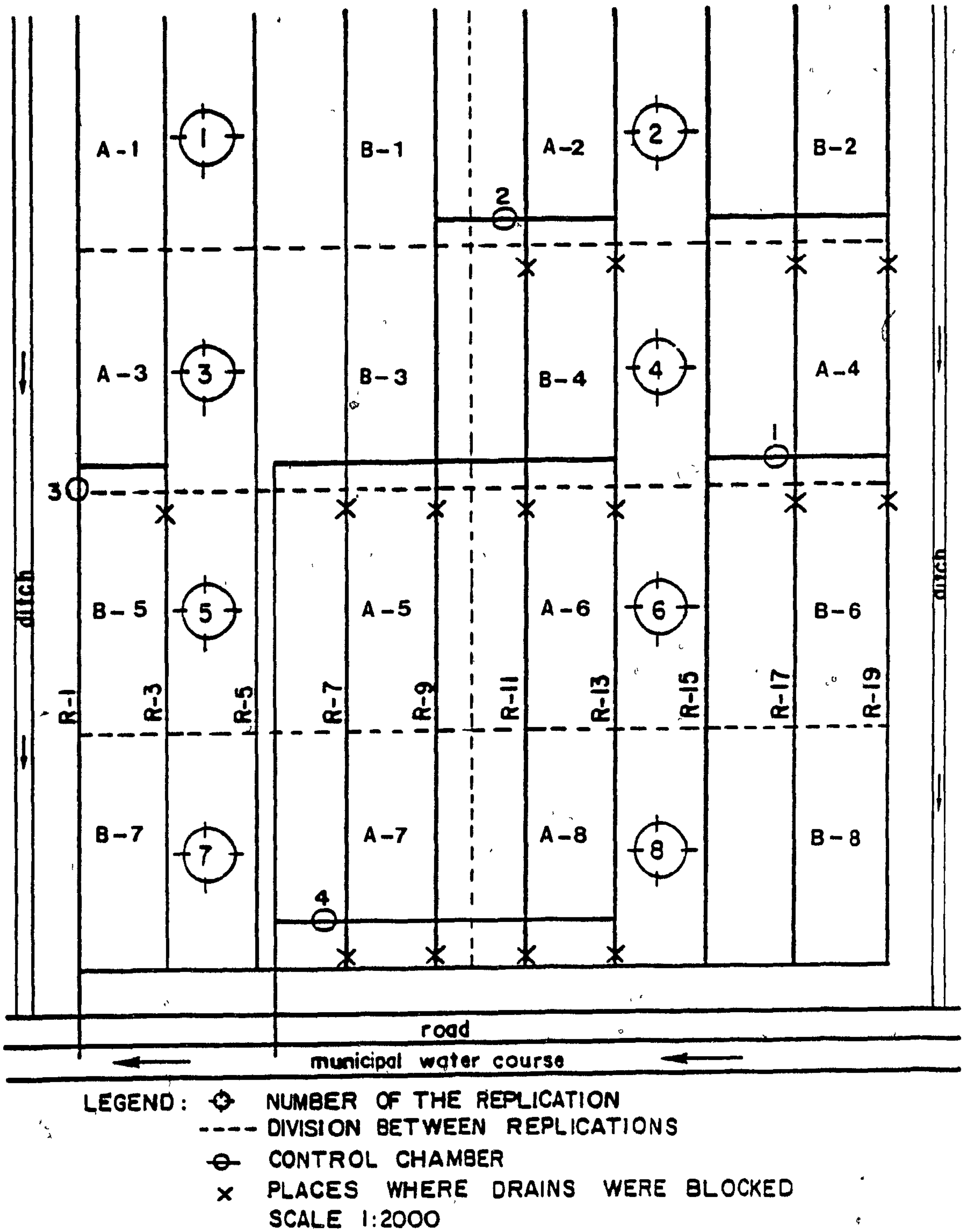

Figure 5.1. Drainage system after modification and location of the plots.

plots. Those six plots did not absorb water as quickly as they were expected to when water was added to the water level control chambers. New subsurface drain laterals enrobed with a knitted polyester envelope were installed in October 1982 on those remaining six field plots.

During the irrigation of 1983, all plots accepted water from the subsurface irrigation system approximately as might be expected.

5.3. Field Experiment Layout

The field experiment was designed to give a randomized complete block design with two treatments in either replicate. The treatments consisted of irrigated and non-irrigated grain corn. Each plot contained two subsurface drains. There were buffer zones between irrigated and non-irrigated plots. Four water table control chambers were installed in such a way that water could be added at those chambers and flow up the subsurface drains to provide subsurface irrigation. Water was pumped into the control chambers from the nearby water course and in late August and early September 1983 from a well.

The water level in the control chambers was kept constant in

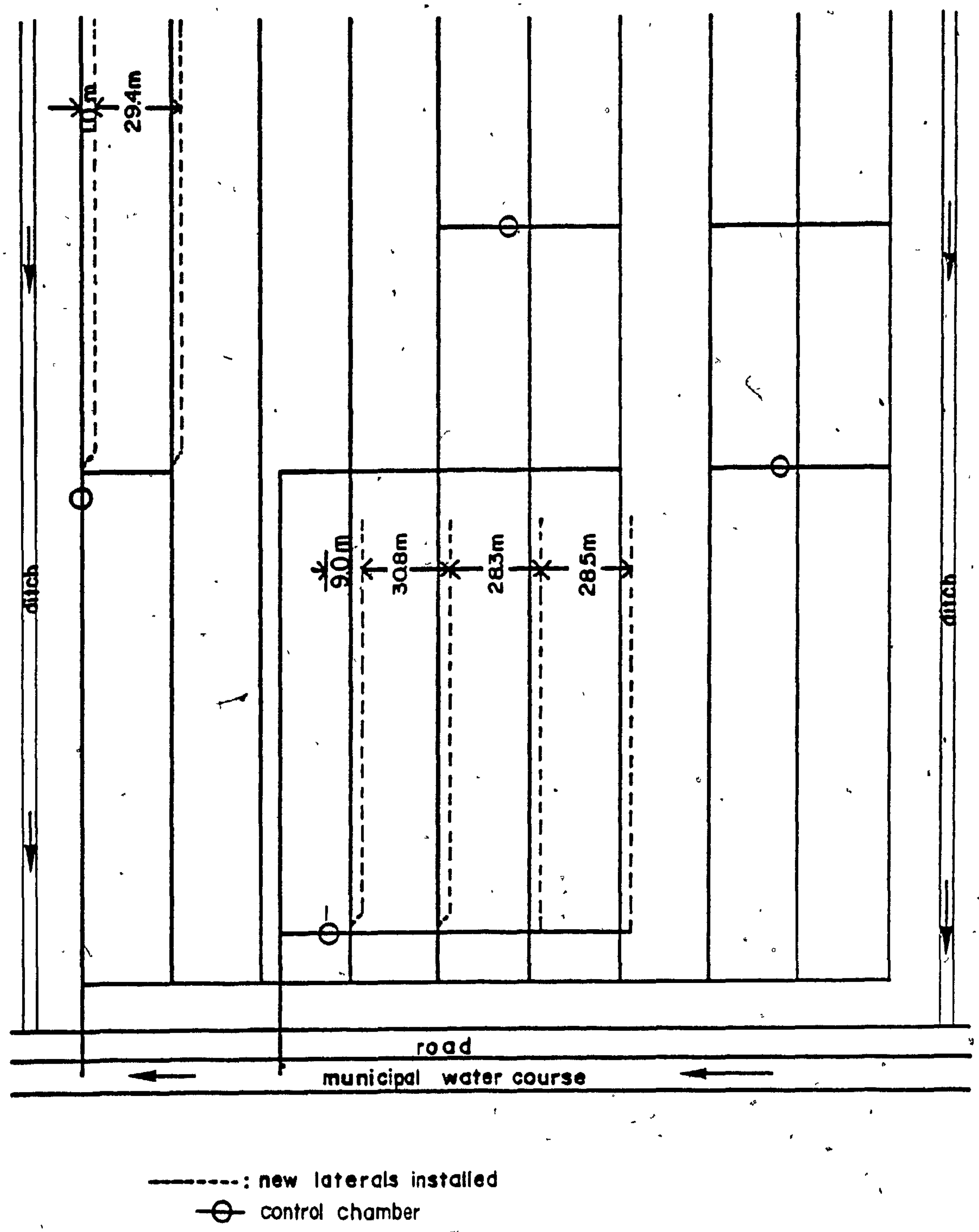

Figure 5.2. Drainage system after installation of new laterals enrobed with a knitted polyster envelope in October 1982.

the 1982 growing season with float valves. The diagram of control chamber is shown in Figure B.4.

In the 1983 growing season the control chambers were extended slightly above ground level to allow a greater head to be placed on the subsurface drain pipes to cause water to flow into the soil more rapidly. Because of delays in getting the water storage reservoir constructed, the water table had dropped to about 1.25 meters below the surface before irrigation began.

While irrigation was underway, measurements were made of the depth to the water table; the soil moisture content, the soil moisture tension was measured with tensiometers; the amount of water added to the chambers was measured with water meters; the distribution of corn roots was sampled . The yield of corn was measured in October of each year.

5.3.1. Water table measurements

The observations of water table depths were made in subsurface irrigated and non-irrigated plots by means of 19 mm I.D., 1.5 m long PVC pipes sealed at the bottom. Following the technique of Broughton (1972), the pipes were perforated with four rows of 6.4 mm diameter holes at 15.2 cm intervals along their length. Alternate rows of holes were drilled at 90° to the first holes at a lengthwise displacement of 7.6 cm. The pipes were covered with a spunbonded polyester filter in order to prevent the entry of sand.

The water table pipes were installed with an auger slightly larger than the pipe and the loose sides surrounding the pipes were packed with dry sand to ensure good contact between the pipe and the soil. Figure 5.3 shows location of the water table pipes in the irrigated and non-irrigated plots. Seven water table pipes were installed in the irrigated plots to study the shape of the water table (Gallichand, 1983 and von Hoyningen Huene, 1984). In this study, only water table pipes midway between the drains in each plot were considered.

Water table measurements were made periodically during subsurface irrigation experiments of 1982 and 1983. A graduated hollow plastic tube about 3 m long, having the lower end connected with two electrodes and a sound emitter at the top of the tube was used. The technique consisted of lowering the plastic tube into the water table pipe slowly until the water table was located with the sound of the beep. A water table depth below the surface of the ground was calculated by subtracting the pipe above the ground level from the observation of the water table.

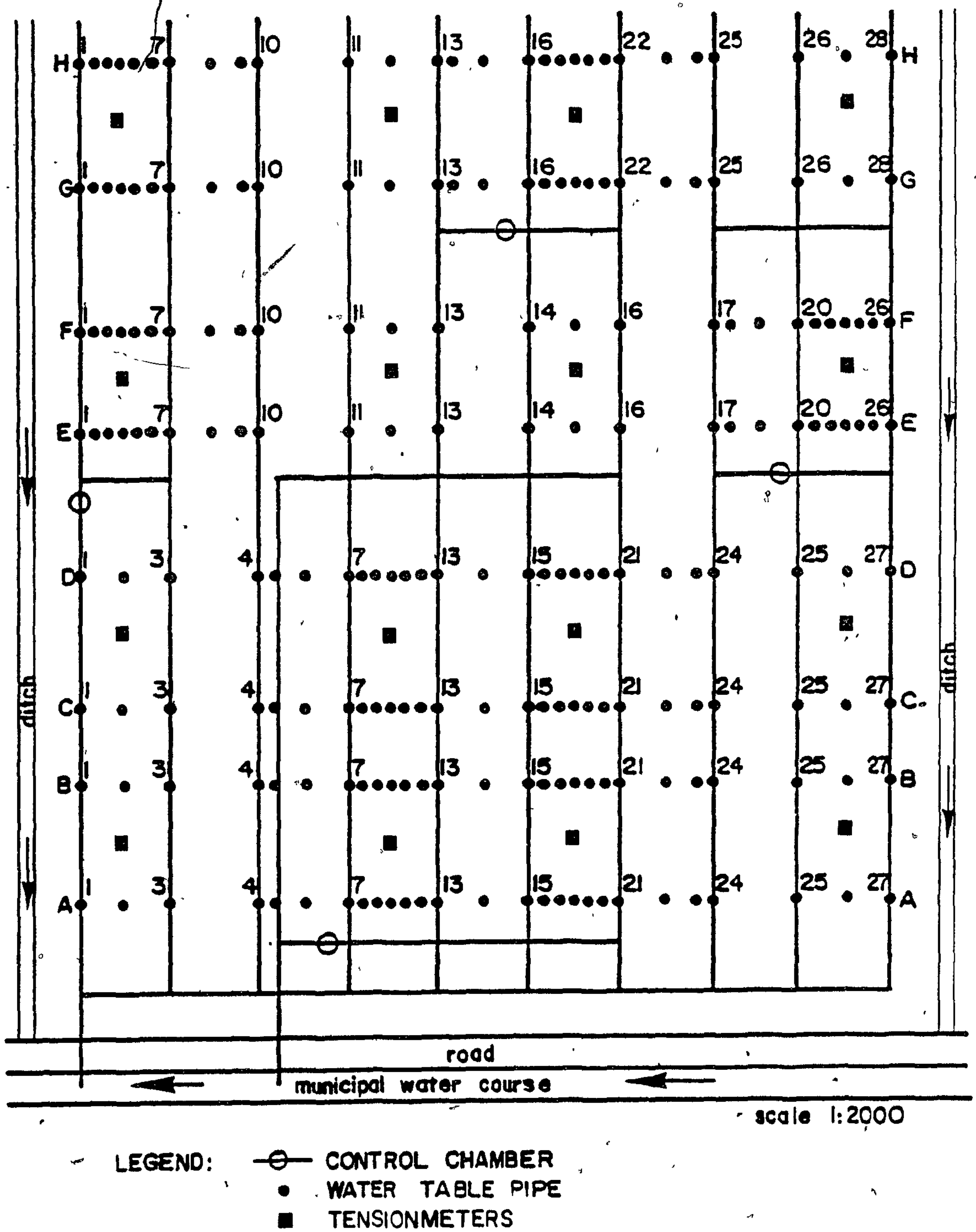

Figure 5.3. Location of water table pipes and tensiometers.

5.3.2. Soil moisture measurements

Soil moisture measurements were done gravimetrically, for samples taken at 7, 22, 37, 52, 67 cm depths from the soil surface in each plot during the subsurface irrigation experiments of 1983. Soil moisture contents at these specific depths were assumed to represent the moisture contents for the depth ranges of 0-15, 15-30, 30-45, 45-60, 60-75 cm respectively.

Undisturbed soil samples were taken from each plot at 5, 20, 35, 50, 65 cm depths from the soil surface in aluminium rings of approximately 7.3 cm diameter and 4.1 cm height. These samples were collected from pits which were dug for the root measurements, with three replicates at each depth, for the determination of bulk densities. These bulk density values were later used to convert soil moisture contents from a weight basis to a volume basis. These soil moisture contents were subsequently used to determine the available water in 30 and 45 cm soil columns.

In addition to the soil samples taken for the determination of volumetric moisture content in each plot three other small undisturbed core samples were taken in each plot from 30, 45, 75 cm depths for the determination of soil moisture characteristic curves, using the pressure plate apparatus following the method of Richards, (1965). Four tensiometers in each of the 8 irrigated and 8 non-irrigated plots were installed at 15, 30, 45, 60 cm depths from the soil surface. Additional tensiometers were installed in non-irrigated plots at 75 cm depth below the soil surface. The location of tensiometers is shown in Figure 5.3.

5.3.3. Yield measurements

To determine whether the subsurface irrigation had any beneficial overall effects, the ear yield and grain yield was measured following the method of Raghavan and McKyes, (1977). Five rows about 10 meters long were randomly selected and staked out in each of the sixteen plots. These rows from each plot were hand harvested. All of the cobs were removed from each row and the weight was recorded. 20 cobs from each row of the sixteen plots were randomly taken for ear yield and grain yield measurements. 10 cobs were taken out of every 20 cobs for drying in the oven to determine the grain yield. The remaining cobs were then chopped and a 1 Kg sample was taken for determination of ear moisture. From this information the ear yield and grain yield were determined on an oven dry weight basis.

In October 1983 the grain yield was also determined by harvesting the complete plots with a grain corn combine. The sixteen plots were separated by first harvesting the buffer zone surrounding the plots. Then the plots were harvested one by one and the grain weight for the complete plot was measured in the field. Samples of the grain from each plot were taken for moisture content determination. Following the above methods, grain yields were determined on a oven dry weight basis.

In October 1982, only two irrigated and two non-irrigated plots were harvested for grain yield determination. The other remaining plots were not harvested because they did not provide specific treatment, thus the treatment effect could not be properly determined for 1982.

5.3.4. Root measurements

Information on the effects of root depth is an important feature which is required in the theoretical calculations of upward flux of water from water table depth to the root zone. Root measurements were taken by driving cores which were 10 cm long and 9.8 cm I.D. at depth increments in each of the sixteen plots. Core samples were taken at 20 cm away from the corn rows. The corn row spacing was 80 cm. To extract the cores from the soil a pit was dug by hand to a depth of 70 cm. Roots from the cores were washed carefully and then the roots were removed. Roots from each core were put in the oven at 65 ^{o}C for 24 hours. The dry weight of the roots was recorded. In this way the dry weight of roots per unit volume was obtained for depth increments of 10 cm.

5.4. Drainable Volume Measurements

Six large PVC tubing cores of 15.24 cm diameter and 120 cm length were used for determination of the relationship between drainable volume and water table depth. Those samples were taken from randomly selected sites in the field. A small backhoe was used to drive the cores with the front end bucket to their full length. The soil cores were then retrieved by digging with the backhoe and by hand. Each core was then sealed at the bottom and carefully transported to the laboratory.

In the laboratory, all of the six cores were mounted vertically on the wooden board. A 5 mm hole was drilled at the bottom of each core and a perforated tube of 4 mm diameter and 50 mm in length, wraped with nylon filter was inserted which served as outlet. The bottom end caps and holes were then glued. Rubber tubing was used to attach one end to the outlet and the other end with the water reservoir. The water in the reservoir was previously boiled to get rid of some of the dissolved air.

Before beginning the experiments to determine the drainable volume and water table relationship, the soil cores were saturated by raising the water reservoir. This process was repeated two times in order to prevent air entrapment in the soil. Finally, the water table was raised to the surface of the soil, the water reservoir was disconnected, and a T-joint was connected at the end of the rubber tube. The tops of the cores were covered with flat end-caps to prevent losses due to evaporation. To begin with the test, the T-joint was lowered by 12.5 cm intervals and held at the specific elevation until the drainage ceased. The drainable volume was measured at each water table level until the water table reached 100 cm from the surface of the soil. The drainable volume was measured in a graduated cylinder covered with parafin wax paper to minimize evaporation. In this way the relationship between drainable volume and water table depth was established.

5.5. Water Balance Model

The primary purpose of developing a water balance model was to optimize subsurface irrigation/drainage design for maize yield. Inputs, in the model are the climatological data, soil properties, subsurface irrigation/drainage system parameters and crop parameters. Climatological data include the daily rainfall and PE. Some of the soil properties such as water content at saturation, relationships of drainable volume , and steady upward flux as a function of water table depth are inputs to the model, based on experiments described. Other pertinent soil water parameters such as saturated hydraulic conductivity, permanent wilting point were obtained from the work of Rashid-Noah, (1981) on this soil, and are assigned to the model. The crop parameters are rooting depth as a function of time, planting date, as well as the parameters for the yield response models given in sections 4.1.1. and 4.1.2. of chapter IV. Subsurface irrigation/drainage system parameters are drain depth and spacing, depth to the impermeable layer, design water table depth (DWT) at a point midway between the drains, limiting drainage coefficient, water table level at the drain, optimum water table depth as a function of maximum ET (in our case 4.5 mm/day) for the case of subsurface irrigation. All these parametric values used in the model are shown in table 5.1.

The model predicts the water table depth, AE/PE ratio, and subsurface irrigation volume, using daily rainfall and PE, and other pertinent soil and water parameters . This information was subsequently used in integrated crop models to predict relative yields.

Economic analyses are done manually from the predicted average relative yield. A flow chart, representing the basic operations in the model, is shown in Figure 5.4.

From various assumptions described in section 4.1., one of the assumptions has been changed for better performance of the model. It was assumed 50% of the rainfall goes into the

TABLE 5.1: Some average soil water properties and drainage system parameters used in the water balance model.

Input	Value
1. Soil properties:	
Saturated hydraulic conductivity, k_s	1.56 m/day
Saturated moisture content, θ_s	0.43 cm^3/cm^3
Permenant wilting point, θ_w	0.031 cm^3/cm^3
2. Drainage system parameters:	
Depth to the impermeable layer, DI	1.60 m
Drain depth , DD	1.05 m
Design water table depth, DWT	0.40 m
Drainage coefficient, q	0.01 m/day
Drain diameter	0.10 m
Drain spacing, W	5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75 and 80 m
Subsurface irrigation parameters:	
Optimum water table at midspacing	1.00 m
Design water table control at the drain	0.60 m
3. Crop parameters (for maize)	
Planting date	May 6
Maximum effective rooting depth	0.30 m

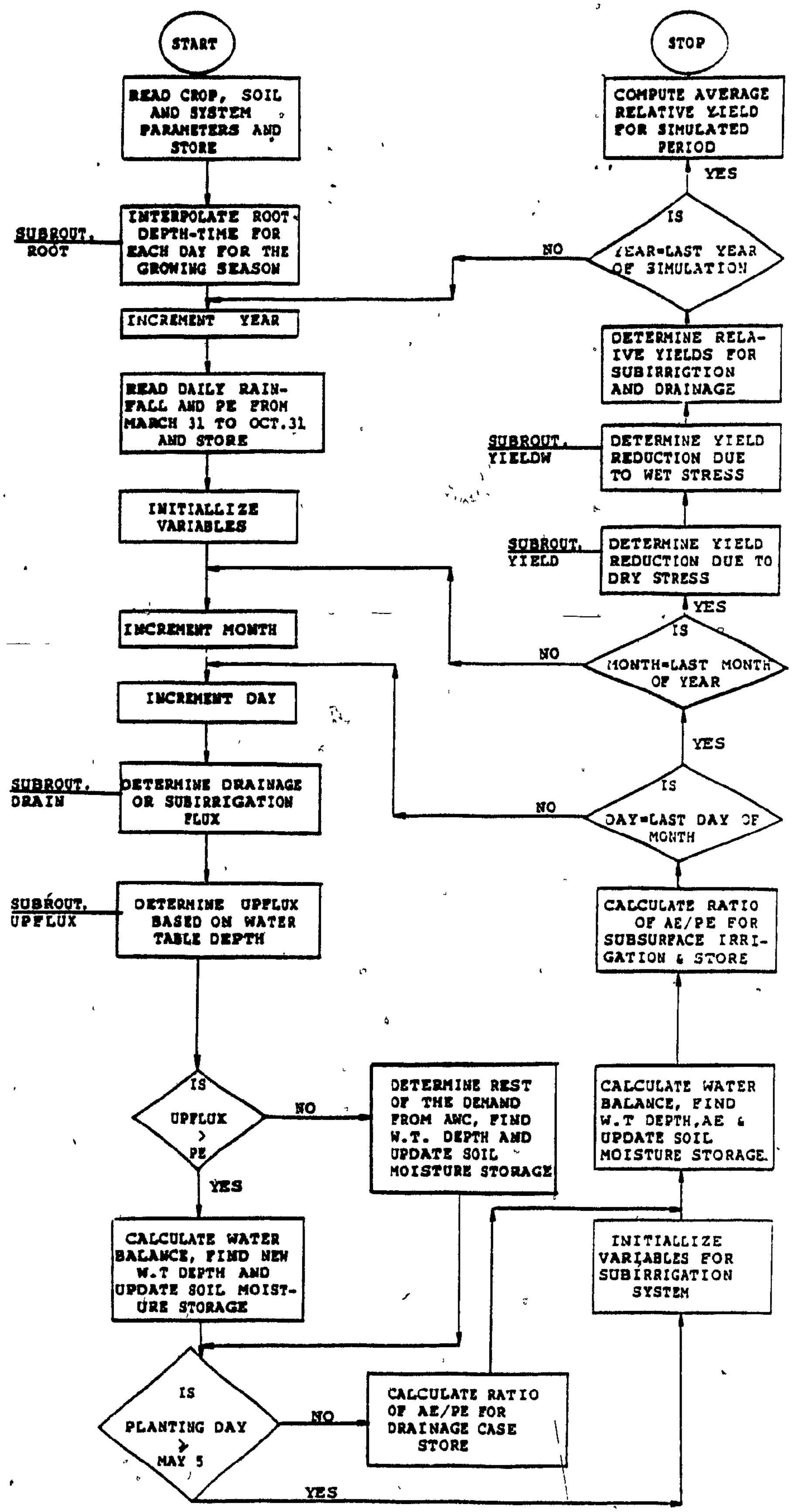

Figure 5.4. Flow chart for the water balance model integrated with crop models.

root zone and 50% goes below the root zone into wet zone soil moisture storage. This assumption is justified from the actual observations of water table depths on July 26, 1983 (see table 6.3, non irrigated) when the water table rose without saturating the root zone. Various input percentage were tried in different computer runs to arrive at the most appropriate value. It was found that 50% input gave the best performance of the model.

5.5.1. PE determination.

A temporary weather station was set up near the field to measure daily maximum and minimum temperatures and rainfall. The temperatures were recorded with standard meteorological thermometers in a Stevenson screen and rainfall was recorded by a tapered rain gage. These readings were taken daily at 8 am and 6 pm.

Weather data was collected at the farm for 23 days (July 15 to August 6) in 1982 and 2 months (July 1 to August 31) in 1983. The weather data for the rest of the months was obtained from nearest weather station. There were three weather stations, that is Sorel, Fleury and l'Assomption located nearest the field. Data from three stations were compared with the recorded data, and l'Assomption was found to be the closest related.

PE values were obtained from tables prepared by Russelo et al., (1974) using the daily maximum and minimum temperatures at Charbonneau's farm when available, otherwise from data from the l'Assomption station.

VI RESULTS AND DISCUSSION

The study reported in this chapter consists of two parts. In the first part, experimental results of response to subsurface irrigation and variations in soil moisture are presented. In the second part, a water balance model is developed for predicting daily water table positions, AE/PE ratio and subsurface irrigation volumes. The predicted data is then compared with field measurements. The results were subsequently used to compute the relative yields of maize and annual profits due to subsurface irrigation/drainage systems, designed with different drain spacings. Some input data for the model was measured during the 1982 and 1983 growing seasons. Two years of weather data, recorded at the experimental site, are used in developing the the water balance model.

6.1 Soil Moisture Regime

6.1.1 Soil moisture distribution in the soil profile

In order to observe the response of subsurface irrigation during the 1982 and 1983 field experiments, available water within 30 and 45 cm soil columns was determined in irrigated and non-irrigated treatments. The determination of available water requires the knowlege of volumetric soil moisture content. Soil moisture measurements, on a volume basis, could not be made in the field due to the large number of samples and sampling depths required. Instead, volumetric soil moisture contents were determined by multiplying the observed gravimetric soil moisture contents by the appropriate dry bulk densities. Therefore, it was necessary to determine dry bulk densities of the soil at different depths.

Tables 6.1 and 6.2 present the average dry bulk density values in the irrigated and non-irrigated plots, respectively, at various depths. The standard deviation indicate the variation within the plot at each depth. To further investigate the variability of dry bulk density with respect to depth and treatment, an analysis of variance was conducted. The results are presented in Appendix, Table C.1.

From the analysis of variance it was found that the dry bulk density was not significantly different with respect to treatment and depth at the 99 percent confidence level. However, this does not necessarily mean that the soil is homogeneous with respect to depth. There are other properties which influence soil homogenity. The largest

TABLE 6.1 : Dry bulk density versus depths in irrigated experimental plots.

Plot		Dry bulk density (g/cm^3) depth from soil surface (cm) 15	30	45	60	75
A-1	Mean	1.39	1.41	1.56	1.52	1.54
	S.D.	0.06	0.03	0.09	0.06	0.03
A-2	Mean	1.42	1.50	1.60	1.58	1.66
	S.D.	0.06	0.05	0.03	0.07	0.03
A-3	Mean	1.28	1.53	1.58	1.56	1.65
	S.D.	0.09	0.04	0.05	0.03	0.03
A-4	Mean	1.39	1.55	1.61	1.52	1.55
	S.D.	0.05	0.06	0.02	0.03	0.07
A-5	Mean	1.36	1.55	1.68	1.60	1.56
	S.D.	0.05	0.05	0.01	0.02	0.08
A-6	Mean	1.33	1.49	1.67	1.50	1.51
	S.D.	0.05	0.14	0.01	0.05	0.05
A-7	Mean	1.45	1.42	1.66	1.53	1.59
	S.D.	0.04	0.04	0.03	0.06	0.01
A-8	Mean	1.41	1.42	1.65	1.60	1.66
	S.D.	0.01	0.04	0.02	0.02	0.02
Overall mean		1.38	1.48	1.63	1.55	1.60
Standard deviation		0.05	0.06	0.04	0.04	0.05

S.D stands for standard deviation.

TABLE 6.2 : Dry bulk density versus depths in non-irrigated experimental plots.

Plot		Dry bulk density (g/cm^3) depth from soil surface (cm) 15	30	45	60	75
(1)		(2)	(3)	(4)	(5)	(6)
B-1	Mean	1.42	1.49	1.60	1.58	1.58
	S.D	0.04	0.04	0.04	0.03	0.04
B-2	Mean	1.41	1.48	1.58	1.56	1.58
	S.D	0.05	0.06	0.07	0.05	0.04
B-3	Mean	1.39	1.56	1.52	1.62	1.55
	S.D	0.08	0.02	0.07	0.06	0.06
B-4	Mean	1.35	1.48	1.44	1.50	1.45
	S.D	0.04	0.03	0.06	0.08	0.11
B-5	Mean	1.46	1.61	1.50	1.52	1.54
	S.D	0.06	0.05	0.05	0.08	0.05
B-6	Mean	1.46	1.63	1.54	1.52	1.54
	S.D	0.06	0.03	0.05	0.08	0.05
B-7	Mean	1.38	1.51	1.53	1.59	1.60
	S.D	0.06	0.06	0.04	0.05	0.07
B-8	Mean	1.37	1.54	1.68	1.64	1.65
	S.D	0.03	0.07	0.01	0.07	0.03
Overall mean		1.40	1.54	1.55	1.57	1.56
Standard deviation		0.05	0.06	0.07	0.05	0.06

S.D stands for standard deviation.

difference in the magnitude of dry bulk density values at 75 and 15 cm depths was found to be 22 % in irrigated plot A-3. For the non-irrigated treatment, the smallest and largest differences in bulk density values were found to be about 9% and 18%, respectively (see B-5 and B-8 plots in Table 6.2 at depths of 30 and 15 cm, and 45 and 15 cm, respectively). The overall mean dry bulk density in irrigated and non-irrigated treatments demonstrate little variation at each depth. The difference in the magnitude of dry bulk density values between irrigated and non-irrigated treatments at each depth was less than 5%. The smallest and largest differences in bulk densities, with respect to depth, were found to be 11% and 15% percent in non-irrigated and irrigated treatments, respectively. An average value of dry bulk density for the overall field can not be used because it will give erroneous estimates of volumetric moisture content and of available water. However, the average dry bulk density for the overall field may be used, with respect to depth, because the difference between irrigated and non-irrigated treatments was found to be insignificant.

The calculated values of average volumetric soil moisture content and water table depth obtained from irrigated and non-irrigated treatments during the growing season of 1983 are shown in Table 6.3. This data was obtained by multiplying the observed gravimetric moisture content by the appropriate average dry bulk density of each soil layer.

TABLE 6.3 : Variation of water table and soil moisture content in irrigated and nonirrigated plots of St.Samuel sandy loam soil in 1983 field experiments.

Date	Water table depth cm	Average soil moisture content in percent by volume for 15 cm soil layers at the following depths.				
		Depths of soil layers (cm)				
		0-15	15-30	30-45	45-60	60-75
Irrigated:						
July 20	86.2	23.5	22.1	35.1	33.0	42.2
22	96.8	18.8	19.4	32.2	33.9	41.2
26	111.9	15.7	20.7	28.7	30.0	39.8
27	109.7	17.2	19.1	28.3	30.6	38.4
28	111.7	16.7	18.8	28.1	30.3	37.5
29	117.6	18.6	20.9	28.0	27.3	37.5
Aug. 02	118.0	17.2	20.5	22.0	25.6	34.0
05	129.7	13.6	16.7	19.6	17.0	25.2
31	99.6	23.0	21.9	25.9	30.0	37.2
Sept.02	95.4	19.3	22.6	26.3	29.0	33.9
05	88.4	18.8	22.0	29.5	34.2	42.2
08	72.8	16.1	20.5	31.4	37.2	42.2
Non-irrigated:						
July 20	131.2	14.0	14.7	19.7	24.5	33.6
22	132.6	12.3	13.4	20.4	25.7	35.0
26	131.0	10.1	12.5	19.0	29.5	34.9
29	132.0	10.3	11.5	17.6	24.8	34.5
Aug. 02	133.8	10.9	12.5	19.0	25.4	35.1
05	134.8	8.5	12.9	19.3	25.1	36.8
10	-	10.7	12.5	17.3	23.6	31.1
23	-	7.8	7.8	11.6	17.0	-
Sep. 08	-	7.5	7.8	14.6	26.4	29.4

Note : The blanks in column (2) indicate that water table was below the observation pipe.

The blank in column (6) indicates that the moisture content was not realised in the field.

The average volumetric soil moisture data is reported for five layers with 15 cm thick. The general trend of soil moisture content variation with respect to water table depth is such that soil moisture content increased or decreased in the soil layers above the water table, depending on the water table position. It should be noted here that the upward flux is a function of the unsaturated hydraulic conductivity, the hydraulic gradient and the water table position. As can be seen in Table 6.3, the soil moisture content in irrigated plots was higher than the soil moisture content in non-irrigated plots in the four upper most soil layers. This is due to the evapotranspiration demand being met by the shallow water table within the irrigated plots. Whereas, within the non-irrigated plots, the deep water tables resulted in lower values of upward flux. The total evapotranspiration demand was also satisfied by the available water in the soil profile, thereby reducing the soil moisture content.

The data in Table 6.3 were used to compute available water at depths ranging from 0-30 cm and 0-45 cm in the soil profile. Available water is defined as the difference between the observed soil moisture content and the permanent wilting point. The permanent wilting point of the experimental soil was determined by Rashid-Noah (1981) and is reported in Table C.2 along with the field capacity and saturated hydraulic conductivity. The average soil moisture content of 0-30 and 0-45 cm in the soil column was computed by multiplying the soil moisture content of the soil layer by the corresponding depth range, summing these products and dividing by the depth of soil column (30 and 45 cm). This was done so that the average soil moisture content for the soil column was not unduly influenced by the very low values of the top soil layer.

During the 1982 field experiments, soil moisture content measurements were not made. Instead, soil suction was observed by tensiometers at 15, 30, 45 and 60 cm depths below the soil surface. However, estimates of soil moisture can be made from the measurements of soil suction if a graph relating soil suction to soil moisture content is available. Tensiometers give useful indications of soil suction upto tensions of 800 cm of water. Above this range, air enters through the porous cup, thus rendering the instrument useless. It is possible that soil suction in the field may exceed the indicated range of the tensiometer and the soil moisture can not simply be inferred. From the field observations, the tensiometer readings exceeded the tensiometric range several times in one of the non-irrigated plots. Thus, from the observed soil suction at various dates, soil moisture was determined from the soil moisture characteristic curve and the results are given in Table 6.4. The determination of the soil moisture characteristic curve is explained in section 6.1.3.

In 1982, six out of eight irrigated plots did not respond to subsurface irrigation and the water table did not rise in those plots. This was due to blocking of drain tubes with fine sand and the extremely low depth of the water table prior to subsurface irrigation. Due to the latter, capillaries were broken. The subsurface drainage system was repaired in the fall of 1982. All plots responded satisfactorily during the 1983 field experiment. Therefore, results of the 1982 experiment pertain to only two irrigated plots (A-2 and A-4).

The computed average available water for the two irrigated and non-irrigated plots is presented in Figure 6.1, along with the recorded subsurface irrigation volumes and the rainfall data. During 1982, rainfall was low in the month of July, but was normal for the remainder of the growing season. Subsurface irrigation was initiated on July 13 and was terminated on August 6, because of the shortage of the water supply. For this reason, subsurface irrigation was not uniform.

Rainfall in June, July and August of 1983 was unusually low.

TABLE 6.4 : Variation of Water table and Soil moisture content in irrigated and nonirrigated plots of St.Samuel sandy loam soil in 1982 field experiments.

Date	Water table depth cm	Average soil moisture ontent in percent by volume for 15 cm soil layers at the following depths.			
		Depths of soil layers (cm)			
		0-15	15-30	30-45	45-60
Irrigated:					
July 20	58.0	15.0	16.0	34.7	36.0
21	70.0	14.0	24.4	29.0	37.1
22	78.0	13.6	21.0	29.0	36.0
23	70.2	7.4	29.0	29.0	35.0
Aug. 04	77.0	7.5	27.4	35.0	38.0
05	72.0	7.4	29.8	35.0	38.0
13	90.6	18.0	27.4	34.7	37.1
20	102.5	14.0	19.7	27.4	34.7
24	110.0	15.2	17.9	26.0	32.0
Non-irrigated:					
July 20	127.2	9.5	9.9	18.5	20.5
21	128.6	9.0	9.7	16.7	18.5
22	129.0	8.6	10.2	15.7	16.8
23	130.1	8.8	9.2	17.7	18.5
Aug. 04	134.0	9.0	9.0	16.7	18.5
05	135.4	9.0	9.8	16.7	17.7
13	131.0	16.5	11.9	20.5	21.8
20	132.0	14.1	11.0	17.8	20.0
24	135.4	15.1	9.2	17.8	23.0

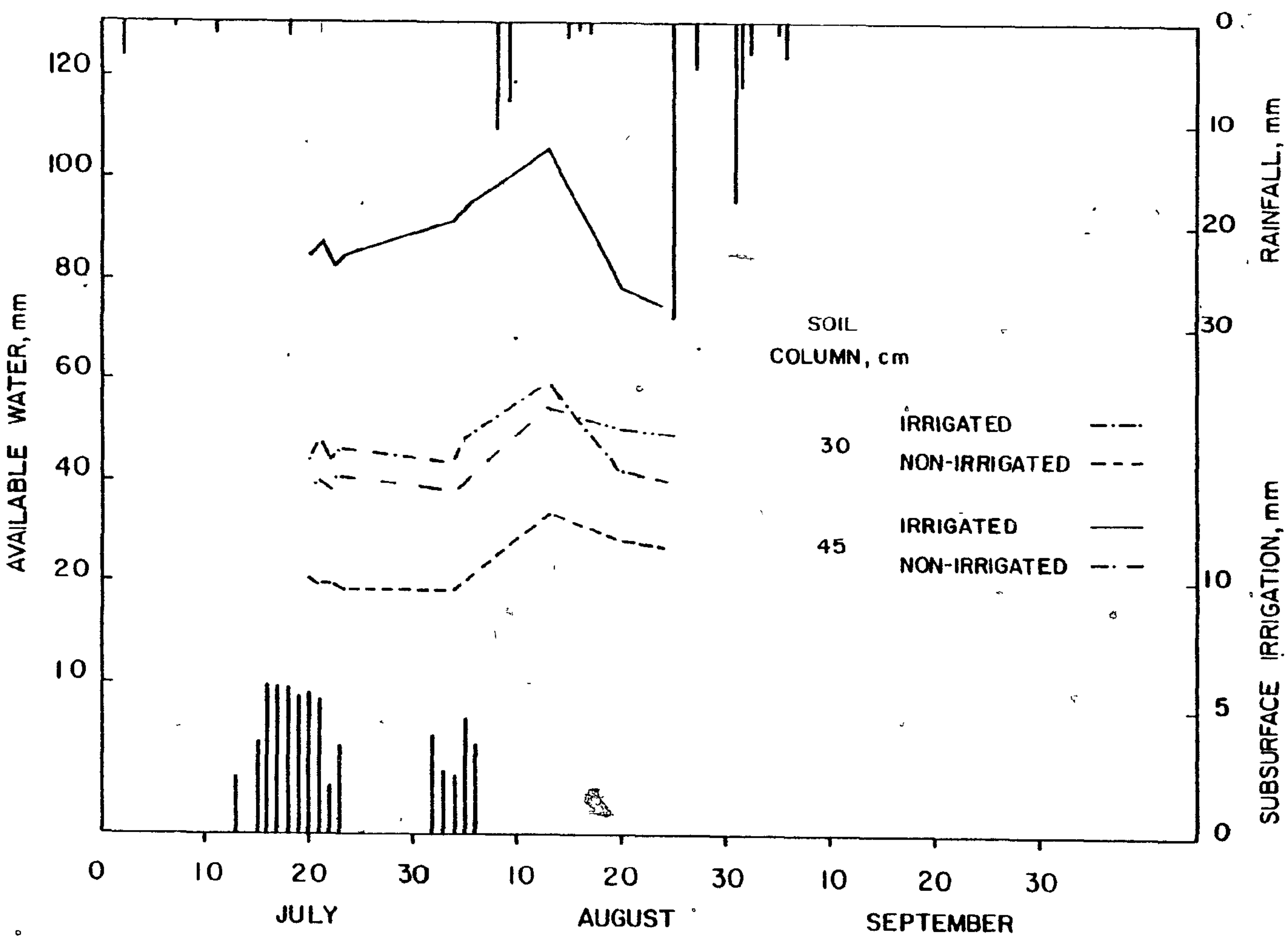

Figure 6.1. Variation of average available water in the soil columns of 30 and 45 cm in irrigated and non-irrigated plots during the field experiments of 1982.

There was little supply of water available in the ditch. Thus, during the initial stages of plant development in 1983, the supply of subsurface irrigation was not continuous. However, a well was installed to provide subsurface irrigation for the latter part of the growing season. There was an interval of about 4 weeks with inadequate water supply. The average daily amount of water supplied by the subsurface irrigation system during sub-irrigation of 1982 and 1983 was about 4 and 4.5 mm per day, respectively.

Figures 6.1 and 6.2 show the results of the soil moisture content at various depths during the growing seasons of 1982 and 1983, respectively, for irrigated and non-irrigated treatments. Soil moisture content is presented in the form of available water for the 0-30 and 0-45 cm soil profiles. For the non-irrigated treatment, there was little available water during both the 1982 and 1983 growing seasons. During the field experiments of 1982, the available water for the irrigated treatment in the 0-30 cm and 0-45 cm soil profiles was never less than 38 mm and 75 mm, respectively. On the other hand, available water for the non-irrigated treatment was below 20 mm and 40 mm for the 0-30 and 0-45 cm soil profiles, respectively. It can be seen in Figure 6.1, that the upward flow from the water table increased the soil

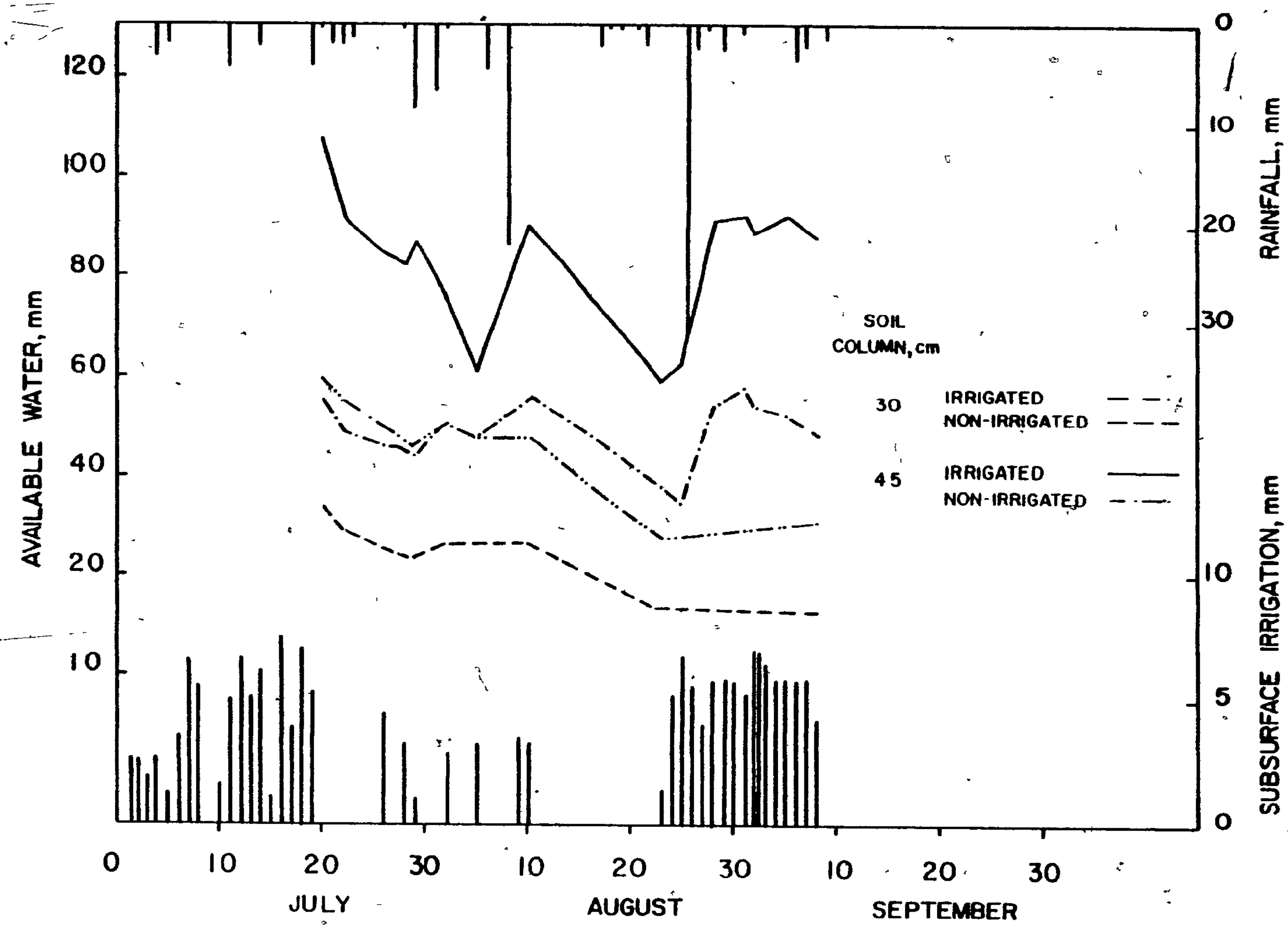

Figure 6.2. Variation of average available water in the soil columns of 30 and 45 cm in irrigated and non-irrigated plots during the field experiments of 1983.

moisture content in the 30-45 cm soil layer, thus increasing the available water in the 0-45 cm soil profile. The available water in the 0-30 cm soil profile remained nearly constant during the supply of subsurface irrigation water. There was approximately twice as much available water for the irrigated than for non-irrigated treatment. For the subsurface irrigation treatment, as shown in Table 6.4, the soil moisture in the 15-30 cm soil layer stayed nearly at field capacity most of the time during the field experiments of 1982. While the 30-45 cm soil layer stayed above field capacity in the sub-irrigated plots. The soil moisture content in the non-irrigated plots was found to be below field capacity in all four layers during the field experiments of 1982. Similar results were obtained for the 1983 experiment.

Referring to Figure 6.2, it is seen that the available water decreased when the subsurface irrigation stopped after July 19 and August 10. The water table continuously dropped due to ET demands. This shows that the upward flow from the water table was not sufficient to supply ET demands. This resulted in a loss of soil moisture and a reduction of the available water in the soil layers.

6.1.2 Pressure head distribution in the soil profile

The data of water table depth and pressure head at various dates after subsurface irrigation is shown in Figures 6.3a and b. Figure 6.3a depicts the results of the 1982 field experiments. In this figure pressure head at 30 cm soil depth is plotted because most of the maize roots are concentrated in the top of 30 cm, For the subsurface irrigation treatment, it can be seen that the pressure head at 30 cm depth follows the water table depth closely for 24 days of observations. This indicates a continuity in the capillary suction from the water table level to the 30 cm soil depth while the water table recedes due to the effect of evapotranspiration. Figure 6.3b shows the results of the 1983 field experiments. Referring to this figure, it can be seen that the pressure head at 30 cm depth is in close agreement with the water table for the first 31 days indicating that the upward flux from the water table is sufficient to satisfy ET demands. After 31 days the pressure head increased rapidly suggesting that the evapotranspiration demand was not met solely by upward flux.

6.1.3 Relationship between steady upward flux and water table depth

The rate at which water can be supplied to the root zone from the water table depends on the unsaturated hydraulic

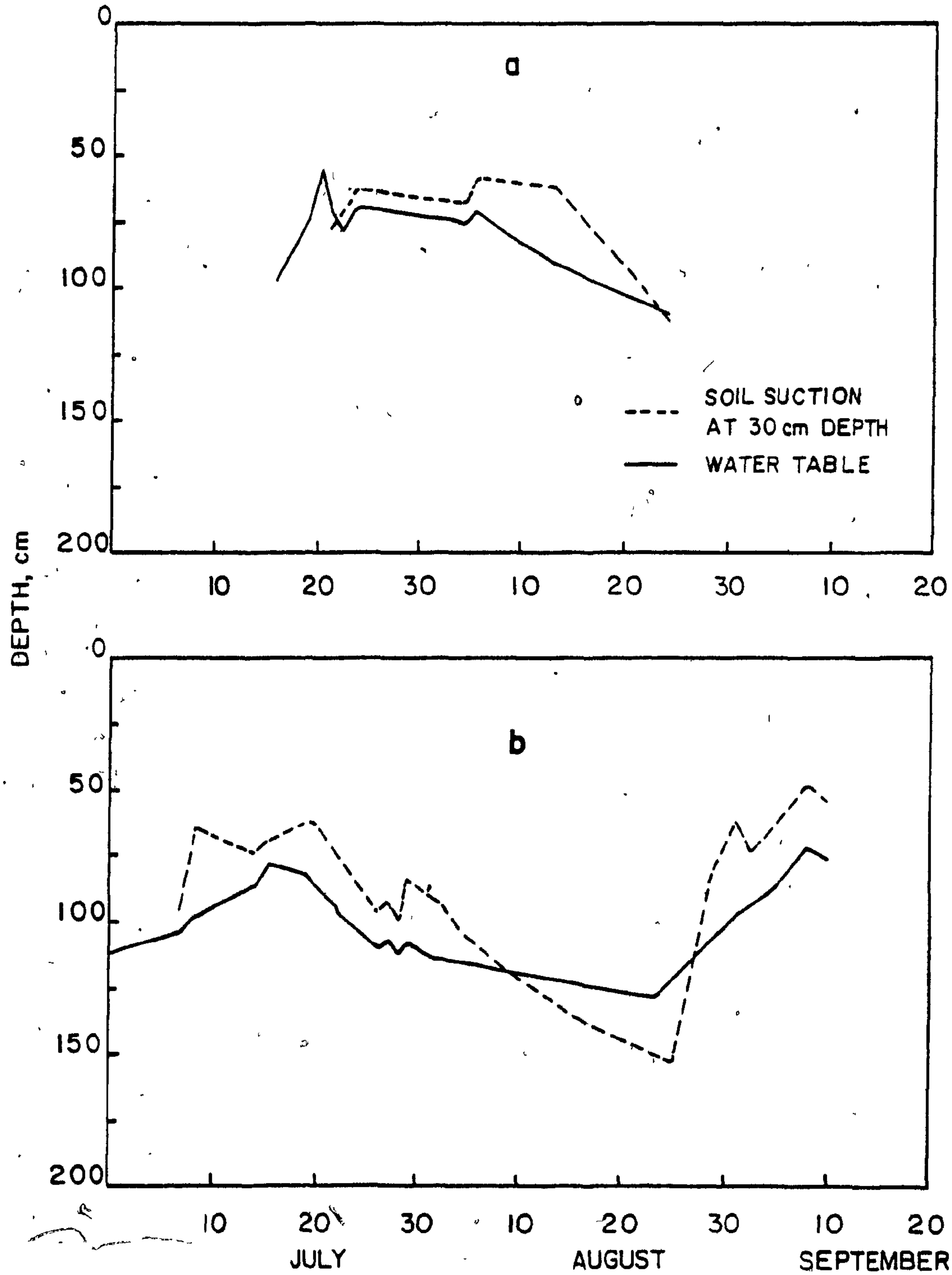

Figure 6.3. Effect of subsurface irrigation on the rise of water table and the soil suction at 30 cm in 1982 and 1983 field experiments.

conductivity function k(h), the soil water pressure in the root zone, or at the soil surface in the fallow case and the water table depth. To determine the depth that the water table should be maintained, the depth distribution of the root zone and the evaporation rate must be known.

Root measurements for corn were made in the irrigated and non-irrigated plots and the results are shown in Table 6.5. Most of the roots were concentrated in the 30 cm soil profile, and there were very few roots at the depths greater than 30 cm in both irrigated and non-irrigated plots. This is unusual because the depth of corn roots in non-irrigated plots was expected to be greater than that in the irrigated plots. Waldren (1983) indicates that non-irrigated corn expands its root system when faced with a low moisture supply. The possible reduction in the root depth may be caused by acidic subsoils. Acidic soils are associated with the presence of high aluminum ion concentration. Soil with a pH of less than 5.5 contain a high aluminum ion concentration (Adams, 1981). Soil pH decreases as the aluminum ion concentration increases. Chemical analysis of this soil was investigated by Rashid-Noah (1981). His results showed that the soil contained 1.05×10^{-2} meq/100 gram of soil aluminum ion concentration at 45 cm depth. Also, it was observed during root sampling that the roots were stubby and distorted. Taylor (1981) indicated that when aluminum activity increased in the soil solution the roots

TABLE 6.5: Dry weight of the roots of corn in subsurface irrigated and non-irrigated plots, as observed in 1983 field experiments.

Plots	Dry weight of the roots, x $10^{-4} g/cm^3$					
	Depth at bottom of 10 cm long core (cm)					
	10	20	30	40	50	60
Irrigated:						
A-1	1.6	1.7	1.7	5.4	-	-
A-2	3.2	4.7	2.8	2.7	0.5	-
A-3	2.6	2.2	3.5	-	-	-
A-4	3.6	8.7	6.6	-	-	-
A-5	0.6	2.6	2.2	0.1	-	-
A-6	2.3	2.3	1.1	0.3	-	-
A-7	1.7	5.2	7.2	1.1	0.9	-
A-8	2.4	3.7	1.3	0.3	-	-
Average	2.3	3.9	3.3	1.7	0.7	-
Non-irrigated						
B-1	4.2	4.1	0.6	1.0	1.1	-
B-2	3.4	5.0	3.8	0.9	-	-
B-3	3.0	4.4	4.6	3.3	1.4	-
B-4	3.6	2.3	1.5	0.3	-	-
B-5	1.7	2.8	2.5	3.7	0.2	-
B-6	1.3	3.5	1.3	-	-	-
B-7	6.3	6.0	1.7	-	-	-
B-8	3.5	3.8	6.1	1.6	-	-
Average	3.4	4.0	2.8	1.8	0.9	-

Note: The root samples were taken at a distance of approximately 20 cm from a row of corn. The spacing between rows was 80 cm.

The blanks indicate that the roots were not found at the respected depths.

tend to become shortened and swollen. It was therefore concluded that the acidic subsoil was the reason for the reduction of root depth.

Evapotranspiration depends on climatic factors, including net radiation, temperature, humidity and wind velocity. Evapotranspiration can be determined with lysimeters. However, such measurements were not made and the evapotranspiration values were obtained from climatological data measured at the research location, using one of the prediction methods. The maximum ET rate of 4.5 mm/day was found suitable for this location. For prevention of physiological damage due to drought, the plant should transpire at the potential rate of 4.5 mm/day. This is regarded as the condition for optimal plant growth. Based on this, the optimum water table depth is selected for the design of subsurface irrigation system. In a water balance study, the fall or rise of the water table is of interest and its effect on upward flux. Therefore, a relationship between upward flux and water table depth is required.

The matric flux potential (MFLP) concept was used to arrive at the relationship between water table depth and steady upward flux. As the unsaturated hydraulic conductivity function $k(h)$ is a prerequisite in the calculation of steady upward flux, the $k(h)$ function was determined from a water retention characteristic curve, using equation (3.13).

Figure C.1 shows the results of the soil moisture characteristic curve for the experimental field. There is a sharp drop in soil moisture content at suction values less than 100 cm. For values greater than 100 cm, soil moisture content decreases very slowly. The soil moisture content drops about 25% when the soil suction is at 100 cm. If the drainage system in this soil is placed at 100 cm depth below the surface, then approximately 25% of the soil volume will be drained. Since this amount of drainage is more than the 15% of the air volume requirement for an optimal plant environment, an excessive drainage condition would exist and less water would be available for plant growth.

By the use of the saturated hydraulic conductivity (Table C.2) and the soil moisture characteristic curve, the unsaturated hydraulic conductivity function, k(h), was calculated, using equation (3.13). The results of k(h) are given in Figure C.2. Figure C.2 was used to determine the pressure head distribution above the water table and the relationship between upward flux and water table depth, using equation (3.12).

Rewriting equation (3.9) in finite difference form as:

$$MFLP_i = k(h_i)(h_{i+1}-h_i) \quad \ldots (6.1)$$

equation (3.12) becomes:

$$Z_{i+1} = \frac{MFLP_{i+1} - MFLP_i}{q_u + [\{k(h_{i+1})+(h_i)\}/2]} + Z_i \qquad ...(6.2)$$

Equations (6.1) and (6.2) were solved on a digital computer to obtain the distribution of pressure head as a function of height above a water table. A water table depth of 120 cm below the soil surface is assumed because this will be a rather realistic estimate, as most of the drainage systems are installed at depths of 120 cm and less from the soil surface in this region. At the water table, Z equals zero, and the pressure head h equals to zero. At the next increment of pressure head (1cm in this case), the water table value Z is calculated. Therefore, Z is calculated for each increment of pressure head h, and both h and Z are simultaneously accumulated. The calculation of capillary rise stops when a prefixed h value is attained or before the upward flux (4.5 mm/day is assumed) reaches the soil surface. For this case Z equals the height above the water table. The results of pressure head as a function of height above the water table are plotted in Figure 6.4.

Figure 6.4 shows that the height of capillary rise increases as the pressure head increases. At a pressure head of 150 cm, the height of capillary rise curve becomes nearly asymptotic. This means that the k(h) function decreases rapidly in this soil due to higher pressure heads which

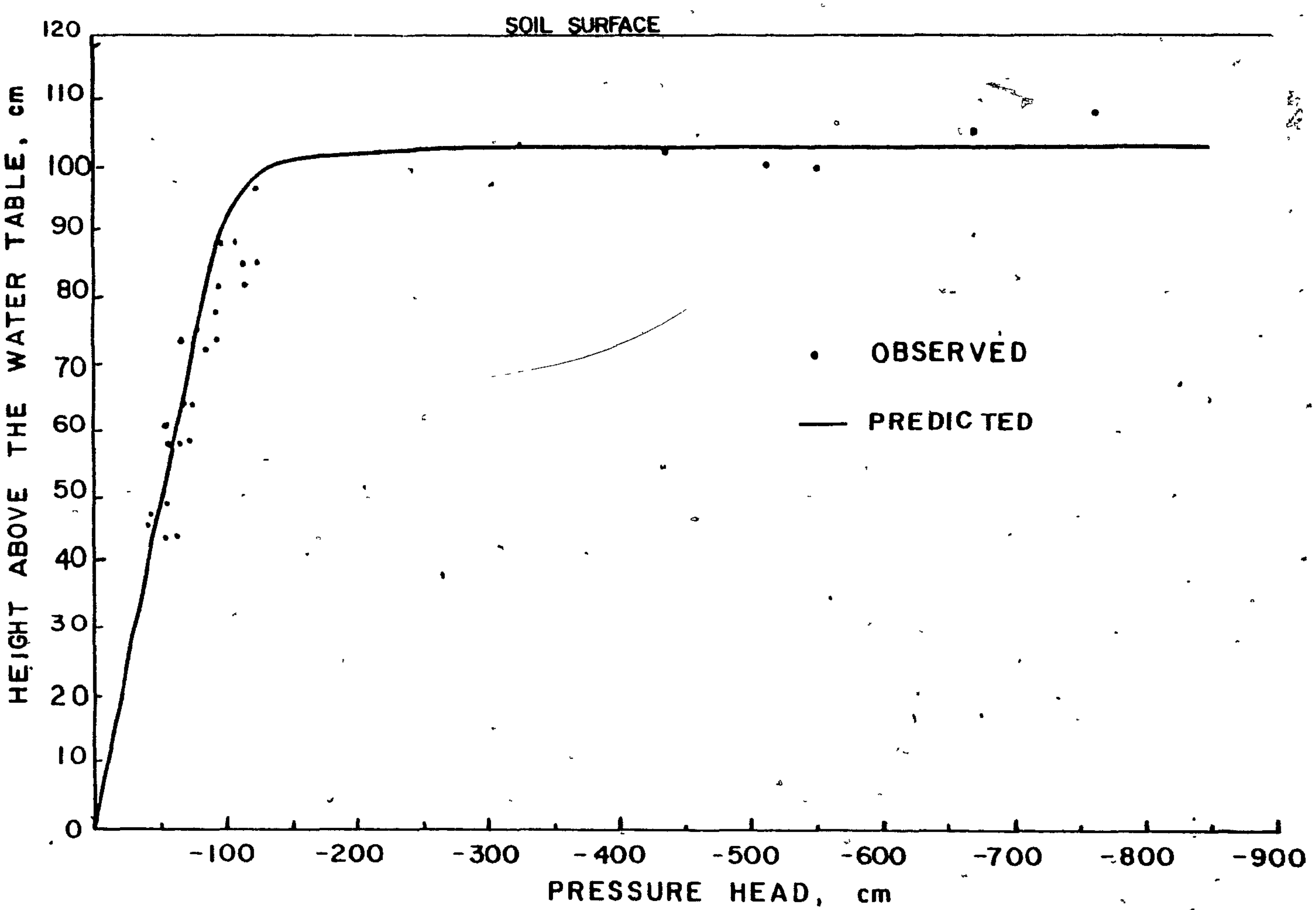

Figure 6.4. Pressure head as a function of height above the water table, using steady upward flux of 4.5 mm/day.

causes the given upward flux to rise very slowly. The points in Figure 6.4 are the observed pressure head values from the experimental field above the water table when the evapotranspiration was approximately equal to the given upward flux (i.e 4.5 mm/day). The observed pressure head values are in close agreement with the theoretical curve, suggesting that the soil profile is homogeneous and that the assumption of soil homogenity is justified (section 4.1 of chapter IV).

Figure 6.4 allows a decision to be made regarding the pressure head at the bottom of the root zone when maximum evapotranspiration in this region is assumed to be 4.5 mm/day.

The values of pressure head for different crops can be obtained from the literature. Taylor and Ashcroft (1972) have given a table of such values. From those tables the maximum allowable pressure head of -500 cm at the bottom of root zone was selected. At this pressure head, the height of capillary rise can be determined from Figure 6.4. This indicates that the water table at 120 cm below the soil surface can supply an upward flux of 4.5 mm/day to a height of 17 cm below the soil surface when the pressure head is -500 cm.

The relationship between upward flux and water table depth is determined by solving equations (6.1) and (6.2), subject to the following boundary conditions. At the lower boundary, the water table pressure head h is equal to zero and z is zero, and at the upper boundary (bottom of the root zone), pressure head h is equal to -500 cm and z equals to d. The calculation of MFLP starts from h equals to zero and the corresponding hydraulic conductivity which was assumed to be the saturated hydraulic conductivity, k_s. The pressure head was divided into 1 cm increments. The calculation of MFLP progresses according to equation (6.1) until h_{max} (equals to -500 cm) is reached. The determination of Z, the water table position is obtained from equation (6.2) by assuming a value of upward flux and looking up the k values at h_i and h_{i+1} and taking the average. In this way Z is determined until h_{max} is reached. The resulting relationship between water table position and steady upward flux is presented in Figure 6.5 for the St. Samuel sandy loam soil.

The depth at which the water table should be maintained to supply the designed ET rate to the crop can now be easily determined from Figure 6.5. It can be seen from Figure 6.5 that the ET rate of 4.5 mm/day would be maintained at a water table depth of 85 cm below the root zone (average root zone of 15 cm is assumed). It can be noted from Figure 6.5 that lowering the water table from 85 to 120 cm below the root zone would decrease the upward flux 15 times. This is due to the transmitting properties of a sandy soil. ET rate is one of the causes to bring the water table down.

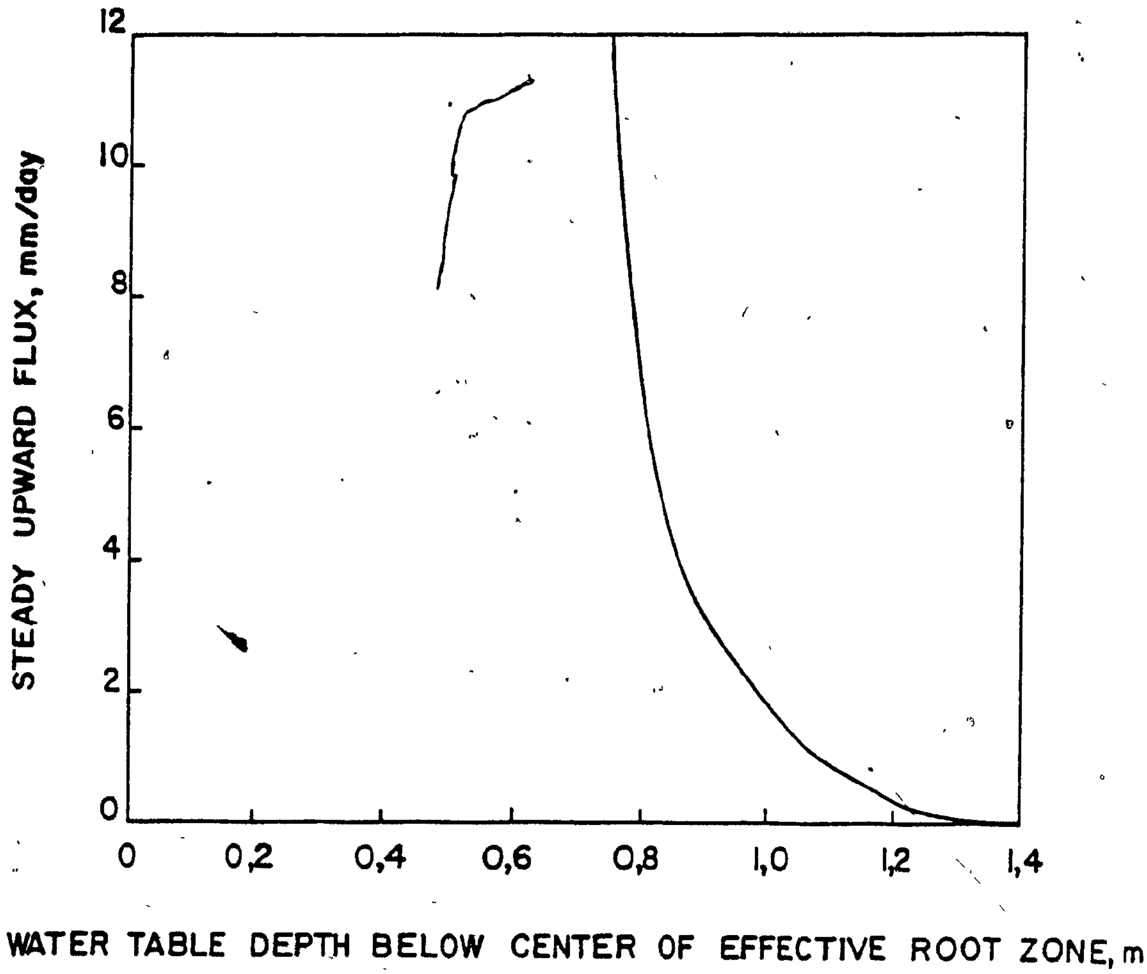

Figure 6.5. Relationship between steady upward flux and water table depth for the St. Samuel sandy loam soil.

Subsequently, there is a decrease in the soil moisture content and hence unsaturated hydraulic conductivity, k, in the subsurface layers. With the result of low k values in the subsurface layers, the upward flux to the bottom of root zone decreases.

The relationship between upward flux and water table depth is used in a water balance model in tabular form to calculate the soil moisture distribution in the soil profile. It is assumed in the model that ET demand can be satisfied directly from the water table for water table depths of 85 cm and less below the root zone. For deeper water tables, the rate of upward movement is not sufficient to supply the ET demand, resulting in a decrease of moisture content in the root zone as explained in chapter IV.

6.1.4 Relationship between drainage volume and water table depth

In chapter IV, the relationship between drainage volume and water table depth was proposed in a water balance model for computing the water table drop or rise due to the volume of water leaving by drainage or ET, or entering by rainfall or subsurface irrigation. For this relationship, large undisturbed soil cores were used to measure drainage volume directly with a certain water table drop. These measurements are shown in Table 6.6 for six cores at

TABLE 6.6 : Laboratory values of drainable pore volume (V_d), at different water table depths, using long undisturbed soil cores.

Water table depth cm	Drainable pore volume (mm)						Average of six soil cores	S.D	C.V
	Soil core numbers							mm	(%)
	1	2	3	4	5	6			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12.5	9.6	10.4	9.2	9.8	9.4	10.0	9.7	0.43	4.4
25.0	28.0	23.8	22.6	28.6	22.4	29.2	25.8	3.08	11.9
37.5	54.1	39.0	47.6	56.2	43.4	56.6	49.5	7.31	14.8
50.0	85.6	90.2	85.2	87.4	71.2	89.0	84.8	6.92	8.2
62.5	111.0	117.2	112.6	118.6	138.8	121.2	119.9	10.00	8.3
75.0	151.4	158.0	153.4	156.8	176.2	162.8	159.8	8.96	5.6
87.5	201.4	202.4	205.4	207.8	222.2	215.6	209.1	8.17	3.9
100.0	250.0	252.8	254.8	260.6	263.2	270.0	258.6	7.45	2.9

TABLE 6.7: Variation of drainable porosity at different water table depths determined from long undisturbed soil cores.

Water table depth cm	Drainable porosity in fraction						Average of six soil cores	S.D
	Soil core numbers							
	1	2	3	4	5	6		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12.5	0.077	0.084	0.074	0.079	0.075	0.080	0.078	0.004
25.0	0.122	0.095	0.091	0.155	0.091	0.177	0.105	0.014
37.5	0.145	0.104	0.127	0.150	0.166	0.151	0.132	0.020
50.0	0.171	0.181	0.170	0.175	0.143	0.178	0.170	0.014
62.5	0.178	0.187	0.180	0.190	0.222	0.194	0.192	0.016
75.0	0.202	0.211	0.205	0.209	0.235	0.217	0.213	0.010
87.5	0.230	0.231	0.235	0.238	0.254	0.247	0.239	0.010
100.0	0.250	0.253	0.255	0.261	0.263	0.270	0.259	0.007

different water table depths along with the coefficient of variation. From the coefficient of variation, one can conclude that the soil profile throughout the field is quite similar. Referring to Table 6.6, it can be seen that there is a large increase of drained volume when the water table drops below 37.5 cm from the soil surface. This is particularly true for sandy soils. When sandy soils are subject to suction, much of the water is released only after a critical suction value is reached. It is, therefore, necessary to place the subdrains above the critical suction value or use a water table control chamber to prevent possible over-drainage.

The values in columns 1 and 8 of Table 6.6 are plotted in Figure 6.6 to obtain a functional relationship between drainable volume and water table depth. The equation that best describes the relationship is of the from:

$$h = aV_d^{\,b} \qquad \ldots(6.3)$$

Where h = water table depth, cm

V_d = drainage volume, mm

a,b = constants determined using the least square fit

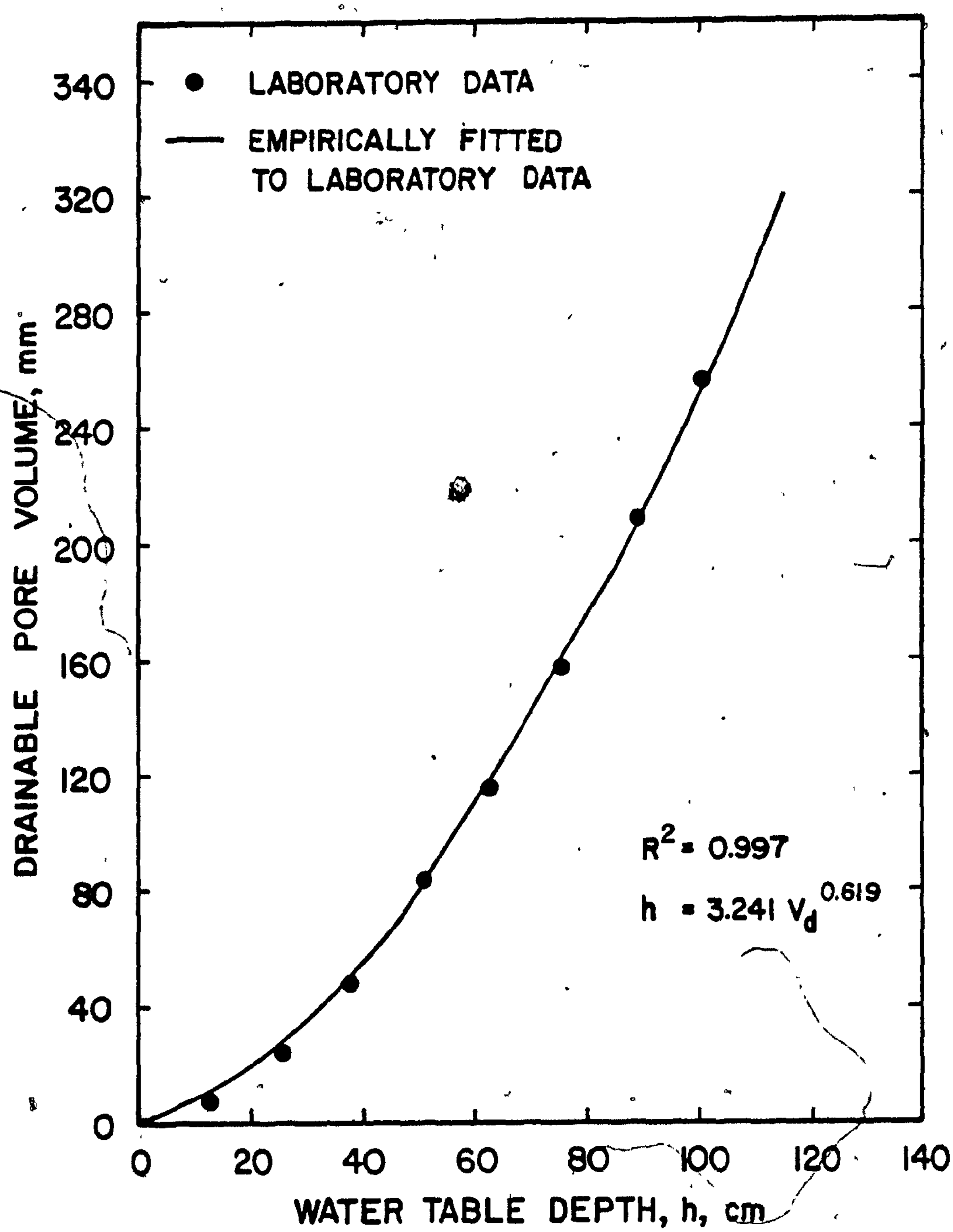

Figure 6.6. Functional relationship between drainable volume and water table depth for St. Samuel sandy loam soil.

The coefficient of correlation for this relationship was found to be 0.997. The V_d-h relationship developed in this study is used in the water balance model to predict the water table depth of the wet zone. This relationship would allow the water table depth to be determined simply from the volume of water that enters (subsurface irrigation and rainfall) or is removed (drainage, ET and seepage) from the profile over an arbitrary period of time. In deriving the relationship, hysteresis effects are neglected.

To emphasize the effect of over-drainage, the relationship between drainable porosity, f, and water table depth, h, was calculated from V_d-h measurements. Drainable porosities can also be determined graphically by computing the slopes of the drainage volume versus water table depth curve (Figure 6.6). The observed drainable porosity values at different water table depths are shown in Table 6.7, along with the average of six soil cores in column (8) and the standard deviation in the last column. It can be seen that for a water table depth of 100 cm below the soil surface, the drainable porosity averages about 26%. The soil has a saturation moisture content of 43%. If the subsurface drains are placed at a depth of 100 cm below the soil surface, over-drainage will occur, since 17% (43% - 26%) moisture content tends towards the permanent wilting point. A drained volume of 26% is 11% in excess of a desirable aeration space of 15%. It can be seen that the concept of water table control for sandy soils becomes desirable. This system prevents the water table from dropping which results in more water being available to the plants roots. The system can be extended for supplemental irrigation during dry periods by adding water to the control chamber for efficient water use by the crop.

6.2 Crop Yield

During the 1982 growing season, yields of maize were obtained from two irrigated and two non-irrigated plots. The results are presented in Table 6.8.

The analysis of variance of the 1982 grain yield results was not done because there was no observations collected from six other replicates of irrigated treatment due to blockage of the drain lines. However, the magnitude of yield difference in Table 6.8 , undoubtedly accentuated the response due to subsurface irrigation. On the average the irrigated treatment produced 40% more grain yield than the non-irrigated treatment. Table 6.8 shows a considerable variation in yield of maize within the irrigated plots. A similar situation was observed in non-irrigated plots. The possible explanation for the lower yields in the A-2 plot might be due to the water table being closer to the soil

TABLE 6.8: Average yield of maize from subsurface irrigated and non- irrigated plots on oven dry basis from 1982 maize crop.

Plots	Grain yield on dry basis Kg/ha	Average grain yield Kg/ha
Irrigated:		
A-2	4413	5314
A-4	6215	
Non-irrigated:		
B-2	3259	3788
B-4	4316	

TABLE 6.9: Average yield of maize in subsurface irrigated and non-irrigated plots on oven dry basis from 1983 maize crop.

Plots	Hand sampling			Machine harvest
	No. of ears	Ear yield Kg/ha	Grain yield Kg/ha	Grain yield Kg/ha
Irrigated:	42564 A	5685 A	4824 A	4445
Non-irrigated:	34797 B	3100 B	2587 B	2431

All the figures are average of 8 plots.

Recommended average grain yield of maize (Cardinal Sx 85A) around this farm was 7019 Kg/ha on oven dry basis (conseil des productions vegetales du Quebec).

Duncan's New Multiple Range Test used for comparing means. Means with same letter are not significantly different at the 5% level of probability.

surface over the drain. During field observations, the water table depth at the G-22 pipe was found to be 18 to 22 cm below the soil surface for 7 consecutive days at the time of tasseling and silking. The yield reduction in the B-2 plot may be due to the deep water tables. The water table in this plot was found to be 5 to 6 cm deeper than the B-4 plot during the field observations. Also in the B-2 plot, the soil at 30 cm depth below the soil surface was quite dry from July 20 through August 4 and the soil suction readings were out of the tensiometric range.

In 1983, all irrigated plots received water from subsurface drain pipes satisfactorily due to improvements made to the subsurface irrigation system in 1982 and 1983. Therefore, various components of yield were measured in the 1983 growing season to examine the effects of subsurface irrigation on maize yields. Table C.5 shows the analysis of variance on the results of maize yields. This table indicates that the grain yield and ear yield of maize are highly significant at the 0.01 probability level. In order to compare the mean yields of irrigated and non-irrigated treatments, Duncan's New Multiple Range test was used and the results of this test are presented in Table 6.9. The results indicate that the mean yields of the irrigated treatment are significantly different than the mean yields of the non-irrigated treatment at 0.05 probability level. The table also shows that the mean yields of the irrigated treatment are double that of the non-irrigated treatment.

Table 6.10 shows the results of various components of yields obtained from individual plots of irrigated and non-irrigated treatments in 1983. It was observed from the yield measurements that the cobs were healthier and better filled in irrigated plots than in non-irrigated plots. For example, the A-6 and B-2 plots produced an equal number of cobs but the ear yield and grain yield was higher in plot A-2 than in plot B-2. Similar results were obtained from plots A-7 and B-5. Although one irrigated plot (A-4) has the same number of cobs as that of A-6, it produced a lower grain yield as compared to plot A-6 or B-2. This may be due to delayed tasseling and silking in this plot and also many cobs from plot A-6 were affected by white smut.

One of the factors which might have caused the lower yield of non-irrigated plots was dwarfing of the plants due to soil moisture deficit. In addition to the observed dwarfing, the moisture deficit also delayed tasseling and silking on non-irrigated plots by about four to five days. Table 6.10 indicates that the soil moisture deficit stunted the size of the cobs, thus reducing the ear yield. There is also evidence that some of the non-irrigated plots did not yield as many cobs due to a severe soil moisture deficit. The last column in Table 6.10 shows the grain yield of maize obtained by the combine harvester. Approximately the same yield was

TABLE: 6.10. Yields of maize from subsurface irrigated and non-irrigated plots on oven dry basis from 1983 crop.

Plot No.	Hand sampling			Machine Harvest
	No. of cobs per hectare	Ear yield on dry basis Kg/ha	Grain yield on dry basis Kg/ha	Grain yield on dry basis Kg/ha
Irrigated:				
A-1	45981	5700	4815	4206
A-2	42253	5059	5260	3882
A-3	45981	6922	5861	4673
A-4	39768	3503	2936	2955
A-5	43496	5980	5131	4625
A-6	39768	5334	4521	3943
A-7	42253	6560	5610	5814
A-8	41010	6423	5457	5465
Mean	42564	5685	4824	4445
Non-irrigated:				
B-1	34379	3138	2611	2301
B-2	39768	3967	3332	2118
B-3	37382	3860	3222	3128
B-4	34797	2785	2301	2278
B-5	42253	4722	3085	3490
B-6	34797	2829	2371	2828
B-7	27340	2058	1715	1722
B-8	27340	1443	1159	1583
Mean	34797	3100	2587	2431

obtained by hand sampling.

The yield response to the subsurface irrigation draws attention to the results of soil moisture data discussed in section 6.1. These results reveal that the available water in the irrigated treatment was never limiting in the upper most layers during the time when subsurface irrigation was applied. When the water table receded below 100 cm from the soil surface, the upward flux was limited and the available water in the uppermost layers supplied the ET needs as evidenced by soil moisture depletion in Figures 6.1 and 6.2. Although subsurface irrigation was not uniform throughout the growing season of 1982 and 1983, the supply was adequate before and after the tasseling period. For that reason, tasseling began 4 or 5 days earlier in irrigated plots than in non-irrigated plots. In addition to the observed tasseling, the plants in the irrigated plots were found to be taller than in the non-irrigated plots. The difference was approximately 40-50 cm. The delayed tasseling of 4-5 days in non-irrigated plots might have caused the plants to be short due to the shortening of internodes at the upper portion of the plant (Robins and Domingo, 1953).

The weather data in Table 6.11 show that the 1983 growing season was relatively drier than 1982 (From 15 May to 30 September). The total rainfall in 1982 was lower than the 30-year average at the L'assomption station. The monthly

TABLE 6.11: Monthly rainfall, PE and subsurface irrigation volume for the year 1982 and 1983.

Month	Rainfall mm	PE mm	Monthly average of 30-year mm	Monthly subsurface irrigation volume mm
1982				
May	25.1	37.9	34.0	0.0
June	97.5	118.8	121.0	0.0
July	25.0	157.8	29.0	44.2
August	120.9	117.4	137.0	16.1
September	112.0	64.7	124.0	0.0
Total	380.5	528.6	445.0	60.3
1983				
May	89.6	66.2	245.0	0.0
June	24.9	119.2	50.0	0.0
July	38.6	125.0	64.0	68.8
August	69.2	111.2	53.0	55.8
September	63.6	96.6	-	43.0
Total	285.9	486.3	412.0	167.6

rainfall for 1982 and 1983 was also lower than the 30 year average monthly rainfall at the above station. It appears that both experimental years were relatively dry years indicating the need for irrigation water for better crop production. The relatively low yields of maize in non-irrigated plots may be attributed to low rainfall in those years. Total amounts of subsurface irrigation supplied in 1982 and 1983 were 60.3 and 167.6 mm respectively. Total rainfall and subsurface water applied, raised the 1982 water supply in irrigated plots to 440.3 mm and the 1983 total to 548.1 mm. May 1983 rainfall was higher than that of May 1982. Therefore, the planting in 1983 was delayed for 15 days. Comparatively lower yields obtained in 1983 than 1982 might be due to delayed planting. Another possible explanation may be due to fewer replicates in 1982 than in 1983.

From the above results and discussion, subsurface irrigation appears to be beneficial in sandy soil. Water table control conserves soil moisture and provides more water for dry periods for plant growth and better yields.

6.3 Water Balance Model

The over-all goal of developing a water balance model was to optimize subsurface irrigation/drainage design for corn yield. Inputs in the model are the climatological data, soil properties, subsurface irrigation/drainage system parameters. Climatological data include the daily rainfall and PE. Saturated hydraulic conductivity, drainable pore space, steady upward flux as a function of water table depth, water content at saturation and wilting point are the soil properties used in the model. The crop parameters are: rooting depth as a function of time, planting date and parameters for the yield response models given in sections 4.1.1 and 4.1.2. Subsurface irrigation/drainage system parameters are: drain depth and spacing, depth to the impermeable layer, design water table depth (DWT) at a point midway between the drains, limiting drainage coefficient, water table control at the drain, optimum water table depth as a function of maximum ET (in our case 4.5 mm/day) for the case of subsurface irrigation. All parametric values used in the model are shown in Table 5.1.

As subsurface irrigation is used during dry years, weather data for two dry years were used in the model. It was realised that the optimization would have been more meaningful if weather data from a larger number of years were used in the model on a probabilistic basis. However, the model was designed so that it can handle several years of weather data. The model does not consider trafficability and yield reduction due to any soil compaction or delay in planting. With minor modifications these parameters could be incorporated . Such additions were considered beyond the scope of this thesis. It is suggested that the incorporation of the above features could be valuable for future research in soil-water-plant relationships.

6.3.1 Comparison of observed and predicted water table depths and maize yield

The model verification was carried out using the 1982 and 1983 input data for the St. Samuel sandy loam soil with no subsurface irrigation. The results of predicted water table depths are shown in Figures 6.7 and 6.8 for the years 1982 and 1983 respectively. Observed water table depths are also plotted in these figures. From these figures the agreement between the observed and predicted water table depths is found to be quite close. The results from the integrated crop model are given in Table 6.12 for 1982 and 1983. This table shows that the general agreement between observed and predicted grain yield was close in 1982, while the agreement in 1983 was not as close as that of 1982. The maximum difference between observed and predicted yields in 1982 and 1983 was found to be 82 and 277 Kg/ha respectively. This means that the model predicted 2% lower yields in 1982 and 11 % higher in 1983. The lack of agreement in 1983 may be the reduction of yields due to delayed planting. Further refinement in this respect was not made in the model. However the model shows close agreement between observed and predicted water table depths and maize grain yields.

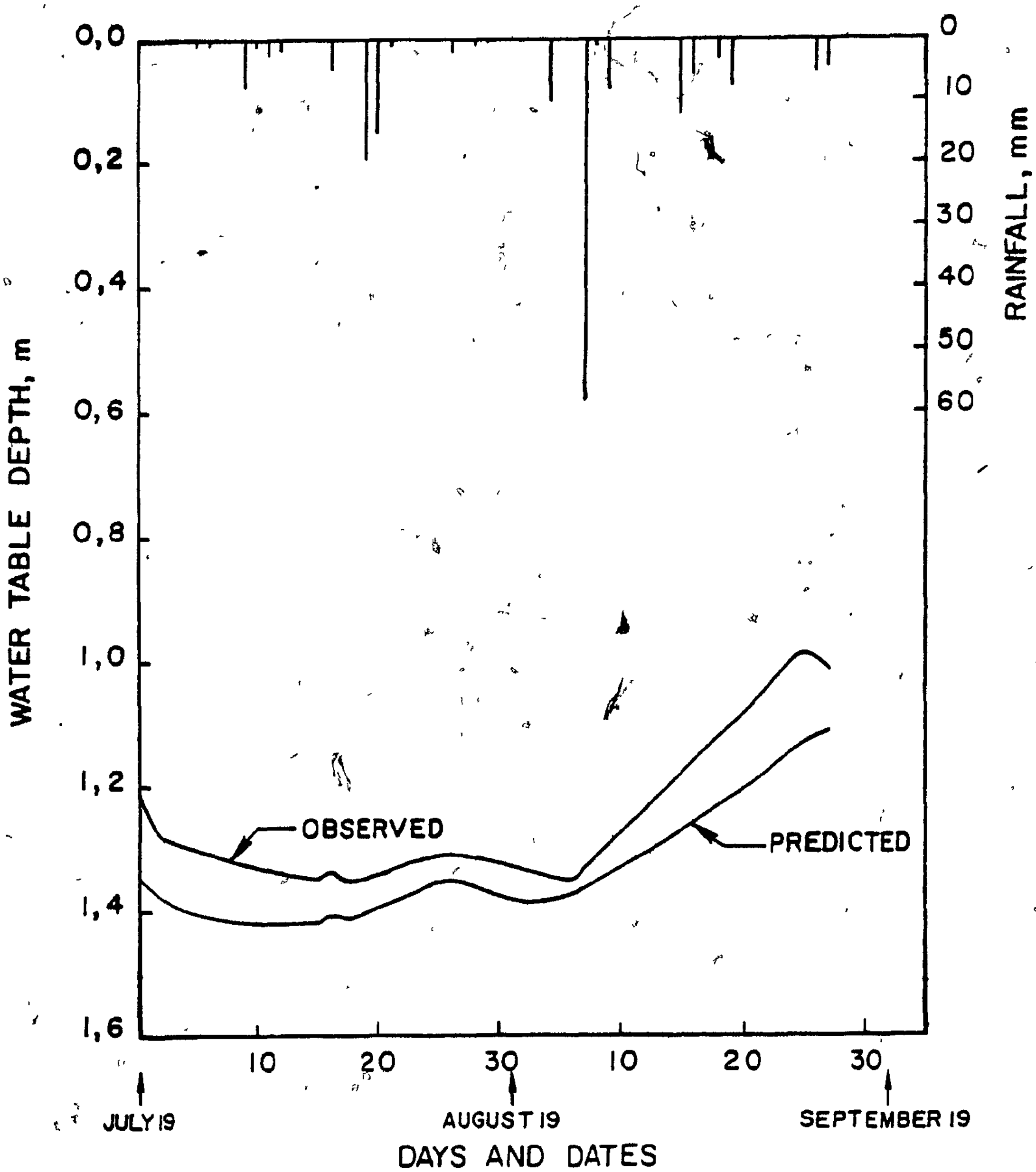

Figure 6.7. Observed and predicted water table depths for the year 1982.

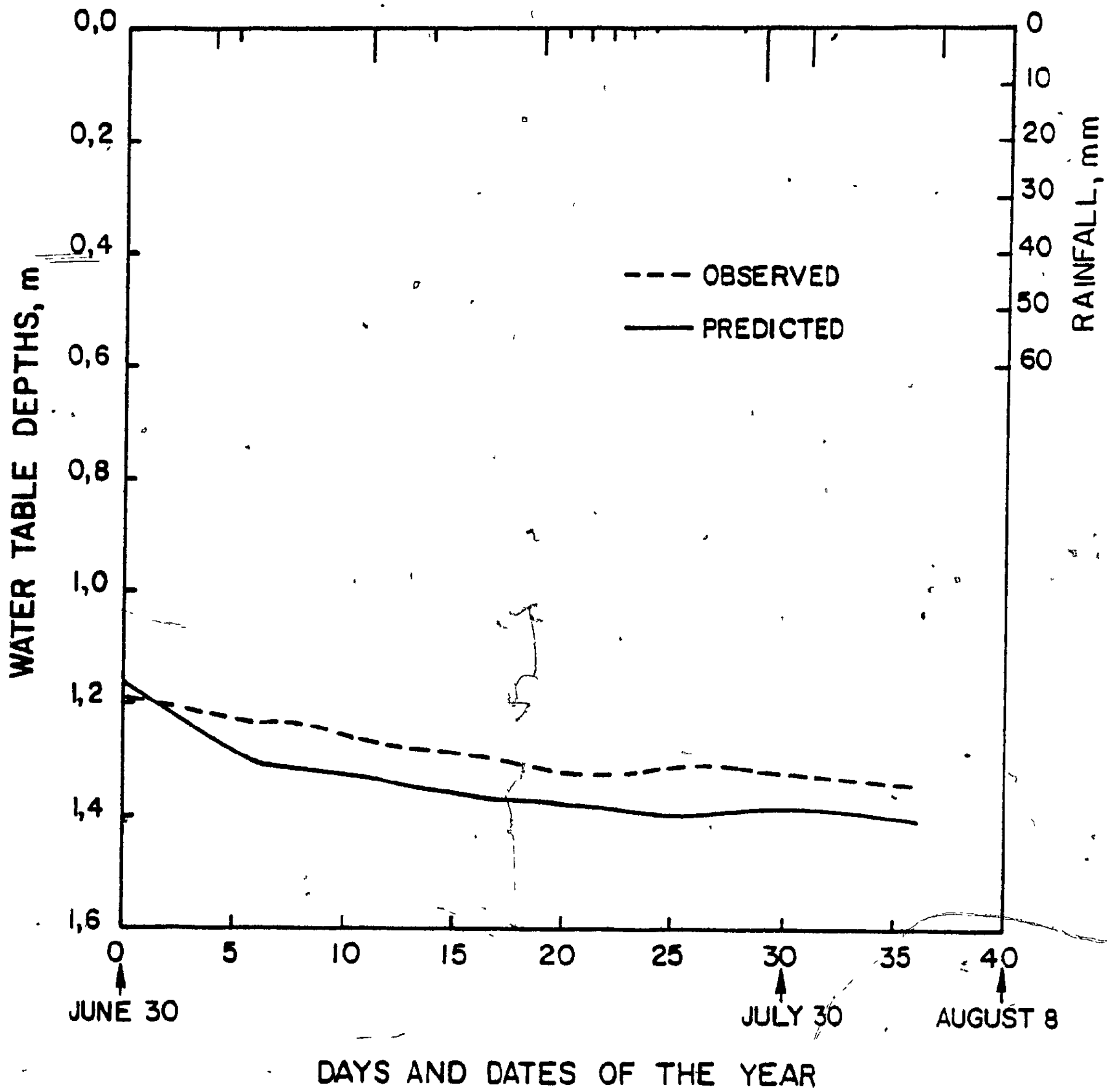

Figure 6.8. Observed and predicted water table depths for the year 1983.

TABLE 6.12: Observed and predicted maize yields in non-irrigated plots for the growing years of 1982 and 1983.

Growing year	Observed maize yield Kg/ha	Predicted maize yield Kg/ha	Maize yield difference Kg/ha
1982	3870	3788	82
1983	2587	2864	277

Potential yield of maize = 7019 Kg/ha (see Table 6.9 bottom note.)

6.3.2 Effect of subsurface irrigation/drainage on maize yield.

Average relative maize yields for the two years are plotted as a function of drain spacing in Figure 6.9 for both subsurface irrigation and drainage systems. These relationships are presented for a St. Samuel sandy loam soil. The relative yields are higher for subsurface irrigation than subsurface drainage. This relationship of subsurface irrigation shows that 100% average relative yield could be predicted for drain spacings of 5 m to 30 m. For spacing greater than 30 m the averge relative yield drops almost linearly to a maximum of 47% at drain spacing, W equals to 80 m. This is attributed to the excessive soil moisture conditions existing due to shallow water tables and also reduced drainage rates. Drainage rate decreases with wider spacings; shallow water tables in subsurface irrigation reduce the amount of storage available for infiltrating rainfall. Either of these two factors or a combination of both may result in excessive soil moisture conditions. In deriving these relationships, the effects of fertilizer, pathological diseases, and relatively wet years which could result in untimely field operations and a delay in planting are ignored.

Figure 6.9 shows that the maximum average relative maize yield of 51.6% is predicted for the case of drain spacing

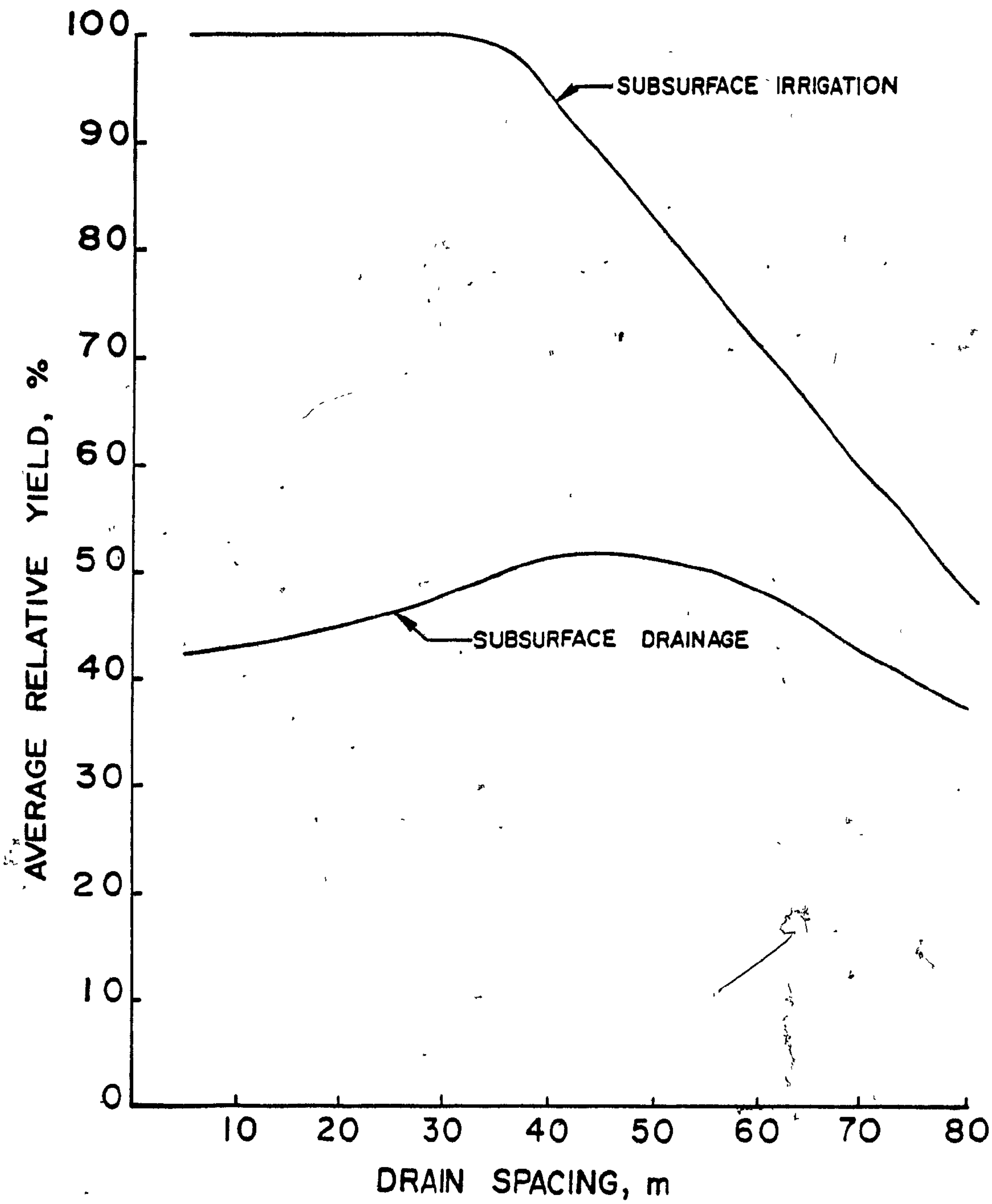

Figure 6.9. Predicted average relative maize yield as a function of drain spacing for both subsurface irrigation and drainage systems, usig mean saturated hydraulic conductivity value.

equal to 45 m with subsurface drainage. Lower average relative yield values (YR) for drain spacings less than 45 m are associated with deficit soil moisture conditions. Whereas lower YR values for drain spacings greater than 45 m are caused by the combination of deficit and excessive soil moisture conditions. Drain spacings less than 45 m have the tendency to cause excessive drainage as evidenced by slightly reduced average relative yields. Higher average relative yields were not obtained because of deficit soil moisture conditions which cause drought stress during relatively dry years.

The results of YR are presented in Table 6.13 for both cases of subsurface drainage and subsurface irrigation during each year. This table shows a variation in yield predictions from year to year. This suggests the need for many years of data if designs are to be based on a water balance model. Results indicate that the YR values predicted in 1983 were less than the YR values in 1982. This may be explained by the fact that 1983 was relatively drier than 1982 and the rainfall was not uniform. Non-uniformity of rainfall produced excessive soil moisture condition in May 1983 at wider drain spacings. Thus an additional yield reduction was found.

TABLE 6.13 : Predicted relative yields of maize for subsurface irrigation and drainage systems at different drain spacings, using 1982 and 1983 weather data.

1982

Drain spacing m	Relative yield in percent		Subsurface irrigation mm
	Subsurface drainage	Subsurface irrigation	
5	53.5	100.0	481.4
10	53.6	100.0	445.0
15	53.9	100.0	399.3
20	54.2	100.0	360.0
25	54.6	100.0	318.2
30	55.1	100.0	275.4
35	55.6	99.9	230.7
40	56.2	98.5	195.4
45	56.6	96.0	163.7
50	57.3	92.9	137.5
55	58.1	90.0	117.2
60	59.1	87.3	100.5
65	60.2	84.8	85.0
70	61.4	83.0	73.6
75	62.6	81.8	64.6
80	63.8	80.8	56.7

1983

5	31.0	100.0	487.9
10	32.4	100.0	417.1
15	33.7	100.0	347.0
20	35.6	100.0	302.1
25	38.0	100.0	263.7
30	40.8	100.0	220.2
35	44.0	98.4	176.1
40	46.9	90.7	143.8
45	46.6	79.9	119.0
50	45.0	72.7	98.3
55	43.1	63.9	82.4
60	38.3	53.8	69.5
65	30.5	40.5	59.3
70	24.2	30.6	50.8
75	17.7	21.4	44.7
80	11.3	13.0	38.8

Similar results were obtained for the subsurface irrigation case (Table 6.13). In this case the excessive soil moisture conditions at wider drain spacings reduced the yield more drastically in 1983. The last column in Table 6.13 shows the predicted amount of subsurface irrigation (from May 6 to Sept 15) for different drain spacings. Both years show a small variation in the amount of subsurface irrigation water required. In 1982, higher amounts of subsurface irrigation were predicted than in 1983. This is because the PE in 1982 was higher than in 1983 (see Table 6.11); and also the excessive soil moisture conditions in May 1983 reduced the subsurface irrigation supply at wider drain spacings. It can be seen in Table 6.13 that the amount of subsurface irrigation decreased as the drain spacing increased. This is consistent with the assumption made in section 4.1 that the irrigation rate follows equation (3.2), in which the subsurface irrigation rate per unit area decreases as the drain spacing, W, increases.

The uncertainty due to non-uniformity of the saturated hydraulic conductivity may produce uncertain subsurface irrigation/drainage designs. It is possible that the uncertainty of the design may affect the relative yield and the relationship given in Figure 6.9.

It is not uncommon that the saturated hydraulic conductivity may vary widely from site to site within a given soil type. The measurements of this soil property of St. Samuel sandy soil have been shown by Rashid-Noah (1981). He observed that the range, encountered in this soil varied from the lowest 0.79 m/day to the highest 4.16 m/day at 0.75 m depth in the soil profile. From this range five values of saturated hydraulic conductivity were taken and the model was run for spacings varying between 5 and 80 m to maximize the relative yield. The results of these runs are shown in Figures 6.10a and b for subsurface drainage and subsurface irrigation cases respectively.

From Figure 6.10a, it can be seen that the maximum average relative yield of 52% was obtained at drain spacings of 25, 40, 50, 60 and 70 m using k_s values of 0.79, 1.19, 2.0, 2.89 and 4.16 m/day respectively. It is seen from the results that even a small variation in k_s, such as for 0.79 to 1.19 m/day, requires 25 and 40 m drain spacings respectively to maximize the relative yield.

For the subsurface irrigation case (Figure 6.10b) drain spacings of 20, 25, 35, 40 and 50 m are required to maximize the relative yield at k_s values of 0.79, 1.19, 2.0 2.89 and 4.16 m/day, respectively. These results emphasise the variation or the risk in the design. The magnitude of the

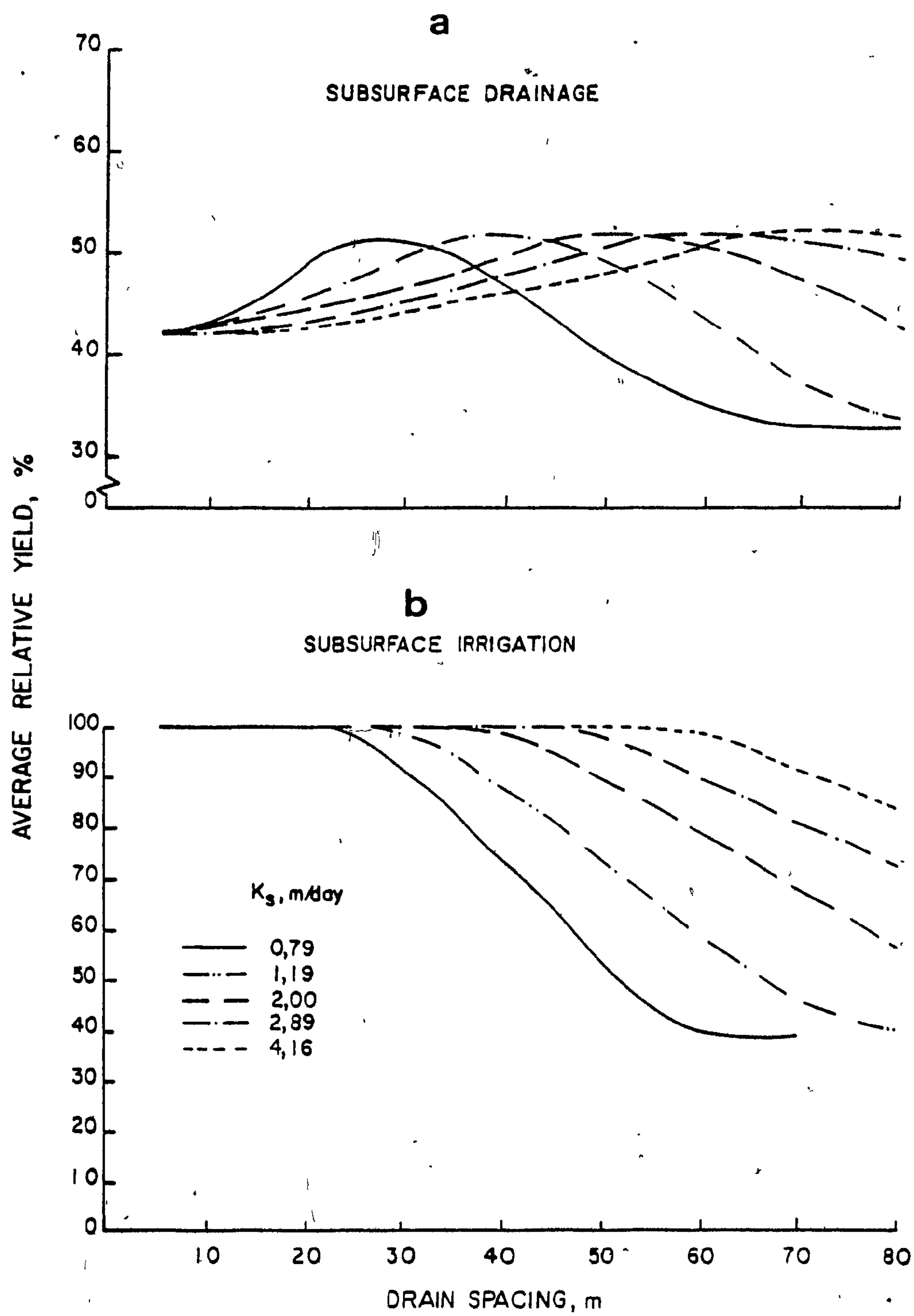

Figure 6.10. Predicted average relative maize yield as a function of drain spacing for various saturated hydraulic conductivity values.

risk is not calculated but the definition is given. There is risk in the design if it exceeds the given bounds. A 90% confidence bound is assumed. To compute this bound, the first step is to make an assumption regarding the probability distribution. The next step is to obtain the mean, S.D and the number of observations. From 120 samples, Rashid-Noah (1981) determined mean and S.D as 1.56 and 1.548 m/day of k_s respectively. Assuming a normal distribution, one can then calculate the upper and lower limit as 1.74 and 1.38 m/day respectively at a 90% confidence level. From these bounds one can deduce that, any value which exceeds the given bound will produce an uncertain design and hence a greater risk.The risks can be reduced by decreasing the spacing but this will increase the cost of the subsurface drainage system.

From the limited data it appears that the average yields are increased significantly by subsurface irrigation even though the spacing between pipes is based on subsurface drainage. While the maximum yield will be attained if the design spacing between laterals is based on the subsurface irrigation system. Figure 6.9 shows that for good subsurface irrigation design the spacing required is approximately 67% of that of the drainage case.

6.4 -Economic Analysis

In the previous section, the yields were maximized to obtain subsurface irrigation/drainage design spacings between laterals. It was found that subsurface irrigation increased the yield compared to the drainage system for a given drain spacing. The results from the field experiments also provided support for the use of subsurface irrigation in dry years if crop production was to be increased.

It should be noted from Figure 6.9 that the model predicted a maximum of 52% average relative yield in 1982 and 1983 for plots with drains but no subirrigation. This means that 48% yield reduction would be obtained during dry years if only a subsurface drainage system is used. This yield reduction represents a sizeable loss of income to the maize growers in this region. Subsurface irrigation was found to increase the yield, but it was not known whether subsurface irrigation would be economically profitable since there is no available economic analysis for this system in this region. Therefore an economic analysis was carried out to determine the effect of subsurface irrigation and drainage design alternatives on the profit of corn in dry years. Annual profit is defined as the gross crop value less the cost of production .

6.4.1 Income

The annual income for the subsurface irrigation and drainage was calculated as:

Income ($) = YR * Potential yield (Kg) * crop price ($/Kg)

The potential grain yield of maize was obtained from the Conseil des productions vegetales du Quebec (Ministere de l'Agriculture des Pecheries et de l'Alimentation, 1983). The potential yield depends on the variety (hybrid) of maize grown. The hybrid that was used at Charbonneau's farm was Cardinal Sx-85A and the average potential yield recommended for this hybrid was 8258 Kg/hectare at 15% moisture content. The average price of $0.183/Kg was obtained from CREAQ, 1983. Another corn price of $0.170/Kg was assumed for calculations to show the effect of variation in maize prices.

6.4.2 Cost

Cost analysis consisted of production cost of corn, initial drainage cost amortized over its estimated useful life and an additional cost for subsurface irrgation. Production costs for maize were obtained from CREAQ (Ministere de l'Agriculture des Pecheries et de l'Alimentation, 1983).

This cost is shown in Table 6.14. Drainage installation costs were obtained from estimates prepared by the Agricultural Engineering Department of Macdonald College, Ste Anne de Bellevue, Quebec. This cost was amortized at an interest rates of 8% and 10% with an assumed system life of 30 years (conservative estimate). The cost of subsurface irrigation depends on the size and shape of the land area, existence of the water supply, availability of power supply and number of control chambers required. These costs, along with the assumed maintenance cost, were estimated for the land area of 10 hectares located at Charbonneau's farm. The capacity of the pump required to irrigate 10 hectares of land was calculated from the estimated volume of irrigation and the seepage losses and is presented in chapter VIII. Respective costs for the components of the subsurface irrigation system are given in Table 6.15. The total cost for production of maize with subsurface irrigation is the sum of the production cost, amortized drainage installation cost and an additional cost of subsurface irrigation. Total annual costs for subsurface irrigation and subsurface drainage systems are shown in Table 6.16.

6.4.3 Profit

Average annual profit as a function of drain spacing was calculated using the relationships of Figure 6.9 and Table

TABLE 6.14: Estimated production cost for maize*.

Items	$/ha
Variable costs:	
- Seed	61.00
- Fertilizer	219.00
- Pesticides	51.00
- Maintenance and reparation of machinery and equipments	60.00
- Fuel and lubricant	50.00
- Storage and Marketing	118.00
- Rent of land without subsurface drains	53.00
- Interest on financing	54.00
Total variable costs	666.00
Fixed costs:	
- Taxes	6.00
- Issurance of fire and responsibility	16.00
- Automobiles and trucks	10.00
- Professional costs	6.00
- Miscellaneous costs	24.00
Total fixed costs	62.00
Total production cost	728.00

* Taken from CREAQ, (Comité de références économiques en agriculture du Québec) 1983. Agdex 111/821

TABLE 6.15: Estimated additional cost for subsurface irrigation*

Item	$/ha/year
Initial cost:	
- Pump 1 hp, 230 volts, 1-phase, max. run amp: 11.0, locked rotar amp. 172 control, 2-regulators**	20.00
- Electric poles, wiring (Assuming*** distance of 500 m), pump house etc.	60.00
- Two control chambers***	100.00
Total initial cost	180.00
Variable Cost	
- Energy cost	8.00
- Maintenance	11.00
- Labour	21.00
Total variable cost	40.00
Total cost	220.00

*Costs are obtained from pump dealers and CREAQ(1983).

**Assumed life of 10 years at 12% interest.

***Assumed life of 30 years at 8% interest.

Note: Pump hp is calculated from total amount of subsurface irrigation required based on 10 hectares of land.

TABLE 6.16: Sample of cost estimates* for subsurface irrigation and drainage systems with respect to drain spacing.

Drain spacing	Drain length per ha.	Initial cost	Annual drainage system cost	Total annual drainage cost	Total annual cost for subsurface irrigation
m	m	$	$	$	$
(1)	(2)	(3)	(4)	(5)	(6)
5	2000	3360	298	1026	1246
10	1000	1680	149	877	1097
15	667	1121	100	828	1048
20	500	840	75	803	1023
25	400	672	60	788	1008
30	333	559	50	778	998
35	286	480	43	771	991
40	250	420	37	765	985
45	222	373	33	761	981
50	200	336	30	758	978
55	182	306	27	755	975
60	167	281	25	753	973
65	154	259	23	751	971
70	143	240	21	749	969
75	133	223	20	748	968
80	125	210	19	747	967

* All costs rounded to nearest 1 dollar.

Column (3) is the product of column (3) and assumed drainage installation and supply cost of $1.68/m (complete job).

Column (4): Assuminginterest rate of 8% and amortization period of 30 years.

Column (5) = Column (4) + Annual production cost of maize ($278).

Column (6) = Column (5) + Annual cost of subsurface irrigation system ($220).

6.16. This may best be described by an example. From Figure 6.9 the maximum average relative yield of 51.6% was obtained at a 45 m drain spacing for the subsurface drainage system. The actual average yield can be found by multiplying the potential yield of 8258 Kg/ha by the average relative yield. That is:

Actual yield = 8258 (Kg/ha) * (51.6/100) = 4262.8 Kg/ha

For a maize price of $0.183/Kg, the average predicted income is $780/ha. Profit is then calculated by subtracting the estimated annual cost at 45 m drain spacing from the predicted income. That is:

Profit = 780 $/ha - 761 $/ha = $19/ha

Repeating the above procedures, the average profit as a function of drain spacing for both subsurface drainage and subsurface irrigation was computed. The relationship found is shown in Figure 6.11. These results show that a maximum profit of $19/ha will be obtained for a drain spacing of 45 m without subsurface irrigation. When subsurface irrigation is used, a higher average profit of $513/ha will be obtained at a 30 m drain spacing. A smaller average profit for subsurface drainage than for subsurface irrigation may have been due to the drought stress during the two years of simulation. For subsurface drainage only, narrower drain spacings had the tendency to cause excessive drainage and

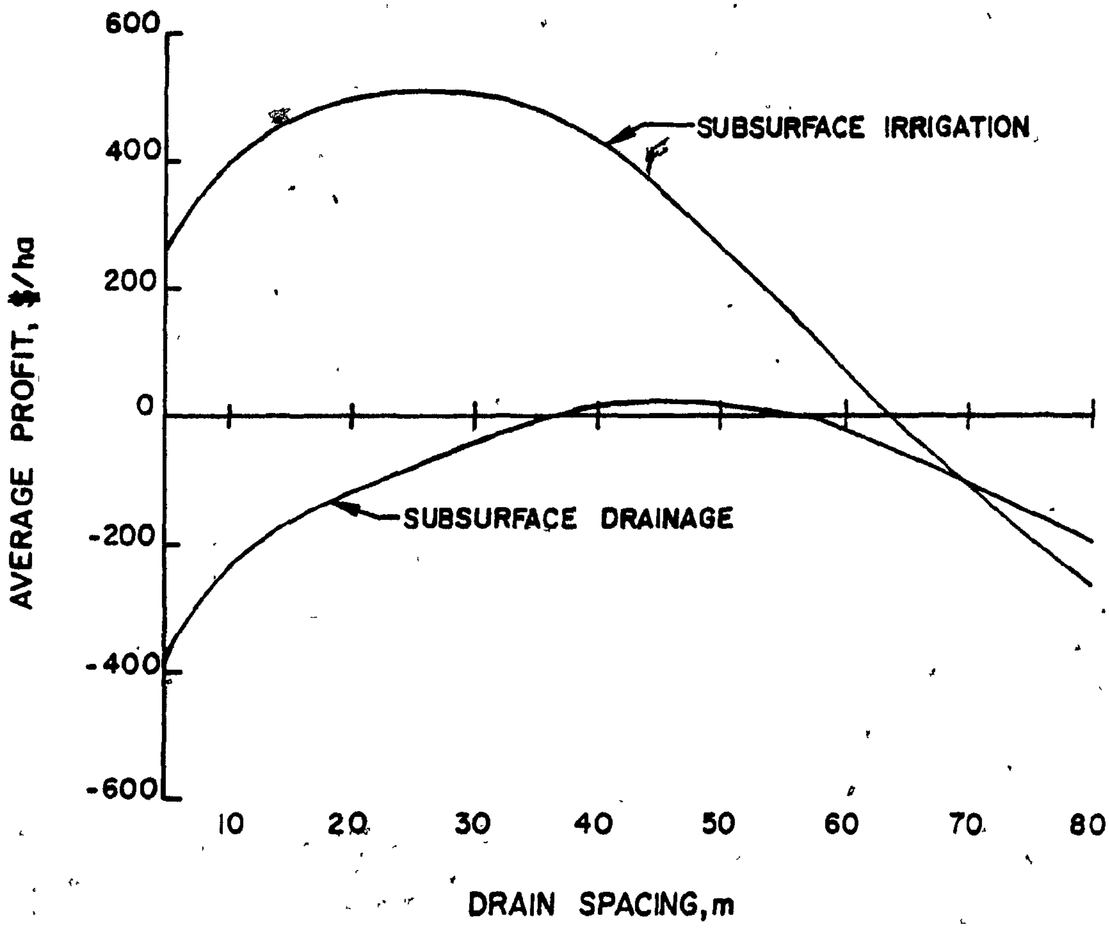

Figure 6.11. Predicted profits at various spacings for subsurface irrigation and drainage systems, using mean saturated hydraulic conductivity value.

thus greater losses; and wider drain spacings increased the losses due to both drought and wet conditions. The results showed that a drain spacing of 45 m is required to maximize average profit for subsurface drainage alone. For the same drain spacing, subsurface irrigation produced higher profit.

Economic analyses were carried out for the range of saturated hydraulic conductivities to maximize average profit for both subsurface irrigation and subsurface drainage systems. The results of predicted average profit are plotted in Figures 6.12a and b as a function of drain spacing for subsurface drainage and subsurface irrigation cases respectively. The results in Figure 6.12a show that the drain spacing required to maximize the average profit, varies from 40 to 70 m as k_s ranges from of 1.19 m/day to a high of 4.16 m/day. The smallest loss of \$5/ha was obtained at 30 m drain spacing when the lowest k_s value of 0.79 m/day was used. However the results showed that the profit increased for higher k_s value due to wider drain spacing required to maximize the profit. This is because the wider spacing costs less than the narrower spacing.

The results of the relationships for subsurface irrigation are plotted in Figure 6.12b for the range of k_s values. These results show that the drain spacing of 20, 30, 35, 45 and 50 m are required to maximise profits for k_s values of

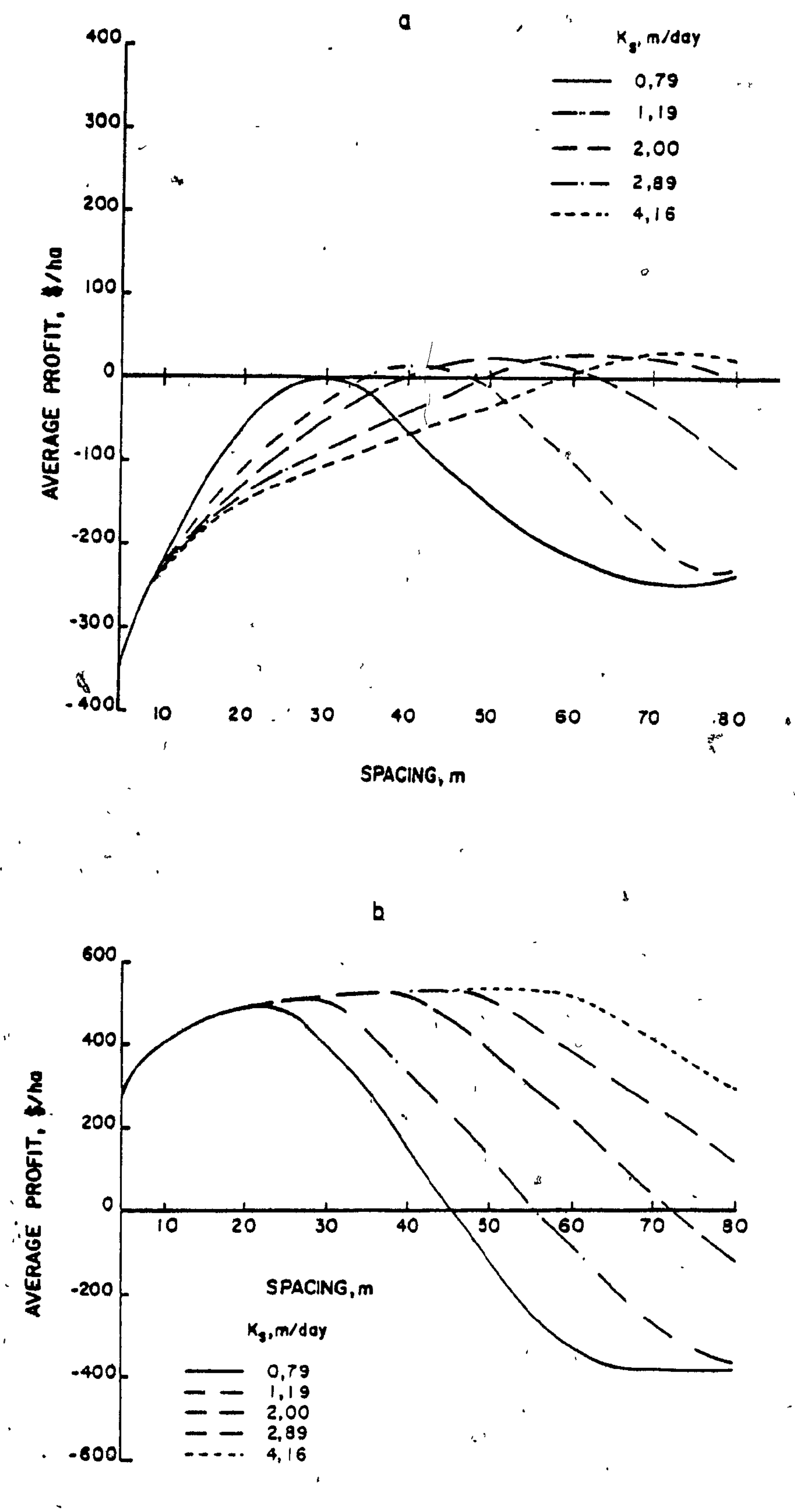

Figure 6.12. Predicted profits for various drain spacings–saturated hydraulic conductivity combinations.

0.79, 1.19, 2.0, 2.89 and 4.16 m/day respectively. A 50 m drain spacing required to maximize profit at a k_s of 4.16 m/day would produce profits less than 4.1, 30.6, 73.2 percent of the maximum if used for k_s values of 2.89, 2.0 and 1.19 m/day respectively. The lower k_s value of 0.79 m/day would produce a loss of $127/ha/year.

From the results it appears that the variation in saturated hydraulic conductivity has considerable effect on the design of subsurface irrigation/drainage systems and potential increase in profit. There will be considerable risk if the design is based on k_s values exceeding the given bound. Considering the relatively high cost of drainage and irrigation, the results suggest that the variation in field measurements of k_s should be considered in the design. Decisions should be based on calculations which take the range of k_s values into account.

The annual cost for subsurface irrigation/drainage systems depends on the useful life of the system and the interest rate used for amortization. Profits obtained with a 10% interest rate amortised for 30 years as a function of drain spacing are presented in Table 6.17 (columns 2 and 3). An interest rate of 10% amortized for 30 years useful life of the system reduced the profit 1.8% compared to the case for an 8% interest rate (column 4 of Table 6.17) for the

TABLE 6.17: Effect of interest rate and various corn prices on the profit of subsurface irrigation and drainage systems at different design spacings.

drain spacing	10% Interest rate*		8% Interest rate	
	Profit due to subsurface drainage	Profit due to subsurface irrigation	Profit obtained from subsurface irrigation for the range of corn price ($ per hectare)	
m	$/ha	$/ha	$ 0.183/Kg	$ 0.170/Kg
(1)	(2)	(3)	(4)	(5)
5	-446	207	265	158
10	-256	385	414	307
15	-185	444	463	356
20	-138	474	488	381
25	-99	492	503	396
30	-62	504	513	406
35	-26	499	507	401
40	6	437	445	343
45	12	341	348	254
50	11	267	273	184
55	5	182	187	104
60	-22	88	93	17
65	-66	-29	-25	-92
70	-106	-115	-111	-172
75	-146	-192	-188	-253
80	-183	-261	-258	-308

Columns (2) and (3): Assuming corn price of $ 0.183/Kg.

k_s = 1.56 m/day.

subsurface irrigation case. The drain spacing required to maximize profit remained the same.

The effect of corn price range on the profitability of subsurface irrigation systems is shown in Table 6.17 (columns 4 and 5). It is obvious that the corn prices will affect the magnitude of profit. That is, the lower the corn price the lesser the profit and vice versa. These results show that a corn price of $0.170/Kg reduced the maximum profit by 20.9% compared to the case with a corn price of $0.183/Kg. The drain spacing required to maximize the profit remained unchange.

It can be concluded from the results that in dry years, a maximum profit of $19/ha would be obtained, if subsurface drainage system is used. This information was used to work out the net benefit due to subsurface irrigation. Net benefit is calculated from the profit obtained due to subsurface irrgation less the maximum profit obtained due to subsurface drainage. These results are shown in Figure 6.13 for a range of drain spacings and k_s, and for two interest rates (8 and 10 percent) for an amortization period of 30 years. Figure 6.13 may help in selecting an appropriate design within the given bounds considered.

This analysis used two years of weather data. Better

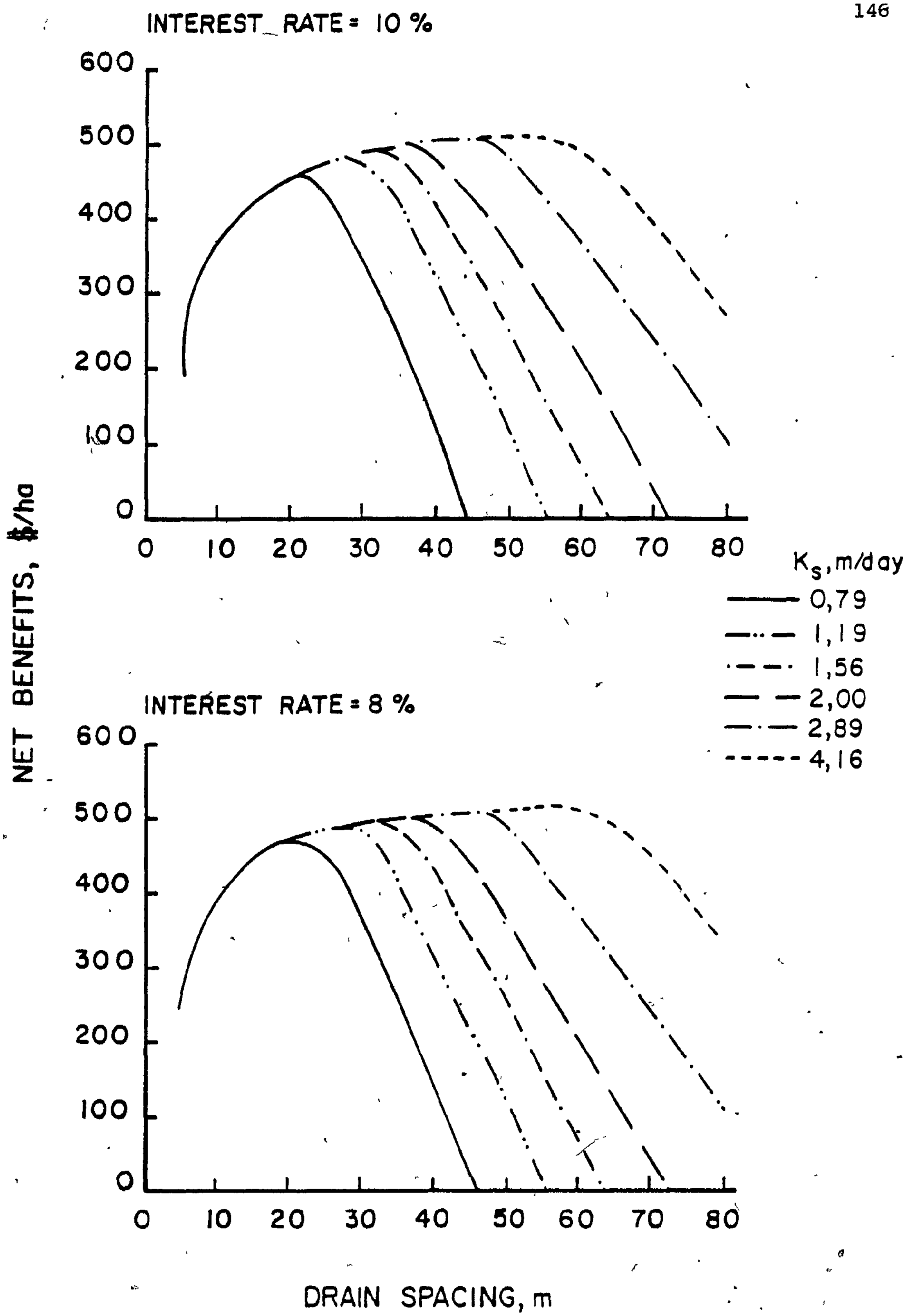

Figure 6.13. Predicted net benefits for a range of drain spacings of subsurface irrigation systems and saturated hydraulic conductivity values at two interest rates.

results would be obtained if a larger number of years are considered in the analysis. Then the decision could be made as to which drain spacing would be appropriate. The corn crop models assumed could be used reasonably for this climate. More years of yield results with or without subsurface irrigation are desirable to improve the model and verify it. The results of the economic analysis strongly suggest the potential benefits of subsurface irrigation and the need for conducting further research work on the response of crop yields to irrigation. Although this analysis is shown for corn only, other crops can be considered by incorporating the appropriate crop models with the water balance model. In general the water balance model worked reasonably well and good results could be obtained under different soil conditions.

VII PARAMETER UNCERTAINTY

Subsurface irrigation is a method of supplying water from beneath the root zone which becomes attractive in humid climates where surpluses and deficits occur. A drainage system can be used for subsurface irrigation by closing the drain outlet and raising the water table to a depth sufficient to provide crop water requirement in the periods of high ET demand. To know the optimum water table depth which can provide the design ET, the unsaturated flow properties must be investigated. Saturated flow properties are used to design a spacing of subsurface irrigation to keep the water table in the field uniform. In rational designs, equivalent hydraulic parameters are defined and used, which may cause an overestimated or underestimated design.

In reality, fields are non-uniform so their hydraulic properties vary from place to place (Nielson et al., 1973, Russo and Bressler, 1981). Thus the use of single-value or average field hydraulic properties in the design may give an improper design. Uncertainty in hydraulic properties can alter the soil water regime. Since crop yield is directly related to the soil water regime, therefore dispersion or uncertainty in hydraulic properties may yield a design with greater risk. An approach is given below to include uncertainty due to variation of hydraulic properties by the use of first and second order moment analysis.

7.1 Techniques For The Analysis Of Uncertainty

A variety of procedures are avaiable to treat the effect of uncertainty in ground water flow. Contribution in this field of study have been made by Cornell, 1972; Freeze, 1975; Bakr et al., 1978; Sagar, 1979; Dagan, 1979, 1982; Smith and Freeze, 1979; Dettinger and Wilson, 1981; . Dettinger and Wilson (1981) presented a critical review of these methods. In describing the advantage of the first and second order moments, they concluded that the first and second order moments are less expensive to apply to the numerical problems than the full distribution method. The trade-offs are cost and accuracy. The full distribution method looses accuracy due to a limited number of simulations whereas the first and second order method looses accuracy due to the Taylor series approximation. In general, approximate models are more practical to use than models which require more complicated mathematics and greater input detail.

First and second order moment methods can be applied by using Taylor series expansion. Analysis based on Taylor series generally expands an analytical or numerical solution of dependent variables or flow governing equations around the expected values of the solution parameters and independent variables. These series expansions may then be used to deduce the probabilistic moments of the dependent variable. Dettinger and Wilson (1981) suggested that the first order analysis of Taylor series yields the same information as other methods of analysis.

First and second moment methods based on a Taylor series expansion have been employed by Cornell (1972), Dettinger and Wilson (1981) and Prasher (1982) to a wide variety of problems and suggested wide application in the field of water resources engineering.

7.1.1 First and second order analysis

First order analysis is defined as the analysis of the mean and variance-covariacnce of a random variable(s) based on its first order Taylor series expansion.

Let y be a function of some random variable x i.e.

$$y = f(x) \qquad \ldots(7.1)$$

The function is expanded in a Taylor series about the expected value of its independent variable x as:

$$y = f(\bar{x}) + f'(x-\bar{x}) + 1/2 f''(x-\bar{x})^2 + \ldots \qquad \ldots(7.2)$$

Where f' and f'' are the first and second derivatives with respect to x, evaluated at $\overline{x}$, the expected value of x. Neglecting the second and higher order terms as being small compared the first two terms, the mean or expected value of y can be calculated as:

$$E[y] =^1 E[\ f(\overline{x}) + f'(x - \overline{x})\ ] \qquad \ldots(7.3)$$

where $=^1$ stands for a first order approximation. E denotes the expected value function. The expected value is a linear operation so that E[a + b] = E[a] + E[b] and E[cb] =cE[b], where c is a constant and a and b are two random variables. Therefore equation (7.3) can be written, using those properties as:

$$E[y] =^1 f(\overline{x}) + f'[E(x) - \overline{x}] \qquad \ldots(7.4)$$

$$=^1 f(\overline{x}) \qquad \text{since } E[x] = \overline{x} \text{ by definition}$$

The second moment of y can be estimated to first order also. The variance is the second moment around the mean value, using the first order series for f, the variance is:

$$\begin{aligned} var[y] &=^1 E[\{f(x) - f(\overline{x})\}^2] \\ &=^1 E[\{f(\overline{x}) + f'(x-\overline{x}) - f(\overline{x})\}^2] \\ &=^1 E[\{f'(x-\overline{x})\}^2] \\ &=^1 [f']^2 E[(x - \overline{x})^2] \\ &=^1 [f']^2\, var(x) \qquad \ldots(7.5) \end{aligned}$$

A second order analysis is carried out in a similar way using second order Taylor series expansion.

$$y =^2 f(\overline{x}) + f'(x-\overline{x}) + 1/2 f''(x-\overline{x})^2 + \ldots \qquad \ldots (7.6)$$

where $=^2$ denotes equal to a second order approximation. Similarly, neglecting the higher terms and taking the expected value yields the second order approximation of the mean:

$$E[y] =^2 f(\overline{x}) + f' E[(x-\overline{x})] + 1/2\, f'' E[(x-\overline{x})^2]$$
$$=^2 f(\overline{x}) + 1/2 f''\ \mathrm{var}(x) \qquad \ldots (7.7)$$

This estimate of the mean is more accurate than the first order estimate, using information about the expected value and variability of x (Dettinger and Wilson, 1981).

The expected mean is based on a second order Taylor series expansion (second order analysis) and the variance-covariance are derived from first order Taylor series expansion. Therefore, by definition, the means derived from first and second order analyses may be different, the variance-covariance will not.

Similar approximations can be made in multivariate situation. In this case, a multidimensional Taylor series expansion is used.

Considering a function:

$$y = f(u,v) \quad ...(7.8)$$

expanding it by a Taylor series:

$$y = f(\overline{u},\overline{v})+[\{f'(u).(u-\overline{u})\}+\{f'(v).(v-\overline{v})\}] + 1/2[\{f''(u).(u-\overline{u})^2\}+\{f''(v).(v-\overline{v})^2\}]+.. \quad ..(7.9)$$

Where $f'(u)$ and $f'(v)$ are the first derivatives of f with respect to u and v evaluated at the mean value of u and v respectively. Similarly, $f''(u)$ and $f''(v)$ are the second derivative of f with respect to u and v evaluated at the mean value of u and v respectively.

$$E[y] \approx f(\overline{u},\overline{v})+1/2[f''(u).var(u)+f''(v).var(v)] \quad ..(7.10)$$

Similarly, variance can be calculated as:

$$var(y) \approx [f'(u)]^2.var(u)+[f'(v)]^2.var(v) \quad ..(7.11)$$

Equations (7.10) and (7.11) can be used to estimate the first and second order moments of dependent variables respectively, once these moments are known for independent random variables.

7.2 Uncertainty Analysis

In this section first and second order moment methods are applied to the subsurface irrigation/drainage design which includes uncertainty in unsaturated and saturated flow parameters. The analysis is done on three soils, which are located in Quebec, Canada. They are St. Samuel sandy loam soil, two other soils i.e Rougemont sandy soil (RM-s) and Rockburn sandy loam soil (RB-s.l) were considered in this study. The data on unsaturated flow properties of RM-s and RB-s.l have been taken from Khatri (1984). The moisture characteristic curves for RM-s and RB-s.l are plotted in Figure C.3. These curves were used to calculate the k(h) function, using the Millington and Quirk method. The results of k(h) function are presented in Figure C.4.

7.2.1 Steady upward flux

1. Unsaturated hydraulic conductivity as a random variable

In equation (6.2), ΔZ, $(z_{i+1}-z_i)$ is a dependent variable and we can investigate uncertainty in ΔZ due to unsaturated hydraulic conductivity. For convenience, equation (6.2) can be written as:

$$\Delta Z = -\frac{k[\{(h_i+h_{i+1})\}/2\{(h_{i+1}-h_i)\}]}{q_u + [\{k(h_{i+1}) + k(h_i)\}/2]} \quad \text{....(7.12)}$$

The first and second order moment method was applied to study the effect of uncertainty in k on the relationship between water table depth and steady upward flux. This method was used with equation (7.12) to analyse the uncertainty in water table depth due to uncertainty in k at a given flux value. Since this method of analysis requires the first and second derivative of the dependent variable with respect to a random independent variable (in our case k). Therefore, the derivatives were obtained numerically. The various steps solving equation (7.12) for derivatives are as follows:

i) Equation (7.12) is solved for a given q_u value using unsaturated hydraulic conductivity (k +Dk), when Dk is a very small deviation in k around the mean of k.
ii) Equation (7.12) is solved again for the same q_u, using unsaturated hydraulic conductivity of (k-Dk).
iii) The required derivative can be estimated numerically from the definition of derivatives, i.e.

$$\Delta Z' = \{\Delta Z(k+Dk) - \Delta Z(k-Dk)\}/2Dk$$

similarly

$$\Delta Z'' = \{\Delta Z(k+Dk) - 2\Delta Z(k) + \Delta Z(k-Dk)\}/Dk^2$$

In order to calculate the variance in k, the coefficient of variation (C.V) in k must be assumed or can be calculated from high and low values of k observed in the field.

In reality the variation in k is very high and can not be used here because this method requires that the C.V must be small in order to get reliable results. Cornell (1972) observed that if the coefficient of variation remains small the method will provide an accurate result. Due to this reason the C.V of 0.4 is assumed. The variance in k is calculated as:

$$\text{var} = (\text{C.V} \times \text{mean})^2 \qquad \ldots.(7.13)$$

Where the mean is the value of k at corresponding pressure heads. By using the definition of first and second order moments the first and second derivatives of the dependent variable ΔZ, with respect to the random variable, k, were obtained from equation (7.12). The estimated mean water table was then calculated by first and second order analysis. The results are presented in Figure 7.1. The results of Figure 7.1 are presented, assuming normal distribution and calculated bounds at a 90% confidence level, for all three soils considered in this analysis. The deterministic solution for the relationships is shown in Figure D.1 (Appendix D) for these soils.

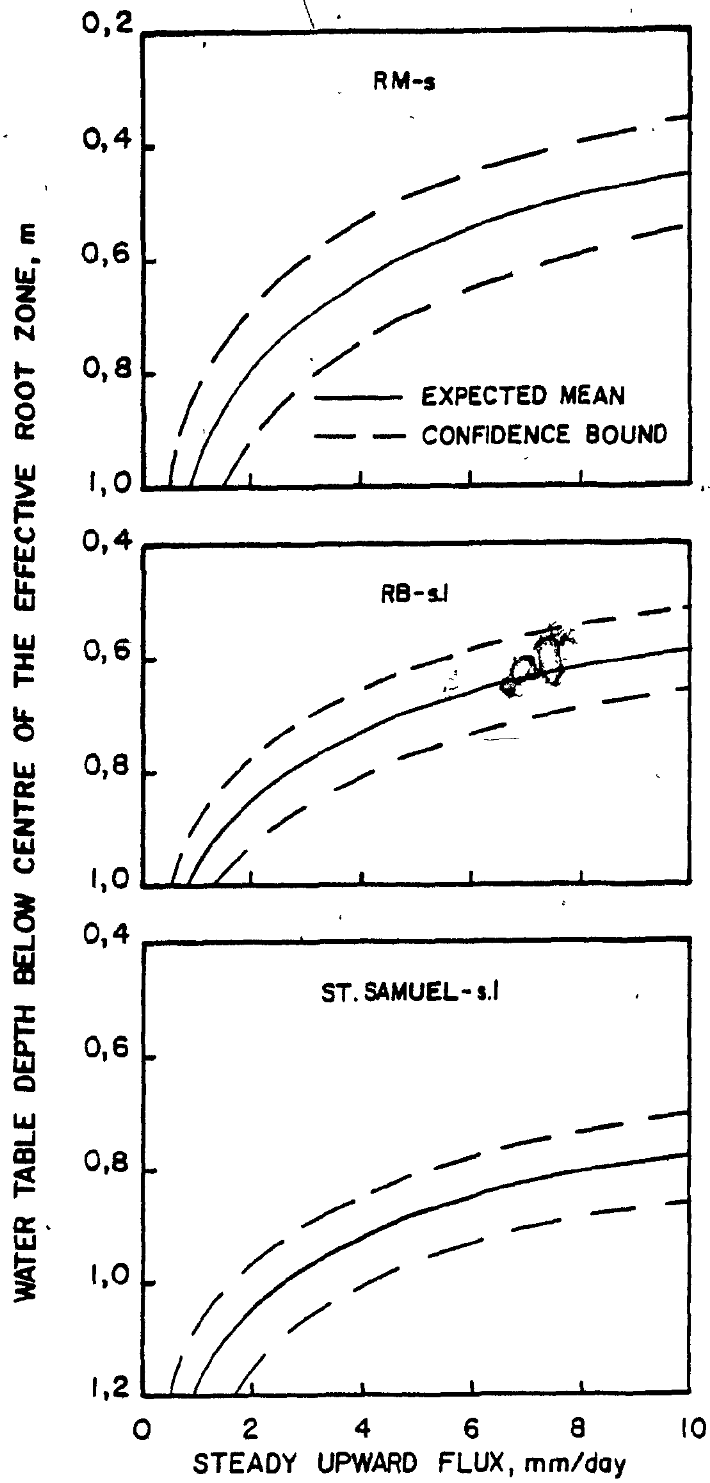

Figure 7.1. Effect of uncertainty due to unsaturated hydraulic conductivity on the relationship between steady upward flux and water table depth.

7.2.2 Design of subsurface irrigation/draiange systems

In steady state equation (3.2), drain spacing is directly proportional to the square root of saturated hydraulic conductivity. The k_s values are obtained by the auger hole method in the field, or by the outflow method, in the laboratory. In a deterministic analysis the observed values are averaged and the design problem is solved. It is noted here that it is not certain that the average k_s value is representative of the field situation, with the result that the design remains uncertain. Therefore, one way to include the uncertainty in the design is to estimate the first two moments of random variable(s) by whatever means available. This estimation of the moment should be easier than the estimation of a complete probability distribution function.

It is possible to estimate mean and the variance of saturated hydraulic conductivity from a low (L), probable (P) and high estimates (H) of the soil property (Russell, 1983). These estimates can be obtained either from the field or laboratory or by quizzing an experienced designer. Statistically, a low value stands for 90% probability that the value does not exceed the actual value. A high value may represent a 90% probability that the value exceeds the actual value. A probable value is the value most likely to represent the actual value. To obtain the mean and variance from L, P, H estimates, an assumption regarding probability distribution must be made. Russell (1983) has given formulae for estimating the mean and variance from L, P, H estimates:

$$\text{Mean} = (L + 2.5P + H)/4.5 \qquad \ldots.(7.14)$$

$$\text{var} = [(H - L)/2.56]^2 \qquad \ldots.(7.15)$$

It should be noted, however, first and second order analysis do not depend on the distribution used in arriving at the estimate of the moments but a distribution is assumed while calculating the mean and variance from L, P, H estimates.

In order to maintain the water table uniformly in the field, the water table depth should not be too close to the surface over the drain, otherwise crop loss may occur. Williamson and Kriz (1970) observed that maximum yields were obtained when the water table was kept in the range of 60 to 76 cm from the soil surface in a loam soil. Deflection is defined as the difference between the water table midway between the drains and the water table depth over the drain. If the water table depth midway between the drains is kept constant (say an optimum water table depth), the increase in water table depth over the drain will decrease the deflection. To see the effect of uniformity on the design of subsurface irrigation spacing, the spacings were calculated from both the deterministic and the uncertainty analysis at various deflections based on an optimum water table depth. In the rest of this section, first and second order analysis is applied to steady state and nonsteady state subsurface irrigation designs. Examples are given for steady state and non-steady state formulae.

7.2.2.1 Steady state subsurface irrigation/drainage design

Case 1. Saturated conductivity as a random variable

Rewritting Hooghoudt's equation (3.2) derived for subsurface irrigation:

$$W = [(4k_s/e)\{2m(h_o+d_e) - m^2)\}]^{1/2}$$

Soil paramter values for each soil considered are presented in Table 7.1. The deterministic solution of equation (3.2) is shown in Table 7.2 at various deflections for St. Samuel-s.l, RM-s and RB-s.l soils. To get the mean and variance, the above equation must be differentiated to obtain first and second derivatives of the function with respect to the random variable (k_s, in our case), that is:

$$W' = [(2mh_o+2md_e-m^2)/e]^{1/2}/(k_s)^{1/2} \qquad \text{....(7.16)}$$

TABLE 7.1: Soil parameter values for different soils used for uncertainty analysis.

Soil parameters		Soil type		
		St.Samuel-s.l	RM-s	RB-s.l
Depth of impermeable layer (m)		1.60	1.80	1.80
Depth of drain (m)		1.05	1.00	1.05
Saturated hydraulic conductivity (m/day)	H	2.10	2.93	3.48
	L	1.30	1.35	1.90
	P	1.56	2.25	3.16
	Mean	1.62	2.20	2.95
var(k_s)		0.098	0.381	0.381

H = High, L = Low, P = Probable.

Table 7.2: Design of subsurface irrigation system at different deflections on the basis of deterministic analysis.

Deflection midway between drains m	Drain spacing (m)		
	St. Samuel-s.l	Rm-s	RB-s.l
0.05	7.15	12.21	13.68
0.10	11.26	18.29	20.42
0.15	14.47	23.21	25.93
0.20	17.47	27.50	30.75
0.25	20.35	31.41	35.13
0.30	22.95	35.06	39.21

Expected mean water table, h, values to be maintained at the midspacing in a subsurface irrigation system design were obtained from Figure 7.2 at steady upward flux, e = 4.5 mm/day.

$$W''= -1/2\ [(2mh_o+2md_e-m^2)/e]^{1/2}/(k_s)^{3/2} \quad ....(7.17)$$

Let us take an example of St. Samuel sandy loam soil for a subsurface irrigation design problem. The values of the soil parameters are obtained from Table 7.2, where d_e = 0.46 m, m = 0.30 m, the optimum water table midway between the drains = 1.05 m, therefore h_o =0.30 m, e = 0.0045 cm/day and k_s values observed were 1.30, 1.56, 2.10 m/day. From equation (7.14) and (7.15), we obtain estimates of the mean and variance as 1.62 m/day and 0.098 respectively.

Using the steady state equation (3.2), the expected value for spacing can be obtained, using the definition for first and second order moments as:

$$E[y] = {}^2f(x) + 1/2f''var(x)$$

And the variance is:

$$var\ [y] = {}^1var(x).[f']^2$$

Therefore the expected value of spacing will be:

$$E[W] = X(W) + 1/2[-1/2(2mh_o+2md_e-m^2)^{1/2} .(e^{-1/2}).k_s{}^{-3/2}].var(k_s) \quad ....(7.18)$$

Where X(W) stands for the equivalent mean value of spacing and is calculated from equation (3.2) as 22.95 m. The expected spacing can be calculated as:

$$E(W) = 22.95 - 0.111 = 22.84 \text{ m}$$

When an equivalent mean value of hydraulic conductivity was used, the spacing for subsurface irrigation was calculated as 22.95 m. But in an uncertain situation when the saturated hydraulic conductivity is not completely known, the expected value of spacing is 22.84 m.

The variance in spacing can be estimated as:

$$\text{var}(W) = \text{var}(ks)[(2mh_o+2md_e-m^2)^{1/2}. e^{-1/2}.ks^{-1/2}]^2 \qquad \ldots.(7.19)$$

That is,

$$\text{var}(W) = 4.92$$

or standard deviation in spacing is:

$$S.D = 2.22 \text{ m}$$

The variance and standard deviation show the risk involved in subsurface irrigation system designs due to uncertainty in the saturated hydraulic conductivity. In statistical terms it implies that for normal distribution,there is a 90% probability that the spacing would not exceed 25.68 m (mean + 1.28 * SD). Similarly, there is a 90% probability that the spacing would exceed 20.00 m (mean - 1.28 *SD). The results of this analysis are presented in tables 7.3 A, B, and C with upper and lower limits at the 90% probability level. These tables indicate that the increase in deflection would result in wide spacings. The magnitude of standard deviation shown in the last column of each table may be regarded as a measure of the risk in selecting the subsurface irrigation design system. It may be noted that the standard deviation increases as the deflection increases. The magnitude of S.D for the St. Samuel-s.1 is smaller than the RM-s and RB-s.1 soils. This is because, it depends on the variation in k_s, the water table above the drain and the geometry of the system.

Case 2. Unsaturated hydraulic conductivity as a random variable

Equation (3.2) does not contain the term unsaturated hydraulic conductivity, k, but the term, m (water table deflection at midspacing) is a function of upward flux. In turn, upward flux depends on the k(h) function above the water table in the soil profile. Therefore, dependency of m on k is obvious and we can say that m is a function of k. However any uncertainty in k would give an uncertain m

TABLE 7.3: Effect of uncertainty due to saturated hydraulic conductivity on the design of a subsurface irrigation at various deflections.

A. St.Samuel-s.1

Deflection m	h_o m	d_e m	E[W] m	Upper limit m	Lower limit m	S.D m
0.05	0.05	0.33	7.12	8.01	6.23	0.70
0.10	0.10	0.39	11.21	12.60	9.82	1.10
0.15	0.15	0.41	14.40	16.19	12.61	1.40
0.20	0.20	0.43	17.39	19.55	15.23	1.70
0.25	0.25	0.45	20.26	22.78	19.74	2.00
0.30	0.30	0.46	22.84	25.68	20.00	2.22
0.45	0.45	0.48	30.09	33.80	26.38	2.90

B. RB-s.1

Deflection m	h_o m	d_e m	E[W] m	Upper limit m	Lower limit m	S.D m
0.05	0.24	0.50	13.61	15.44	11.78	1.43
0.10	0.29	0.56	20.31	23.05	17.57	2.14
0.15	0.34	0.59	25.79	29.27	22.31	2.72
0.20	0.39	0.61	30.58	34.70	26.46	3.22
0.25	0.44	0.63	34.94	39.66	30.22	3.69
0.30	0.49	0.64	39.00	44.26	33.74	4.11

C. RM-s

Deflection m	h_o m	d_e m	E[W] m	Upper limit m	Lower limit m	S.D m
0.05	0.29	0.49	12.09	14.27	9.91	1.70
0.10	0.34	0.57	18.11	21.40	14.82	2.57
0.15	0.39	0.60	22.98	27.14	18.82	3.25
0.20	0.44	0.63	27.23	32.17	22.29	3.86
0.25	0.49	0.64	31.10	36.73	25.47	4.40
0.30	0.54	0.66	34.72	41.03	28.41	4.93

value. From the definition of first and second order moments, one can estimate the first two moments of the dependent random variable(s), if the first two moments of the independent random variable(s) are known. In section 7.2.1, we have already calculated the mean and variance of the water table depth, h (or m) at a design ET rate of 4.5 mm/day, when unsaturated hydraulic conductivity was considered as a random variable. Using this information we can investigate the design of subsurface irrigation due to uncertainty in the random variable m. We will need the following derivatives for the analysis.

$$W'(m) = 2(k_s/e)^{1/2}\{(h_o+d_e-m)/(2mh_o+2md_e-m^2)^{1/2}\} \quad \ldots.(7.20)$$

$$W''(m) = -2(k_s/e)^{1/2}\{(h_o+d_e)^2/(2mh_o+2md_e-m^2)^{3/2}\} \quad \ldots.(7.21)$$

Thus,

$$E[W] = \{2(k_s/e)^{1/2}(2mh_o+2md_e-m^2)^{1/2}\} +1/2[-2(k_s/e)^{1/2}\{h_o+d_e)^2/(2mh_o+2md_e-m^2)^{3/2}\}.\ var(\bar{m})\}] \quad \ldots.(7.22)$$

and

$$var(W) = [2(ks/e)^{1/2}\{(h_o+d_e-m)/(2mh_o+2md_e-m^2)^{1/2}\}]^2.var(m) \quad \ldots.(7.23)$$

Let us consider the same values as in the previous problem, however m is now a random variable. From figure 7.2 for St.Samual s.1, the mean and variance of water table depth are as 1.05 m and 0.0038 at evapotranspiration rate of 4.5 mm/day respectively.

From equations (7.22) and (7.23), E[W] and var(W) are calculated as 22.76 m and 3.16 respectively. Thus the standard deviation for spacing is:

$$S.D = 1.78 \text{ m}$$

For a normal distribution, it implies that there is a 90% probability that the spacing would not exceed 25.04 m. Similarly, there is 90% probability that the spacing would exceed 20.48 m .

The results of this analysis are presented in Tables 7.4 A, B and C. The interesting point to note from these tables is that, the standard deviation decreases as the deflection increases. This is opposite to the first case when k_s was taken as a random variable. This is because the denominator of the first derivative increases significantly due to increase in the magnitude of m, thus resulting in a decrease of W.

TABLE 7.4: Effect of uncertainty due to unsaturated hydraulic conductivity on the design of a subsurface irrigation at various deflections.

A. St.Samuel-s.l

Deflection m	h_o m	d_e m	E[W] m	Upper limit m	Lower limit m	S.D m
0.05	0.05	0.33	5.59	10.83	0.34	4.10
0.10	0.10	0.39	10.60	14.54	6.66	3.08
0.15	0.15	0.41	14.06	17.27	10.85	2.51
0.20	0.20	0.43	17.18	19.98	14.38	2.19
0.25	0.25	0.45	20.12	22.63	17.61	1.96
0.30	0.30	0.46	22.76	25.04	20.48	1.78
0.45	0.45	0.48	30.11	31.91	28.31	1.41

B. RB-s.l

Deflection m	h_o m	d_e m	E[W] m	Upper limit m	Lower limit m	S.D m
0.05	0.24	0.50	11.48	20.75	2.21	7.24
0.10	0.29	0.56	19.55	26.28	12.82	5.26
0.15	0.34	0.59	25.42	30.95	19.89	4.32
0.20	0.39	0.61	30.09	34.88	29.30	3.74
0.25	0.44	0.63	34.86	39.15	30.57	3.35
0.30	0.49	0.64	38.99	42.88	35.10	3.04

C. RM-s

Deflection m	h_o m	d_e m	E[W] m	Upper limit m	Lower limit m	S.D m
0.05	0.29	0.49	7.62	19.97	0.0	9.69
0.10	0.34	0.57	16.49	25.74	7.24	7.23
0.15	0.39	0.60	22.16	29.75	14.57	5.93
0.20	0.44	0.63	26.77	33.40	20.14	5.18
0.25	0.49	0.64	30.86	36.74	24.99	4.59
0.30	0.54	0.66	34.61	39.99	29.23	4.20

Case 3. Saturated and unsaturated conductivities as random variables

It is shown in the above paragraph that the uncertainty involved in the unsaturated hydraulic conductivity has also an effect on the subsurface irrigation design. It is most likely that uncertainty in both saturated hydraulic conductivity, k_s and m may have an effect on the design spacing. For this case, a multivariate analysis is used to estimate first and second order moments of dependent variables (drain spacing, W, in our case).

In this case the derivatives are needed with respect to the independent random variables k_s and m. These derivatives were already obtained in case 1 and case 2 and are given as equations (7.16), (7.17) and (7.20) and (7.21) respectively.

Recalling the definition of first and second order moments, the first two moments can be estimated as:

$$E[W] = \{2(k_s/e)^{1/2}(2mh_o+2md_e-m^2)^{1/2}\} + 1/2[\{-1/2(2mh_o+2md_e-m^2)^{1/2} . e^{-1/2}.k_s^{-3/2}.var(k_s)\}+\{-2(k_s/e)^{1/2}(h_o+d_e)^2 .(2mh_o+2md_e-m^2)^{-3/2}.var(m)\}] \quad ...(7.23)$$

$$var(W) = \{2(k_s/e)^{1/2}(h_o+d_e-m)(2mh_o+2md_e-m^2)^{-1/2}\}^2 .var(m)+\{(2mh_o+2md_e-m^2)^{1/2} .e^{-1/2}.k_s^{-1/2}\}^2.var(k_s) \quad ....(7.24)$$

Thus expected design spacing is:

$E[W] = 22.66$ m

And variance is

$var(W) = 8.08$

or $S.D(W) = 2.84$ m

Therefore, for a normal distribution the 90% confidence bounds for high and low levels of W are 26.30 and 19.02 m respectively. The results are shown in Tables 7.5 A, B and C for all the three soils considered.

These tables show that the risk (S.D) is higher when both saturated and unsaturated properties are uncertain, when compared the other cases. This is because the two variances var(W), (due to uncertainty is k_s and k) are pooled together. It is very interesting to note that the standard deviation decreases upto a 0.20 m deflection in the case of St. Samuel and RB-s.1 soils and 0.25 m deflection for RM-s.1. Then it increases for the larger deflections. This is due to pooling of two variances in which one decreases and other increases as explained earlier. If we base our decision on selecting a design with little or no risk then the smaller risk suggest the design at 0.2 m deflection for St. Samuel and RB-s.1 soils and a 0.25 m deflection for RM-s soil would be selected. Although the standard deviations at those designs are smaller, the probability of it being exceeded is not negligible and therefore there is some risk

TABLE 7.5: Effect of uncertainty due to saturated and unsaturated hydraulic conductivities on the design of a subsurface irrigation system at various deflections.

A. St.Samuel-s.1

Deflection m	h_o m	d_e m	E[W] m	Upper limit m	Lower limit m	S.D m
0.05	0.05	0.33	5.56	10.87	0.25	4.15
0.10	0.10	0.39	10.54	14.71	6.37	3.26
0.15	0.15	0.41	14.00	17.69	10.31	2.88
0.20	0.20	0.43	17.10	20.63	13.57	2.76
0.25	0.25	0.45	20.03	23.59	16.47	2.78
0.30	0.30	0.46	22.66	26.30	19.02	2.84
0.45	0.45	0.48	29.97	34.09	25.85	3.22

B. RB-s.1

Deflection m	h_o m	d_e m	E[W] m	Upper limit m	Lower limit m	S.D m
0.05	0.24	0.50	11.40	20.85	1.95	7.38
0.10	0.29	0.56	19.44	26.71	12.17	5.68
0.15	0.34	0.59	25.28	31.81	18.75	5.10
0.20	0.39	0.61	30.23	36.54	23.92	4.93
0.25	0.44	0.63	34.67	41.04	28.30	4.98
0.30	0.49	0.64	38.78	45.32	32.24	5.11

C. RM-s

Deflection m	h_o m	d_e m	E[W] m	Upper limit m	Lower limit m	S.D
0.05	0.29	0.49	7.55	20.15	0.0	9.84
0.10	0.34	0.57	16.31	26.13	6.49	7.67
0.15	0.39	0.60	21.93	30.58	13.28	6.76
0.20	0.44	0.63	26.50	34.77	18.23	6.46
0.25	0.49	0.64	30.55	38.69	22.41	6.36
0.30	0.54	0.66	34.27	42.55	25.99	6.47

involved in such a design. However, the selection of the design is based on the particular need of a farmer and his acceptance of a risk. But the knowledge of risk is necessary due to uncertain properties, which can help designers in selecting a design.

To show the use of the uncertainty analysis in subsurface drainage design, an example of St. Samuel sandy loam soil is considered only.

In designing the subsurface drainage spacing in an uncertain situation where k_s is not completely known, the same analysis can be carried out as before. Rewriting Hooghoudt's formula (3.1) for steady state case as:

$$W = [(4k_s/q)(2d_e m+m^2)]^{1/2}$$

where q is the drainage rate and m is the height of the water table at the midspacing above the drain center.

Using the definition of first and second order moments to obtain estimates of the mean and variance, the above formula must be differentiated to get first and second derivatives with respect to the random variable k_s:

$$W' = [(2d_e m + m^2)/q]^{1/2}/k_s^{1/2} \qquad \text{....(7.25)}$$

$$W'' = -1/2[(2d_e m + m^2)/q]^{1/2}/k_s^{3/2} \quad \ldots.(7.26)$$

Therefore, the expected value of drain spacing can be obtained using first and second order moment definition.

$$E[W] = [(4k_s/q)(2d_e m+m^2)]^{1/2} + 1/2[-1/2\{(2d_e m+m^2)/q\}^{1/2}/k_s^{3/2}].var(k_s) \quad \ldots..(7.27)$$

and variance in W can be estimated by:

$$var(W) = var(k_s)[\{(2d_e m+m^2)/q\}^{1/2}/k_s^{1/2}]^2 \quad \ldots(7.28)$$

Let us assume values for the parameters for a design problem as d_e = 0.48, m = 0.7 m, and q = 0.01 m/day (for the province of Quebec) and k_s along with the mean and variance as already given for the subsurface irrigation design.

The expected drainage design spacing is then:

$$E[W] = 27.44 - 0.128 = 27.31 \text{ m}$$

and the variance is:

$$var(W) = 7.03$$

hence the standard deviation will be:

$$S.D = 2.65 \text{ m}$$

Therefore, for a normal distribution, the 90% probability bounds for the high and low values of drainage spacing are 31.0 and 23.92 m respectively.

7.2.2.2 Non-steady state: water table rise

In a subsurface irrigation system, the water table is raised to a predetermined depth where it is maintained to supply ET demand as explained previously. It is possible that the water table may be far below the predetermined water table depth at the beginning of the growing season or it may fall due to equipment breakdown during the growing season. In such cases, the system should be designed so that the time to raise the water table should be acceptable.

It is, therefore, necessary to include this aspect while designing the subsurface irrigation system. The first and second order moment method is applied to analyse input uncertainty for such designs.

The methods available to calculate the time to raise the water table were discussed in chapter III. Equation (3.6) is used here to approximate the time to raise the water table and can be written as:

$$t = fw^2/8k_s(d+h_o) \ \ln \ [(h_o+2d+y)/(h_o-y)]/[h_o+2d+y_o)/(h_o-y_o)]$$

Where all the terms in the above equation are defined previously. It should be mentioned here that equation (3.6) does not consider the transition period (from drainage to sub-irrigation). It can only be used when the water table is rising. Therefore, an allowance should be made when calculating the time to raise the water table. However for design purposes this equation can be used to get first approximation. For convenience, the above equation (3.6) may be written as:

$$t = (fw^2/8k_sh) \ \ln \ [\{(h+y_1)/(h-y_1)\}/\{(h+y_o)/(h-y_o)\}] \quad \text{....(7.29)}$$

where $h = h_o+d$, the height of the water table above the impermeable layer at the drain.

$y_1 =$ y+d, the height of the water table above impermeable layer at a point midway between drains.

$y_o =$ the distance from the impermeable layer to the water table at a point midway between drains at t = 0.

d = distance from the impermeable layer to the drain depth.

To adjust for convergence effects, d_e is substituted for d in equation (7.29).

To illustrate the use of uncertainty analysis the first and second derivatives of equation (7.29) are required with respect to the random variable (in our case k_s).

$$t' = (-1)(fw^2/8k_s{}^2h)\ \ln\ [\{(h+y_1)/(h-y_1)\}/\{(h+y_0)/(h-y_0)\}] \quad \ldots.(7.30)$$

$$t'' = (-1)(-2)(fw^2/8k_s{}^3)\ \ln\ [\{(h+y_1)/(h-y_1)\}/\{(h+y_0)/h-y_0)\}] \quad \ldots.(7.31)$$

Let us solve the example that was discussed in the last section, that is, W = 23.29 m, d_e = 0.46 m, mean k_s =1.62 m/day and var(k_s) = 0.098. The water table is raised midway between drains from a initial water table depth of 1.2 m below the soil surface to a water table depth of 1 m below the soil surface. A water table of 0.75 m below the soil surface is maintained at the drain, h = 0.76 m, y_1 = 0.51 m, y_o = 0.31 m and f is 0.27 with a 1.2 m suction.

The expected t will be calculated as:

$$E\,[t] = 11.299 + 1/2(8.601) = 15.59 \text{ day}$$

$$\text{var}\,(t) = 0.098\,(6.966)^2 = 4.756$$

$$\text{S.D} = 2.181 \text{ day}$$

Therefore, for normal distribution the 90 % confidence limits for high and low values of t are 18.38 and 12.80 days respectively.

The above solution is applicable only when the water table depth at the drain is kept at 0.75 m below the soil surface. What would happen if a large pressure head was maintained at the drain? It should be noted that the water table depth to be maintained at the drain, depends on the root zone depth and crop tolerance for the wet conditions. The effective root zone of the corn was found to be 0.3 m and the water table depth at the drain of 0.60 m is assumed, then h equals to 0.91 m. Applying the uncertainty analysis we found:

$$E[t] = 6.92 + 1/2(5.27) = 9.56 \text{ day}$$

$$\text{var}(t) = 0.098\ (4.27)^2 = 1.78$$

$$S.D = 1.337 \text{ day}$$

For a normal distribution, the 90% confidence limits for high and low values of t are 11.27 and 7.85 days respectively.

Notice that the estimated time to raise the water table to the same height is reduced by 38.7%, when a water table depth of 0.6 m is maintained at the drain. This means that the higher the pressure head maintained in the control chamber, the faster the water will move into the field to raise the water table.

The results of the uncertainty analysis, as a time to raise the water table, are plotted in Figure 7.2 in relation to drain spacing. These relationships are presented for St. Samuel, RB and RM soils. The broken lines in Figure 7.2 show the 90% confidence bounds for assumed normal distribution. It can be seen that the expected time to raise the water table and the S.D increase as the drain spacing increases. St. Samuel sandy loam soil, with a 30 m drain spacing, takes about 11.75 days to raise the water table by 0.2 m. Whereas RM soil, with the same drain spacing, requires about 7 days to raise the water table by 0.24 m. This is because the k_s for the RM soil is higher than the k_s of St. Samuel soil. RB soil gives a more rapid water table rise because of its higher hydraulic conductivity relative to the other two soils.

In selecting a design one has to consider the time to raise the water table in order to meet the requirements for a particular crop. For example a maize crop in St. Samuel soil can grow for the first 12 days in the early growing stage from the existing moisture content in the soil profile.

From this information one can select from Figure 7.2 a 30 m drain spacing which meets this requirement but a 90%

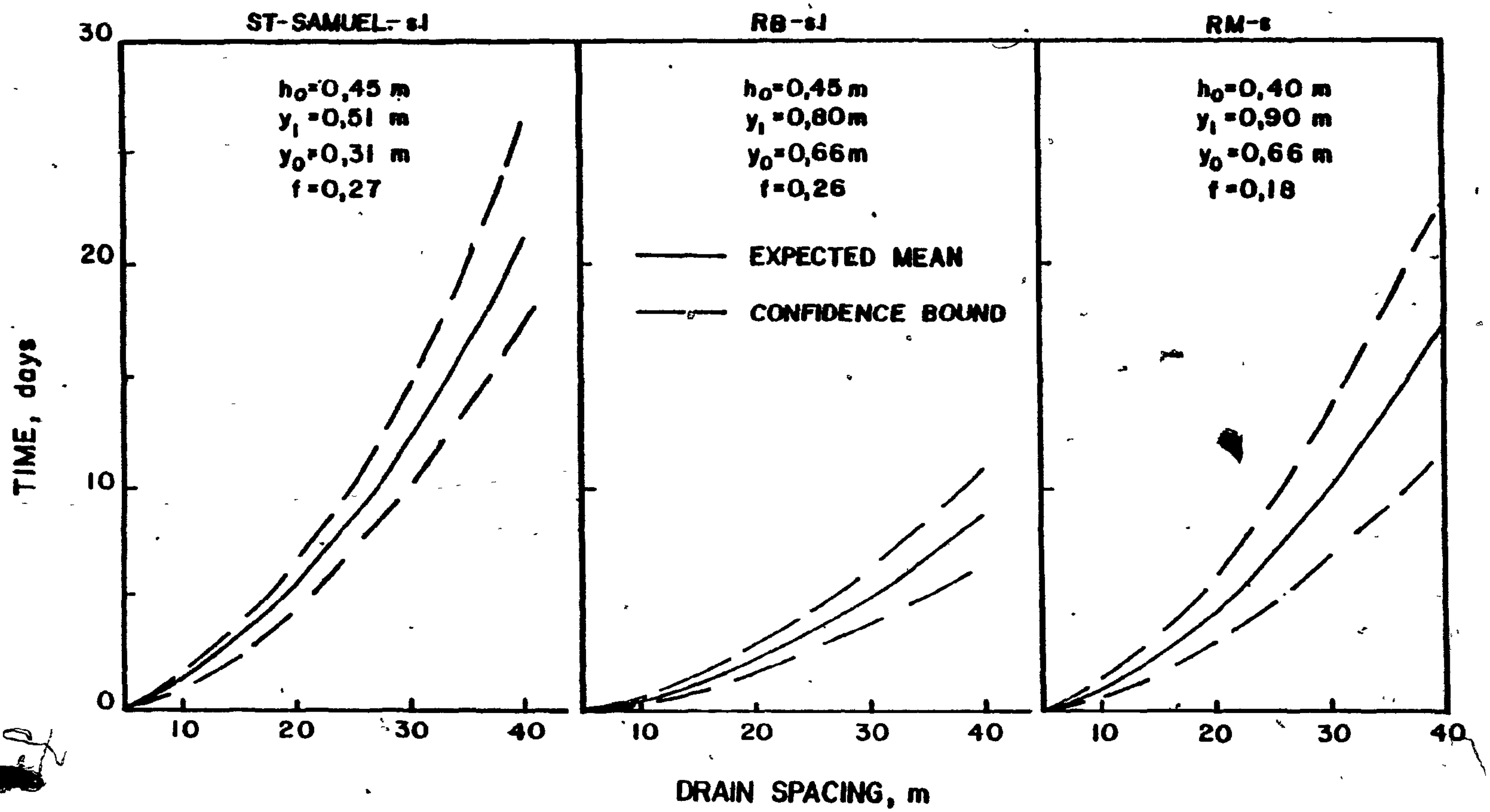

Figure 7.2. Effect of uncertainty due to saturated hydraulic conductivity on the time to raise the water table for various drain spacings of subsurface irrigation system.

probability shows that the time may be exceeded. There is some risk involved in such a design. The procedure may be repeated to arrive at a drain spacing that meets the design criterion with an allowable risk. Apparently the knowledge of risks due to uncertain input data should be of considerable help to a designer to select a design according to the requirements of a particular farmer.

In this section, saturated hydraulic conductivity is treated as the single uncertain parameter. It was selected because it is the most important parameter in the rise/fall of water table level. However, it could be any other parameter such as drainable porosity, depth to the impermeable layer or midspacing water table depth etc.

Risk can be reduced and better subsurface irrigation performance can be achieved by taking care to adjust the overflow level in the control chambers early in the spring to prevent the water table from dropping more than 75 cm below the surface before the start of subsurface irrigation.

The results of this chapter are shown in the tables and graphs to identify the extent of risk in designs due to uncertain parameters. The solutions are also presented for deterministic analysis. The expected value solution and the deterministic solution to the problem are nearly the same. It is worthy to note that the uncertainty analysis gives us true picture of the variation in the required probability for designing a system which infact is not possible in a deterministic analysis. It also leads one to design the subsurface irrigation/drainage system depending upon the amount of risk a particular farmer is prepared to accept.

A decision, however, may be made to choose a design which is efficient and economically feasible. It is suggested that the results of this chapter may be used with Figure 6.13 (chapter VI) to select a design which meets the above requirements.

VIII GUIDELINES AND RECOMMEDATIONS FOR SUBSURFACE IRRIGATION DESIGN

The purpose of this chapter is to examine the design of subsurface irrigation in the light of experimental and theoretical results presented in Chapters VI & VII. An example of St. Samuel sandy soil is considered. The methods are based on results obtained from a steady state formula and the water balance model.

For the situation considered in Figure 8.1, the topographic survey done on the 10 hectare field shows that the land is flat and an impermeable layer exists at 1.6m below the soil surface. The soil was quite permeable with a mean saturated hydraulic conductivity of 1.56 m/day. The maximum evapotranspiration during dry periods, in summer, was 4.5 mm/day. Drains are installed at an average depth of 1.05 m. Corn was grown on this soil since 1967. A 30 cm effective root depth was observed during field investigations. Figure 6.5 showed that the water table upto 1 m deep at the midspacing could satisfy an upward flux of 4.5 mm/day.

Design calculations by the water balance model showed that a 30 m drain spacing is required to optimize the profit. Nearly the same result was obtained by the steady state formula, when the water table above the drain was held at 0.45 m depth below the soil surface. The design was checked

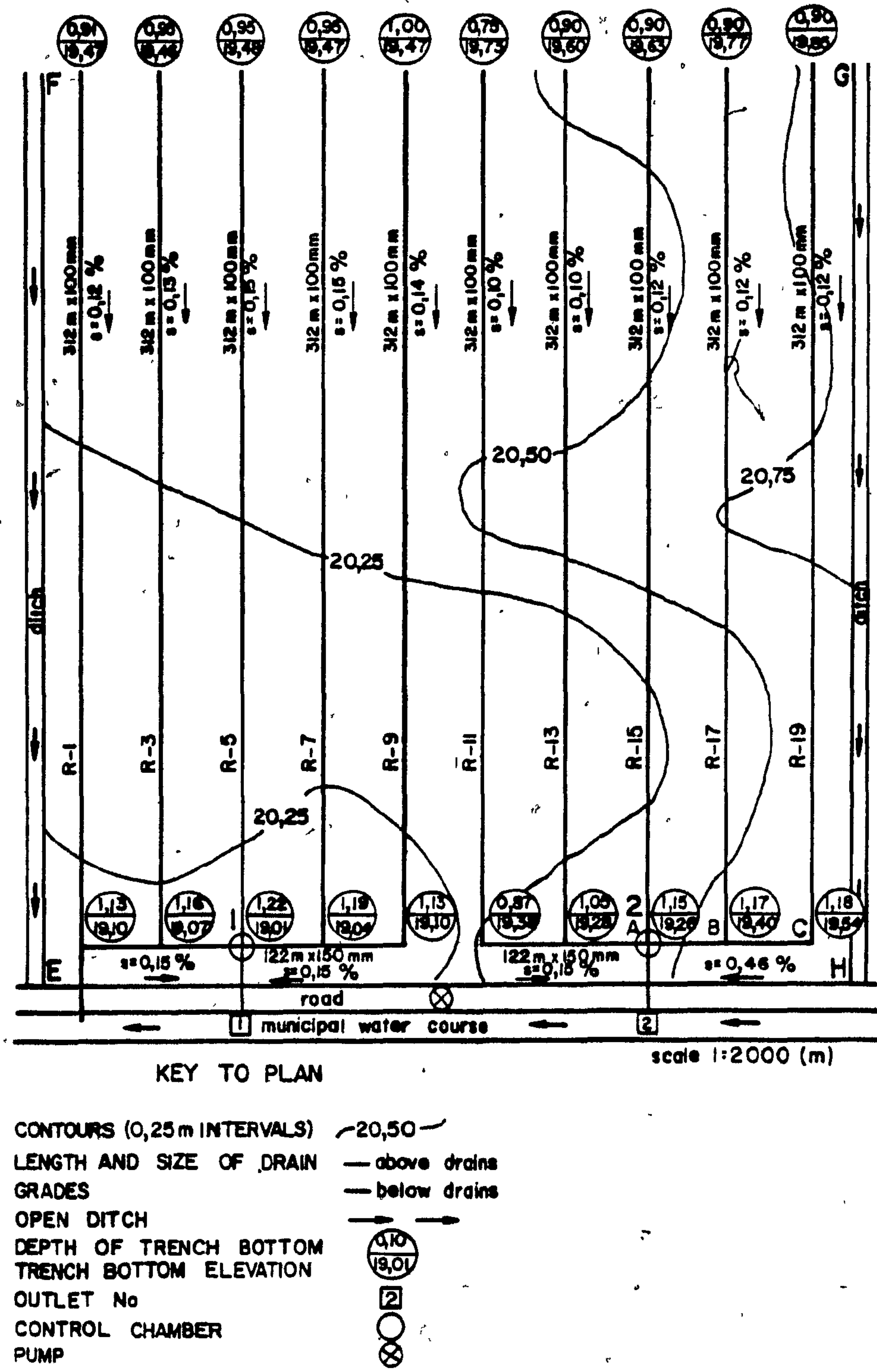

Figure 8.1. Plan of a subsurface irrigation/drainage system for the St. Samuel sandy loam soil.

to determine whether the time required to raise the water table was limiting. Equation (7.29) was used to determine the time required to raise the water table to a 1 m depth from an assumed initial water table depth of 1.20 m . The water table above the drain is assumed to be 0.60 m. The results showed that about 8 days are required to raise the water table to the desired depth. This is acceptable during crop germination. Therefore, a 30 m drain spacing was used in the design.

The design is presented in Figure 8.1. The field is subdivided, each section having 5 laterals. Two control chambers are proposed, serving 5 laterals each. These control chambers are located near the ditch, which serves as a water reservoir on the west side of the field. The pump can be conveniently located beside the ditch half way along the end of the field to supply water into the control chambers through a PVC pipe with T-joints. A control chamber in Figure B.1 is proposed which is automated with a float valve. The float valve serves to keep the water level constant in the control chamber during the main growing period.

8.1 Water Requirement and Water Table Control System

One of the most important criteria in developing subsurface irrigation is to determine the amount of water required for plant use and the leakage losses from the system. The leakage losses occur due to higher hydraulic head maintained in the irrigated field, relative to the surrounding areas. The magnitude of leakage losses depends upon the hydraulic conductivity of the soil and the elevation of the water table in the field, in relation to surrounding water table depths.

Skaggs (1978) derived the equations from a steady state analysis for calculating the seepage rate (leakage rate). Seepage losses to nearby drains may be expressed as (refer Figure 8.2):

$$q = \frac{k_s(h_1^2 - h_2^2) + es^2}{2s} \quad \text{....(8.1)}$$

where q is the rate of flow per unit length of drainage ditch (m^3/m day)

k_s is the saturated hydraulic conductivity (m/day)

h_1 is water table height above the impermeable layer at the drain pipe in the subsurface irrigation field

h_2 is the water level in the ditch above the impermeable layer.

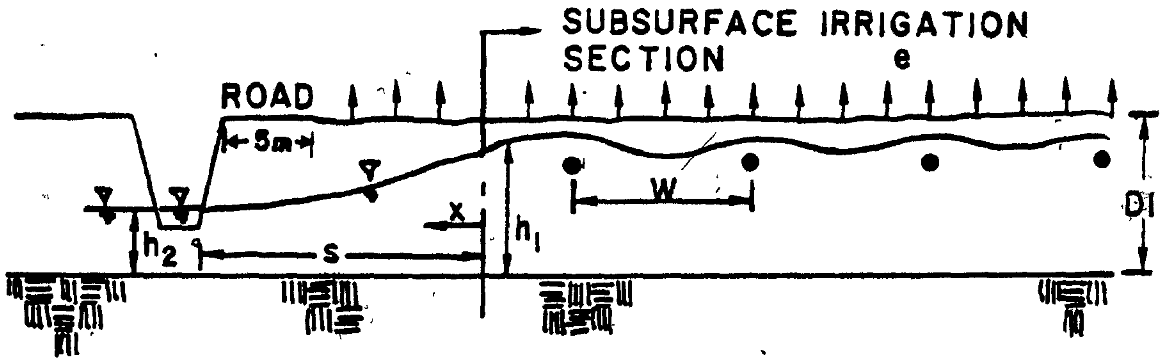

Figure 8.2. Water table profile for seepage from a subsurface irrigation field to drainage ditch. (Redrawn from Skaggs, 1978)

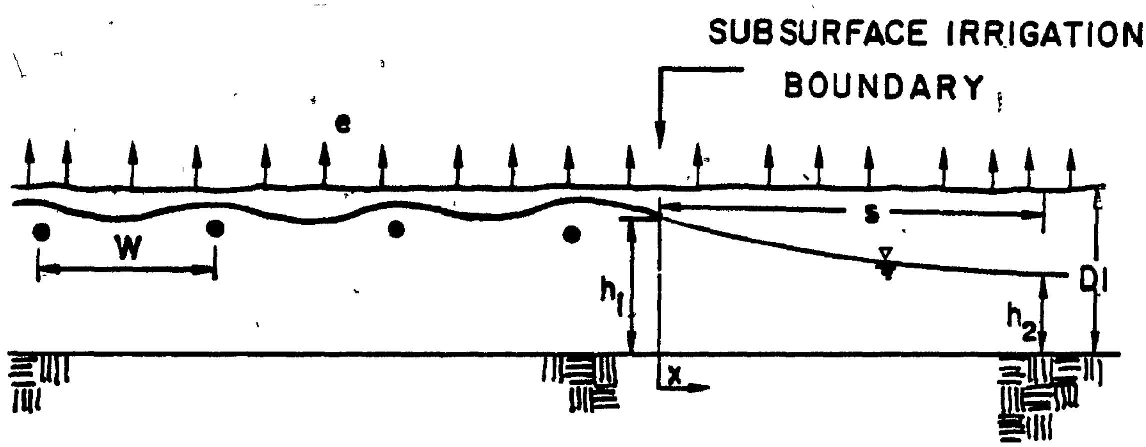

Figure 8.3. Seepage from a subsurface irrigation field to a non-irrigated field which has water table drawdown due to ET. (Redrawn from Skaggs, 1978)

s is the distance from the subsurface irrigation field boundary to the bottom edge of the ditch.

e is maximum design evapotranspiration.

Figure 8.1 shows the boundary of the field (EFGH). The boundary E-H is adjacent to the ditch. For this side, leakage losses can be calculated by equation (8.1).

Substituting the values of the parameters shown in Table 8.1, gives h_1 and h_2 as 0.8 m and 0.3 m, respectively. Applying equation (8.1), the fate of leekage per unit length of field boundary E-H may be calculated as:

$$q_{E-H} = \{ 1.56 \text{ m/day } (0.8^2 - 0.3^2) + 0.0045 \ (25)^2\} / \ 2 * 25$$
$$= 0.0734 \text{ m}^3\text{/m day}$$

and the rate of leekage for whole length of boundary E-H may be determined as:

$$Q_{E-H} = q*L_1 = 0.0734 \text{ m}^3\text{/m day} * 300 \text{ m} = 22.02 \text{ m}^3\text{/day}$$

However, it should be noted that the 10 m strip of the field supplies the ET demand between the collector and the road and should not be considered as leakage losses. The rate of water used in the 10 m strip is,

$$Q_e = 0.0045 \text{ m/day} * 10 \text{ m} * 300 \text{ m} = 13.50 \text{ m}^3\text{/day}$$

TABLE: 8.1. Values of the parameters for determination of seepage losses from subsurface irrigated field.

Parameter		Values
1. Saturated hydraulic conductivity, k_s		1.56 m/day
2. Maximum design evapotranspiration rate, e		4.5 mm/day
3. Depth of impermeable layer, DI		1.6 m
4. Water table depth at midspacing as a function of steady upward flux of 4.5 mm/day (Figure 6.8)		1.0 m
5. Water table depth at the drain throughout the boundaries E-F and G-H (assumed)		0.6 m
6. Water table depth throughout the boundaries E-H and G-H (assumed a mean of 4 and 5)		0.8 m
7. Water level below the soil surface in the ditch (assumed)		1.3 m
8. Distances from the subsurface irrigation field to the bottom edge of the ditch for the following boundaries, (s):		
	E-H	10.0 m
	E-F	8.0 m
	G-H	8.0 m
9. Width of the road		5.0 m
10. Length of the subsurface irrigation field boundaries are as follows: (L_1)		
	E-H	300.0 m
	E-F	312.0 m
	G-H	312.0 m
	F-G	300.0 m

then,

$$Q_{E-H} = 22.02 - 13.50 = 8.52 \ m^3/day$$

For boundary E-F, the lateral is parallel to the ditch, therefore the water table depth over the drain is taken to calculate h_1. Then h_1 is equal to 1.0 m and s equals to 15 m. Hence,

$$q_{E-F} = \{1.56(1.0^2-0.3^2) + 0.0045 \ (15)^2\} \ / \ 2*15$$

$$Q_{E-F} = 0.0811 * 312 \ m = 25.30 \ m^3/day$$

Again, a 8 m strip is under production as previously stated. That is,

$$Q_e = 0.0045 * 8 * 312 = 11.23 \ m^3/day$$

Then,

$$Q_{E-F} = 25.30 - 11.23 = 14.07 \ m^3/day$$

Since the boundary G-H is similar to boundary E-F,

$$Q_{G-H} = Q_{E-F} = 14.07 \ m^3/day$$

Leakage losses along the East boundary F-G are different than the above case. In this case neither h_2 nor s is known. According to Skaggs, (1978), h_2 can be assumed from which the rate of upward movement is not sufficient to support a maximum ET rate. He derived an equation which may be expressed as (refer Figure 8.3):

$$q = [(h_1^2 - h_2^2) \, k_s e]^{1/2} \qquad \ldots . \; (8.2)$$

The relationship between steady upward flux and water table depth (Figure 6.5) indicates that an evapotranspiration rate of 2 mm/day (conservative estimate) can be sustained with a water table depth of 1.0 m below the root zone. If the effective root zone of maize is assumed to be 0.30 m, then the water table depth from the soil surface is equal to 1.30 m. Hence h_2 will be 0.3 m and h_1 equals to 0.8 m. Putting these values in equation (8.2) we get,

$$q_{F-G} = [(0.8^2 - 0.3^2) \, 1.56 * 0.0045]^{1/2}$$
$$= 0.0621 \text{ m}^3\text{/m day}$$

$$Q_{F-G} = 0.0621 * 300 \text{ m} = 18.64 \text{ m}^3\text{/day}$$

The total seepage loss, Q_t, can be obtained by adding all the losses from four boundaries.

$$Q_t = Q_{E-H} + Q_{E-F} + Q_{G-H} + Q_{F-G}$$
$$= 8.52 + 14.07 + 14.07 + 18.64$$
$$= 55.30 \text{ m}^3\text{/day}$$

This leakage loss could be reduced by keeping the subsurface irrigation pipes further from the field boundaries. This leakage water will have to be supplied in addition to the irrigation water necessary to satisfy ET demand during the growing period. Water requirement for plant use, Q_{ET} can be calculated by:

$$Q_{ET} = 0.0045 \text{ m/day} * 312 \text{ m} * 300 \text{ m}$$
$$= 421.2 \text{ m}^3\text{/day}$$

Then the total water supply capacity, Q_C, will be:

$$Q_C = 421.2 + 55.30 = 476.50 \text{ m}^3\text{/day}$$

Then each chamber has to receive 238.25 m^3/day of water. The power required to deliver the water supply capacity to the chambers may be determined by:

$$KW = \frac{9.8 * Q * H}{E_p} \qquad \text{....(8.3)}$$

where KW = (input) power delivered to pump

Q = discharge rate, m^3/s

H = total pumping head (10 m is assumed for lift of water from a well plus friction loss in a delivery system).

E_p = pump efficiency (70% assumed)

$$KW = 9.8 * 476.50\ m^3/day * day/24\ hrs * hrs/60\ min * min/60\ s * 10\ m / 0.7$$

$$= \underline{0.772\ KW} \approx \underline{1\ hp}$$

Therefore a 1 hp electric motor is required.

8.2 Head Loss

The control chambers are designed to distribute water to the field through drain pipes. A head is maintained in the control chamber to force the water to move to the field against certain friction losses. If the friction losses are estimated, then the control chambers can be designed accordingly.

Gallichand (1982) and von Hoyningen Huene (1983) calculated head losses during the experiments on subsurface irrigation on St. Samuel sandy loam soil. The former, found that the head loss of water exiting from the pipe into the soil was larger than the head loss due to pipe friction. The latter author found that the exit and convergence head losses are important in subsurface irrigation.

Approximate head losses can be calculated with Manning's equation. Manning's equation may be written as:

$$V = 1/n\ R^{2/3}\ Se^{1/2} \qquad ....(8.4)$$

where V is the velocity (m/s), n is Manning's roughness coefficient, R is the hydraulic radius (m), and Se is the slope of the energy grade line (m/m).

For circular pipes:

$$R = d/4 \qquad ....(8.5)$$

Substituting (8.5) in (8.4) we get,

$$V=1/n\ (d/4)^{2/3}\ Se^{1/2} \qquad ....(8.6)$$

The continuity equation for full pipe flow gives

$$Q = A\ V = \pi d^2/4 * V$$

Substituting equation (8.6) in the above equation will yield,

$$Q = \pi d^2/4 * 1/n\ (d/4)^{2/3} * Se^{1/2}$$

or

$$Se= 10.29359\ Q2\ n2\ /\ d5.333 \qquad ....(8.7)$$

Head loss h_L due to friction may be obtained in each particular section of collector pipe by multiplying the slope of energy grade line Se by the length of pipe, L, in question:

$$h_L = Se * L \qquad \text{....(8.8)}$$

Considering the collector at the location of control chamber 2, the head losses are calculated for the collector of section AB, BC, laterals R-15, R-17, and R-19. The total flow rate Q in the control chamber is evaluated from the previous section as 238.25 m^3/day (0.00276 m^3/s). It is assumed that the flow rate is equally distributed among five laterals by the control chamber. Therefore each lateral will receive 1/5th. of the total flow rate. Head loss for collector AB and BC can be calculated by assuming that the flow rate is decreasing at each section B and C. Then, applying equation (8.7), assuming Manning's roughness coefficient, n, for corrugated plastic tubing as 0.016 (Schwab, 1983) and substituting the values such as:

$d = 0.15$ m $\quad Q_{A-B} = 0.0011\ m^3/s$

$Q_{B-C} = 0.00055\ m^3/s$

The energy gradient can be computed as,

$$Se_{A-B} = 10.29359\ (\ 0.0011\ )^2\ (\ 0.016\ )^2 / (\ 0.15\ )^{5.333}$$
$$= 8 * 10^{-5}\ m/m$$

and

$$Se_{B-C} = 10.29359\ (\ 0.00055\ )^2\ (\ 0.016\ )^2 / (\ 0.15\ )^{5.333}$$
$$= 2.0 * 10^{-5}\ m/m$$

Head loss for sections A-B and B-C is calculated by equation (8.8) as follows:

$$h_{L,colA-B} = 8 * 10^{-5} * 30\ m = 0.00237\ m$$

$$h_{L,colB-C} = 2 * 10^{-5} * 30\ m + 0.00237m = 0.00296\ m.$$

To obtain head losses in the laterals, one modification needs to be made in the flow rate Q, because the flow rate decreases with distance from the collector since the laterals are perforated. Assuming that, the flow rate in the lateral decreases linearly then the following equation may be used.

$$Q_{lat} = Q_{col}\ [(\ L-X\ )/\ L\ ] \qquad ....(\ 8.9\ )$$

Where, Q_{lat} is the flow in the lateral at a particular distance X away from the collector (m3/s), Q_{col} is the flow that enters the lateral (m^3/s) and L is the total length of the lateral (m)

If it is assumed that the flow is constant within a small distance, say for example 1 m , then equation (8.9) can be substituted in equation (8.7). The following equation will yield,

$$Se = 10.29359 \{ Q_{col} (L-X)/L \}^2 \; n^2/d^{5.333} \qquad \ldots(8.10)$$

Taking the values of Q_{col}, that is the flow rate which enters in the lateral R-15 equal to 0.00055 m^3/s, and other values are:

L_{lat} =312 m   d = 0.1 m   n = 0.016

Substituting above values, and simplifying equation (8.10) will yield,

$$Se = 0.00017 \; (1-X/312)^2 \qquad \ldots(8.11)$$

The head loss can be computed from equation (8.11) for particular point in the lateral.

Another component of the head loss is the exit loss. Exit loss is defined as the head loss due to the resistance encountered by the flow of water exiting from the lateral .

into the soil. Equation (8.12) (Bravo and Schwab, 1977) can be used to calculate head loss that occurs due to exit resistance, and may be expressed as:

$$h_{L,exit} = \ln (rs/re) Q/2\pi k_s L \qquad ....(8.12)$$

Where re is the effective drain radius (m), $h_{L,exit}$ is the exit head loss (m), rs is the drain radius (m) and k_s is the saturated hydraulic conductivity. Mohammed and Skaggs (1983) found from experimental results that the effective radius, re, for different types of tubing varies between 8.0 * 10^{-7} cm and 3.9 cm. The effective drain radius for 10 cm diameter pipe with a perforation area of 21 cm^2/m is approximately 1.5 mm. In Quebec, the minimum drain perforation area is 21 cm^2/m of drain. Therefore the effective radius of 1.5 mm is assumed.

The head loss due to exit loss is calculated for a 10 cm diameter corrugated plastic drain pipe of length L with an effective drain radius of 0.0015 m. Since the flow is assumed to decrease linearly, the mean flow per unit length is used :

$$Q_o = Q_{col}/L_{lat} \qquad ....(8.13)$$

Where Q_o is the flow out of the drain per unit length

(m^3/day). Substituting equation (8.13) in equation (8.12) gives,

$$h_{L,exit} = \{ \ln (rs/re) Q_{col}/L_{lat} \}/2\pi k_s L \quad ....(8.14)$$

Solving equation (8.14) for the various values of components, such as:

$L = 1$ m $re = 0.0015$ m $L_{lat} = 312$ m

k_s=1.56 m/day rs =0.05 m $Q_{col} = 47.5\ m^3$/day (0.00055 m^3/s)

Then

$$h_{L,exit} = \{ \ln (0.05/0.0015)(47.5/312) \}/(2\pi * 1.56 * 1)$$

$$= 0.0545 \text{ m}$$

If the pipe has more than the minimum opening area of 21 cm^2/m the exit loss will be less than 0.055 m.

Another head loss component that occurs in the system is the convergence of the flow lines near the drain. Gallichand (1983) and von Hoyningen Huene (1984) calculated the convergence losses by flow net analysis. The results of latter author on head loss due to convergence are reproduced and are given in Appendix D (Table D.1) along with exit losses at various Q_o values. It is interesting to note from his results that the convergence losses are approximately 1.45 times the exit losses at similar flow rates. Therefore one can approximate convergence losses without doing the flow net analysis. The head loss due to convergence is calculated as:

$$h_{L,con} = 1.45 * h_{L,exit} \quad \ldots.(8.15)$$
$$= 1.45 * 0.0545$$
$$= 0.0790 \text{ m}$$

It should be mentioned here that the head loss due to exit is much smaller than the head loss obtained by von Hoyningen Hüene shown in Table D.1. This is because the flow rate per unit length in our case is much smaller than the flow rate per unit length used in his experiment.

Total head loss can be calculated for lateral R-15 as:

$$h_{L,tot} = h_{L,lat} + h_{L,exit} + h_{L,con}$$
$$= 0.01313 + 0.0545 + 0.0790$$
$$= \underline{0.1466 \text{ m}} \text{ or } \underline{14.66 \text{ cm}}$$

Other head losses such as entrance head loss, Tee , elbow are not considered here because those losses are very small and can be neglected.

The results of total head loss for R-15, R-17 and R-19 are shown in Table 8.2. From these results, the water level in the control chamber can be designed so that the water table at the midspacing can be maintained at the desired depth. The profiles of the water table over the laterals R-15, R-17 and R-19 are plotted in Figures 8.4, 8.5 and 8.6 respectively. These profiles were used to determine the shape of the water table above the laterals R-15, R-17 and R-19.

Water table depth at midspacing can be determined using Hooghoudt's equation (3.2). This equation is solved for deflection, m , with known parameter values such as:

d_e = 0.48 m k_s = 1.56 m/day

W = 30 m e = 0.0045 m/day

After simplifying, the equation (3.2) may be expressed as:

$$m^2 = 2(h_0 + 0.48)m + 0.6490 = 0 \qquad ....(8.16)$$

This is a quadratic equation and the solution may be found by:

$$m = \frac{-b + (b^2 - 4ac)^{1/2}}{2a} \qquad ....(8.17)$$

TABLE: 8.2. Various head losses in subsurface irrigation system.

Lateral	Head loss due to friction, m		Head loss due to exit m	Head loss due to convergence m	Total head loss m
	Collector	Lateral			
R-15	0.0	0.0131	0.0545	0.0790	0.1466
R-17	0.0024	0.0131	0.0545	0.0790	0.1490
R-19	0.0030	0.0131	0.0545	0.0790	0.1496

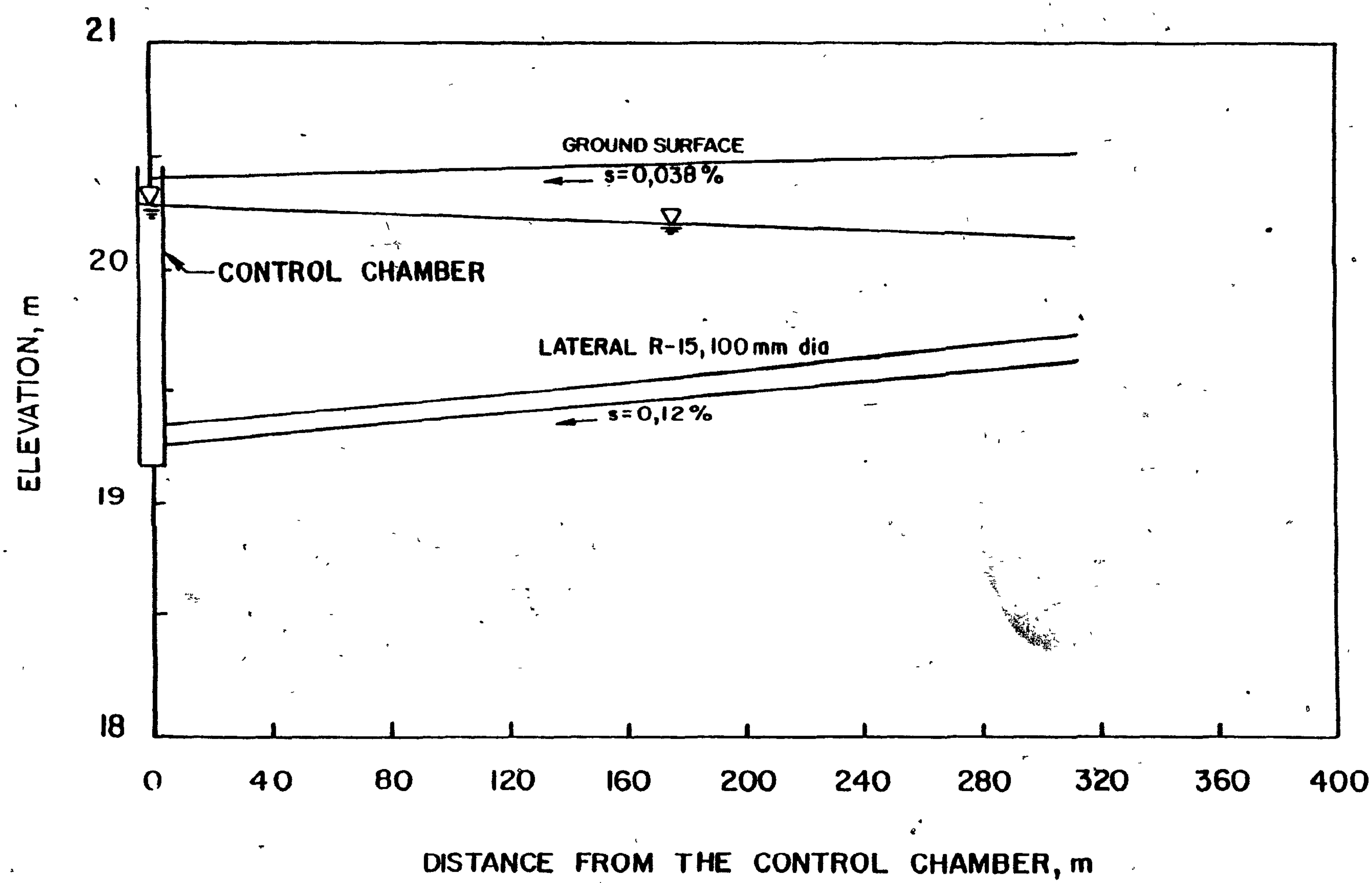

Figure 8.4. Profile of a subsurface drain lateral R-15, water table and the design of water level elevation in the control chamber.

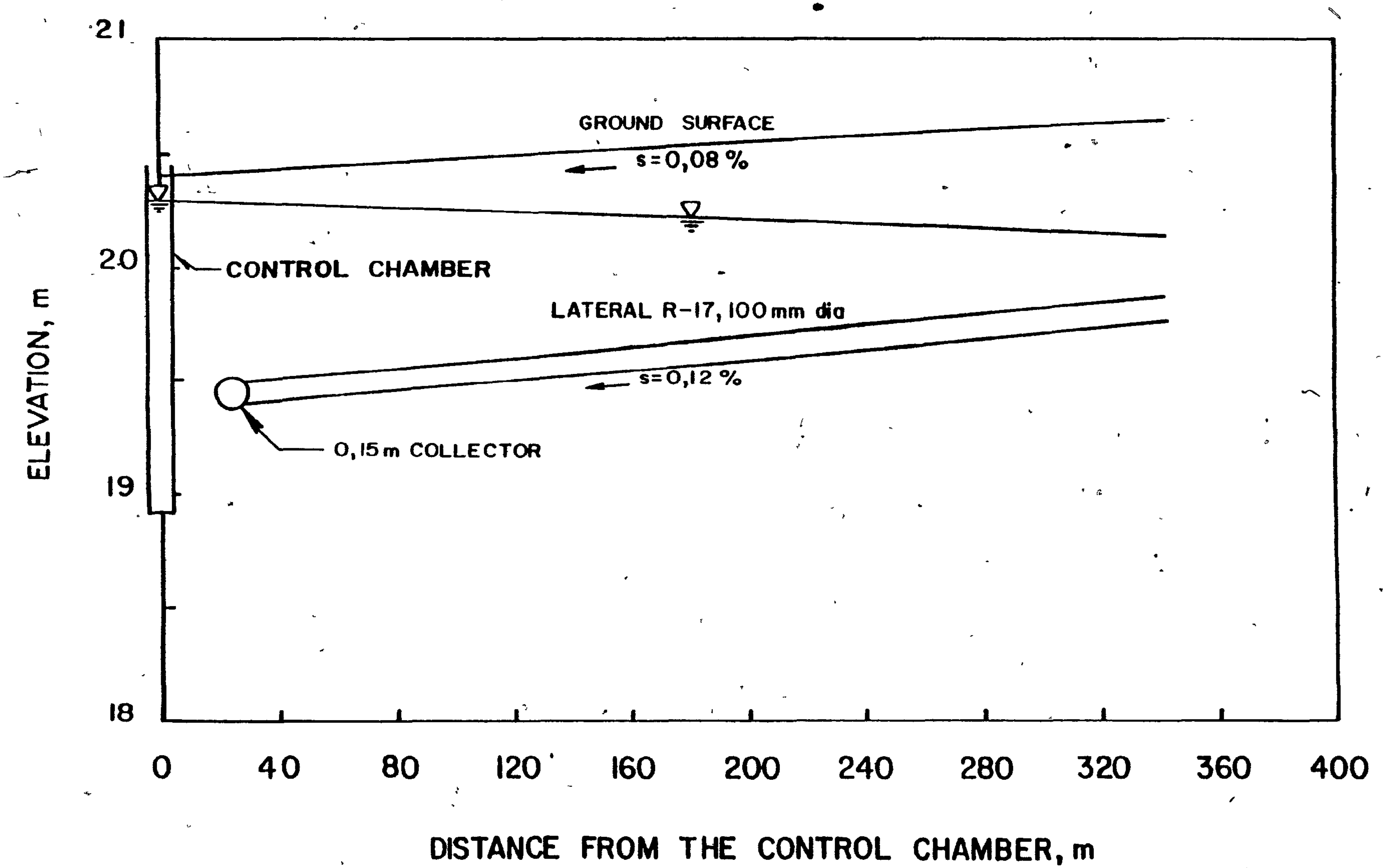

Figure 8.5. Profile of a subsurface drain lateral R-17, water table and the design of water level elevation in the control chamber.

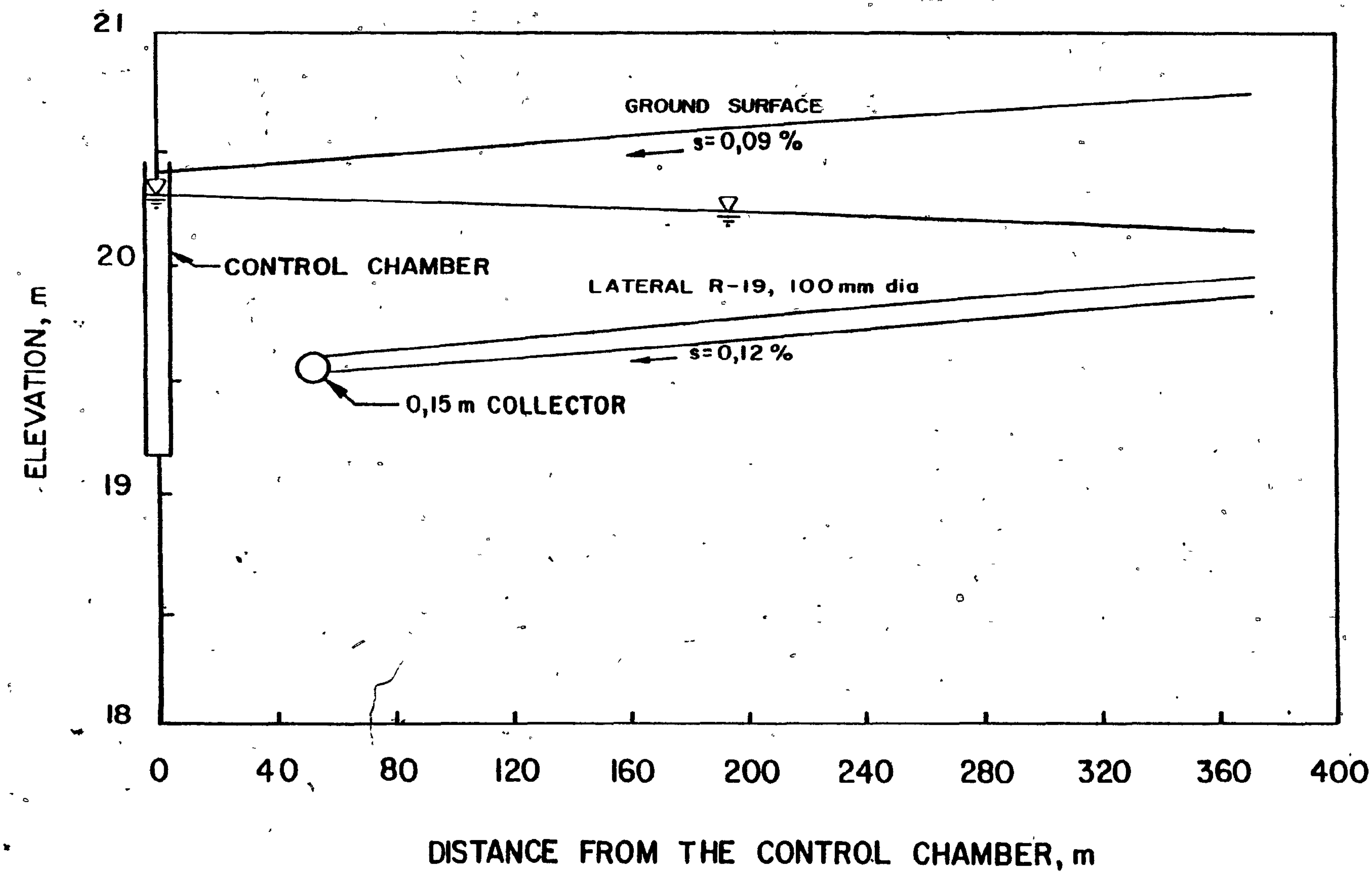

Figure 8.6. Profile of a subsurface drain lateral R-19, water table and the design of water level elevation in the control chamber.

Where $a = 1$

$b = -2\ (h_o + 0.48)$

$c = 0.6490$

The water table depth at midspacing can be determined using the value of h_o, water table height above the drain, which can be obtained from Figures 8.4, 8.5 and 8.6. Since the water table heights above drains are not equal, a mean value was taken for h_o in equation (8.17).

The results are presented in Figures 8.7 and 8.8 for a distance of 100 and 300 m from the collector, respectively. The water table depth at a point midway between drains varies from a minimum of 0.65 m (Figure 8.7) to a maximum of 1.18 m (Figure 8.8). The water table depth of 1.18 m is deeper than the optimum water table depth of 1.0 m required to maintain the design ET rate of 4.5 mm/day (Figure 6.5). Therefore, one way to decrease the water table depth is to level the ground in Figure 8.8 in order to achieve the required water table depth.

8.3 Operational Guide

Following the design of subsurface irrigation, one should consider the operation of the system. The following points should be noted:

1) Water level in the control chamber should be maintained

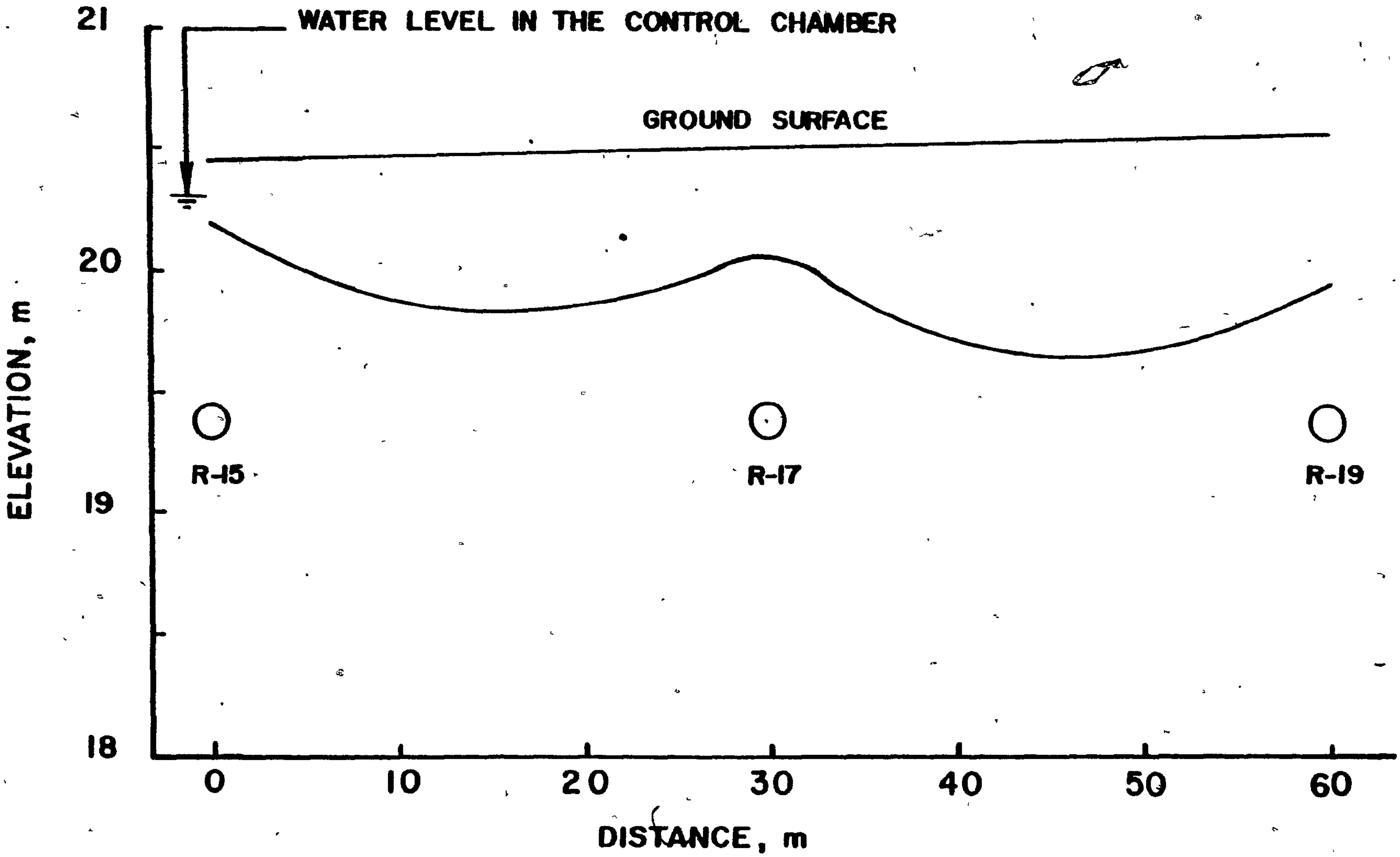

Figure 8.7. Shape of the water table elevation at a distance of 100 m from the collector A-D during steady state operation of subsurface irrigation.

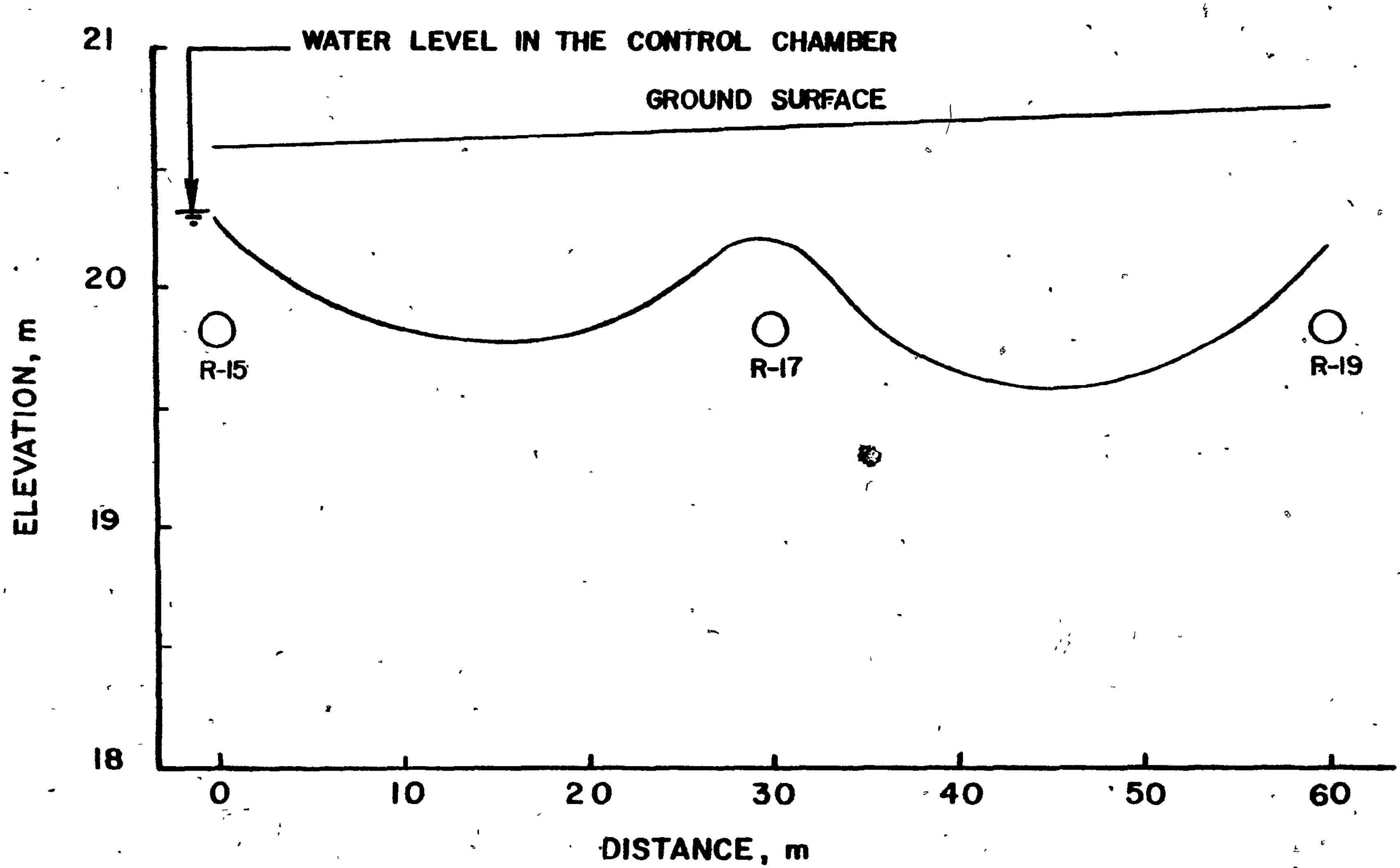

Figure 8.8. Shape of the water table elevation at a distance of 300 m from the collector A-D durin steady state operation of subsurface irrigation.

at 10 cm below the ground surface to obtain the desired water table elevation in the field (Figures 8.4 , 8.5 and 8.6).

2) These control chambers should be installed in such a way that they should not hinder the usual field operations.

3) The control chambers must be covered with lids to avoid trash and soil from depositing into it.

4) Irrigation should be stopped when the grain filling is nearly completed in order to avoid excess irrigation costs.

5) The drain valves should be opened before harvest or during any large rainstorm after stage 4.

6) The valves should be closed when the soil is found to be workable for seed bed preparation in the spring. This will prevent the water table from dropping 60-70 cm. It will also take less time to raise the water table to a desired level, when irrigation is started.

7) Float valves should be installed in the control chamber to keep the water level constant during the irrigation season.

8) The overflow pipes in the control chamber should be set at 8 cm below the soil surface such that excess water should spill over and leave the system. This will prevent the water table from rising so high as to limit the aeration of the soil in the root zone.

9) In the event of large rainfalls during the growing

season irrigation should be stopped and the overflow level reduced, so that drainage can take place.

IX SUMMARY AND CONCLUSIONS

Subsurface irrigation is a relatively new method of irrigation. It functions in combination with drainage systems. Its installation and operation in some parts of the world is based on a trial and error basis since it is quite difficult to design. However, subsurface irrigation is a relatively low cost form of irrigation when the topography and climatic conditions are suitable.

There are approximately 30,000 hectares of more permeable sandy soils in the south-western region of Quebec, which are suffering from drought and need supplementary irrigation for better crop production. It is physically possible to control the water table in these soils by means of a subsurface irrigation system thus reducing physiological damage due to drought.

This was the first time that subsurface irrigation was introduced into this region. The primary objective was to set up a field experiment to investigate the soil water regime and maize yield response, with and without subsurface irrigation. The ultimate objective was to propose suitable designs which could maximize the profitability of corn production.

A field experiment was carried out for two years on a 10-year old subsurface drainage system in a sandy soil. The existing drainage system was modified in order to achieve a randomized complete block design with eight replicates, each replicate consisted of one irrigated and one non-irrigated maize plot.

In the field experiments, soil suctions and water table depths were measured periodically in order to determine the soil water regime. Root density was measured for theoretical calculation of upward flux; yield measurements were done in each year to determine the effect of subsurface irrigation. Statistical analyses were carried out on the observed yield.

A computer water balance model was developed and integrated with crop models based on the stress day index concept to maximize the profit from maize cultivation for subsurface irrigation and drainage design alternatives. The inputs into the model were the daily rainfall and potential evapotranspiration, soil and crop parameters and some fixed parameters. Daily rainfall values were obtained from the experimental site during the subsurface irrigation experiments. Potential evapotranspiration was calculated from observed maximum and minimum temperatures during the subsurface irrigation experiments. AE was calculated from an assumed relationship between available water and AE/PE ratio. Steady upward flux and drainable volume were expressed as a function of water table depth. Laboratory experiments were conducted to determine soil moisture characteristic curves and drainable volume in relation to suction.

The moisture characteristics data were used to obtain unsaturated hydraulic conductivity functions. This information was used to establish relationships between steady upward flux and water table depths. A relationship of drainable volume versus water table depth was determined from long soil cores and was expressed in a non-linear functional form. The model was then operated with weather data for the period from March 31 to October 31 for two years.

The predicted daily water table depths and yield were compared with the observed data from the non-irrigated plots. The average relative yield of corn was predicted as a function of drain spacing for both subsurface irrigation and drainage cases and income was calculated for the range of corn prices considered. Initial investment cost for subsurface drainage and irrigation was determined for the range of spacings. This cost was amortized for a given useful system life , using suitable interest rates in order to obtain the annual cost per unit area. Annual production and maintenance costs were also added to the above cost to get the total annual cost per unit area. From this information, profit was determined for a range of spacings. Additional net benefits due to subsurface irrigation were computed. The variation in saturated hydraulic conductivity was considered and assigned a 90% confidence bound. The risk was thus defined.

The effects of uncertainty in the unsaturated and saturated flow parameters on the subsurface irrigation/drainage designs were studied. A simple approach which uses the first and second order moment method was utilized to perform these analyses. Examples were given for steady unsaturated/saturated flow equations.

Finally, a suitable water control system was proposed and operational guidelines were recommended. Based on the results of this study the following conclusions were drawn :

1. Subsurface irrigation performed satisfactorily in all irrigated plots. It raised the water table, improved the soil moisture regime in the root zone and increased the maize yields significantly. This indicates that subsurface irrigation is possible on sandy soils in south-western Quebec and that significant yield increases can be obtained during periods when precipitation is inadequate.

2. The results of soil moisture contents and soil suctions

in the root zone suggest that a water table depth less than 100 cm can supply the maximum ET demand since moisture content stayed almost at field capacity when water table depth varied in the range of 70-100 cm.

3. The relationship between steady upward flux and water table depth of St Samuel sandy soil supported the results in (2) that the maximum upward flux of 4.5 mm/day can be supplied from a water table as deep as 100 cm.

4. Available water in subsurface irrigated plots was found to be more than twice that of plots which did not receive irrigation. This clearly showed that, in non-irrigated plots, the ET rate exceeded the upward flux resulting in a loss of moisture content in the root zone. Hence, an optimum water table depth of 70 to 100 cm at the midspacing should be maintained in subsurface irrigation systems for St Samuel sandy soil in order to maintain adequate moisture supply to the root zone.

5. A highly significant maize yield increase of 40% in 1982 and 50% in 1983 were found in subsurface irrigated plots, even though irrigation was not continuously applied. These results suggest that subsurface irrigation can be very beneficial in south-western Quebec in dry years.

6. It was found that the water balance model could achieve

reasonable accuracy in simulating fluctuating water table depths and soil moisture distributions in the field. These results, when used in crop models, predicted maize yields which were sufficiently close to that of observed yields in non-irrigated plots.

7. In simulating the weather data of 1982 and 1983, it was found that the average relative yields could be increased significantly by subsurface irrigation even though the spacing between laterals was based on a subsurface drainage system. However, maximum relative yields could be obtained if a drain spacing of 30 m was used for subsurface irrigation systems and 45 m for subsurface drainage systems. The results of the simulations indicated that an average relative yield could be increased by 48% by providing subsurface irrigation in dry years.

8. Maximum profits of $513/ha could be obtained by providing the subsurface irrigation system with 30 m drain spacings compared to $19/ha for subsurface drainage system with 45 m drain spacing based on the mean saturated hydraulic conductivity measured in the experimental field .

9. The magnitude of net benefits was found to be influenced by all the parameters considered such as: interest rate, corn price, drain spacing, and saturated hydraulic conductivity (k_s). However, the variation in saturated

hydraulic conductivity had a greater effect on drain spacing in maximizing net benefits, while other parameters were independent of drain spacing. This adds emphasis to the consideration of field measurements of saturated hydraulic conductivity. Decisions regarding design should be based on calculations which take the range of actual k_s values into account within a permissible risk.

10. First and second order methods of analysing uncertainty can be used to study the effects of uncertainties in soil parameters. These soil parameters include : unsaturated and saturated hydraulic conductivities or combinations of both or other soil properties on the design of the subsurface irrigation/drainage systems. Confidence bounds can be assigned on the results which will help the designer to develop a subsurface irrigation/drainage system design based on the risk a farmer is willing to accept.

11. A subsurface irrigation system should be designed and operated on the basis of guidelines and recommendations discussed in chapter VIII of this thesis.

9.1 Recommendations For Future Related Research

As a result of the study conducted and the limitations in scope of this research, the following items are recommended for further research:

1. Field experiments on subsurface irrigation should be conducted at different locations with different crops to investigate the effect of subsurface irrigation on crop yield.

2. Soil cores with a depth of 1.0 to 1.2 m should be used for the drainable pore volume - water table depth relationship and a functional relationship should be established for a particular soil type if possible. The advantages of long soil cores are obvious because they take into account the heterogenity of the soil profile, samples are not easily disturbed; one long soil sample is better than many small soil samples at different depths. The disadvantage is, long cores are difficult to install and extract. However, efforts should be made to devise a mechanism which can easily be used for driving and extracting the soil cores.

3. Long soil cores should be used for the development of relationships between upward flux and water table depths for different soil types and should be verified with theoretical methods. This will help for future design work in subsurface irrigation/drainage systems.

4. Detailed experiments should be planned and conducted to

investigate root development of crops with respect to time. This is very important in terms of water table management.

5. During 1983 field experiments, saline groundwater was found in the newly established well. It is recommended that this saline water should be incorporated with the drainage water and the mixture be used for subsurface irrigation. Further experiments are required to determine the effects of saline water on soil structure and subsequent plant growth.

6. The computer water balance model developed in this study was not tested with the water table depths in the subsurface irrigation system because initial conditions such as: water table depth at the midspacing and presssure head at the drain at time,t is equal to 0 were not known. However, it is suggested that observations of initial conditions and fluctuating water table depths should be made by keeping a constant pressure head over the drain. These results of water table depth observations at midspacing then can be tested with the results of the model to gain confidence in its predictions. Also more observations of water table depths should be made in different areas with and without subsurface irrigation to test the water balance model predictions.

7. In this study, only two years of weather data were used in the water balance model. It is suggested that a larger

number of years of weather data and more years of yield results be considered. It is also suggested that the effects of delay in planting due to slow drainage be iccorporated in the model. Incorporation of the above data will increase the reliability of the economic analysis for subsurface irrigation/drainage systems.

8. It is recommended that the effects of uncertainty due to soil and weather parameters in the design of subsurface irrigation/drainage systems be included. Efforts should be made to improve the analysis for practical designs.

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APPENDICES

APPENDIX A

A. Derivation of Steady State Equations for Subsurface Drainage and Irrigation Systems Design

In Hooghoudt's analysis it is assumed that the rain is falling at a constant rate on the surface as shown schematically in Figure A.1. In order to simplify the mathematical analysis, the Dupuit-Forchheimer (D.F.) assumptions are made. Considering flow towards drains in a saturated zone only, it is assumed that the hydraulic gradient at any point is equal to the slope of the water table above that point. The flux per unit width can be expressed as:

$$Q = -k_s y \frac{dy}{dx} \qquad \ldots.(1)$$

Where y is the distance between the water table and the impermeable layer and is a function of x, dy/dx is the hydraulic gradient at the point x considered. From the conservation of mass we know that the flux at any point x is equal to the flow q, into or out of the unit area of the soil multiplied by the surface area of the plane. The surface area of the plane is equal to (W/2-x)*1, where 1 stands for a unit distance measured out from the plane of the paper. In other words we are cosidering a unit thickness of soil. Therefore, the quantity of water flowing per unit time through the plane is given by

$$Q = -\left(\frac{W}{2} - x\right)q \qquad \text{....(2)}$$

Substituting equation (1) into equation (2) we get,

$$k_s y\frac{dy}{dx} = -\left(\frac{W}{2} - x\right)q \qquad \text{....(3)}$$

Separating variables and integrating the equation (3) subject to the boundary conditions for drainage (refer to Figure A.1), that is y=d at x=0 and y=d+m at x=W/2, we get,

$$k_s(m^2+2dm) = \frac{qW^2}{2} - \frac{qW^2}{4} \qquad \text{....(4)}$$

Simplifying equation (4) and rearranging the terms will yield Hoogoudt's equation for drainage flux.

$$q = \frac{4k_s}{W^2}(2dm+m^2) \qquad \text{....(5)}$$

The convergence near the drain can be accounted for by substituting an equivalent depth de, for d, then the D.F. assumption would appear reasonable.

A similar approach can be used for the derivation of a subsurface irrigation design formula. In this, the drainage flux q, in equation (5) is replaced by evapotranspiration, e. During subsurface irrigation, pressure head h_o, is maintained at the drain to raise the water table in the field to supply the required e, to the root zone. Subject to the boundary conditions for subsurface irrigation, such as $y=h_o+d$ at $x=0$, and $y=y+d$ at $x=W/2$, the equation (5) can be solved for subsurface irrigation flux as:

$$e = \frac{4k_s}{W^2}[\ 2m(\ h_o+d\ ) - m^2\ ] \qquad \text{....(6)}$$

Where $m=h_o-y$.

Substituting d with equivalent d_e, the equation (6) can be expressed for drain spacing as:

$$W^2 = \frac{4k_s}{e}(\ 2mh_o+2md_e-m^2) \qquad \text{....(7)}$$

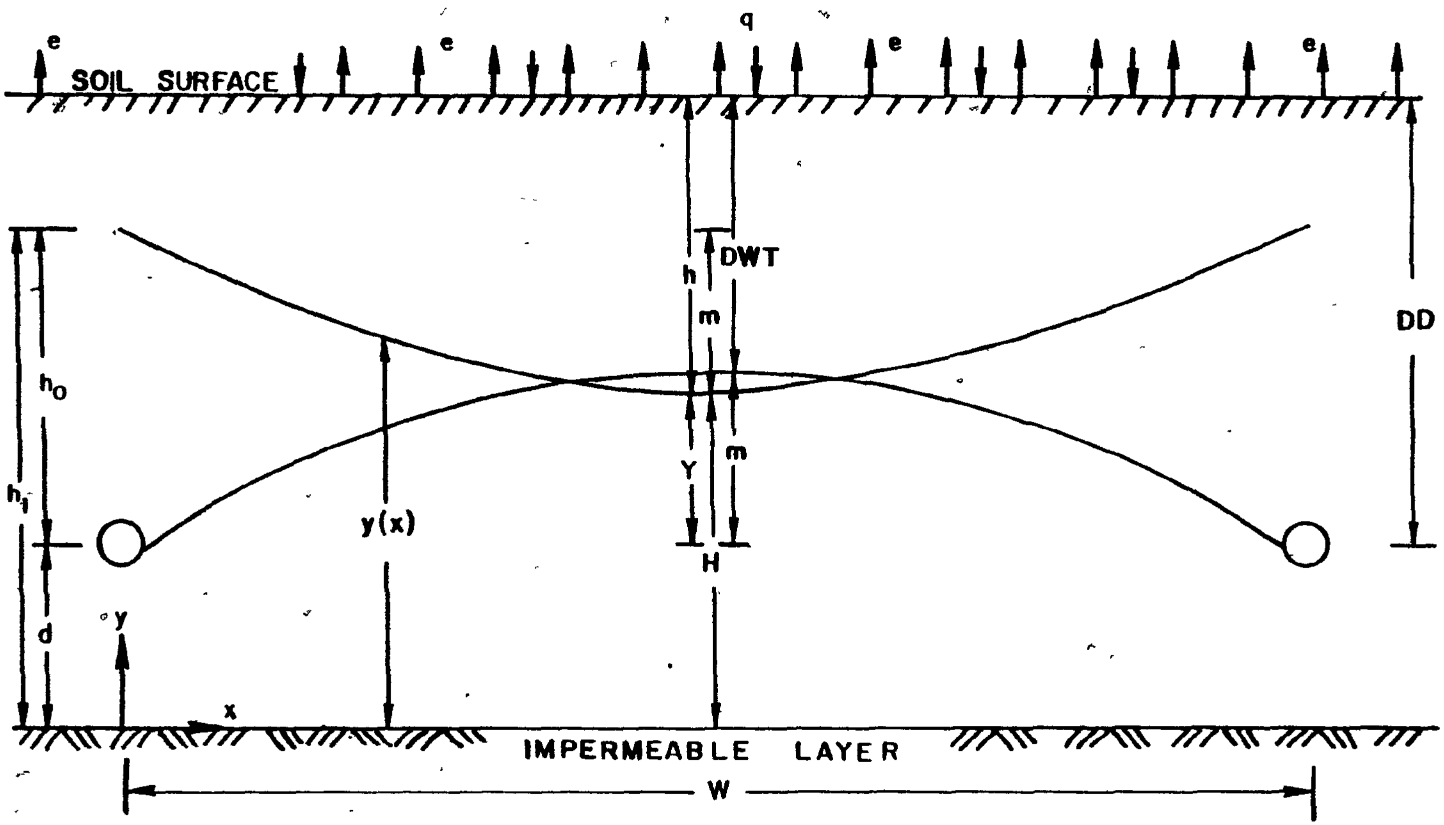

Figure A.1. Schematic water table position for subsurface irrigation and drainage with drain tubes under steady state flux.

APPENDIX B

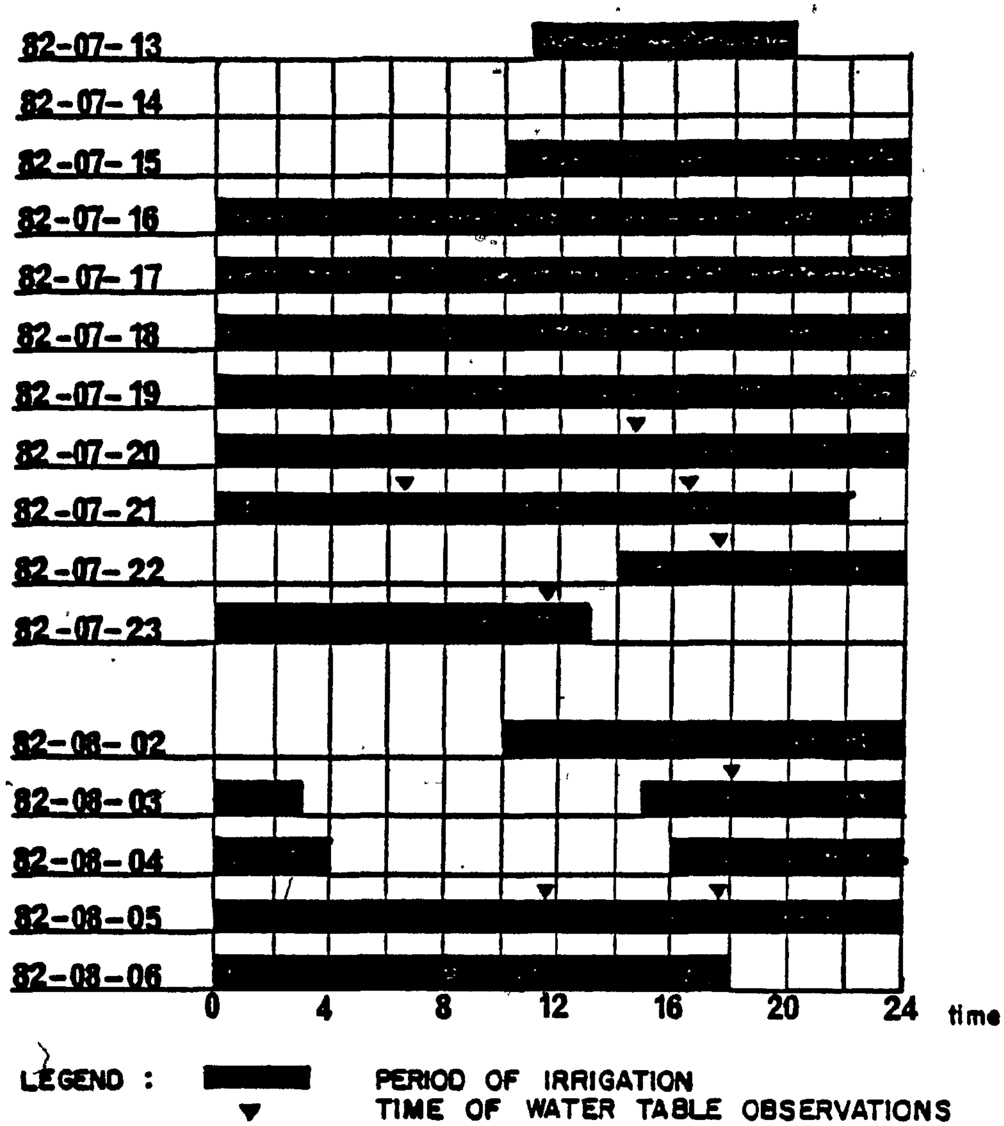

Figure B.1. Periods of irrigation and time of water table observations in 1982 field experiment.

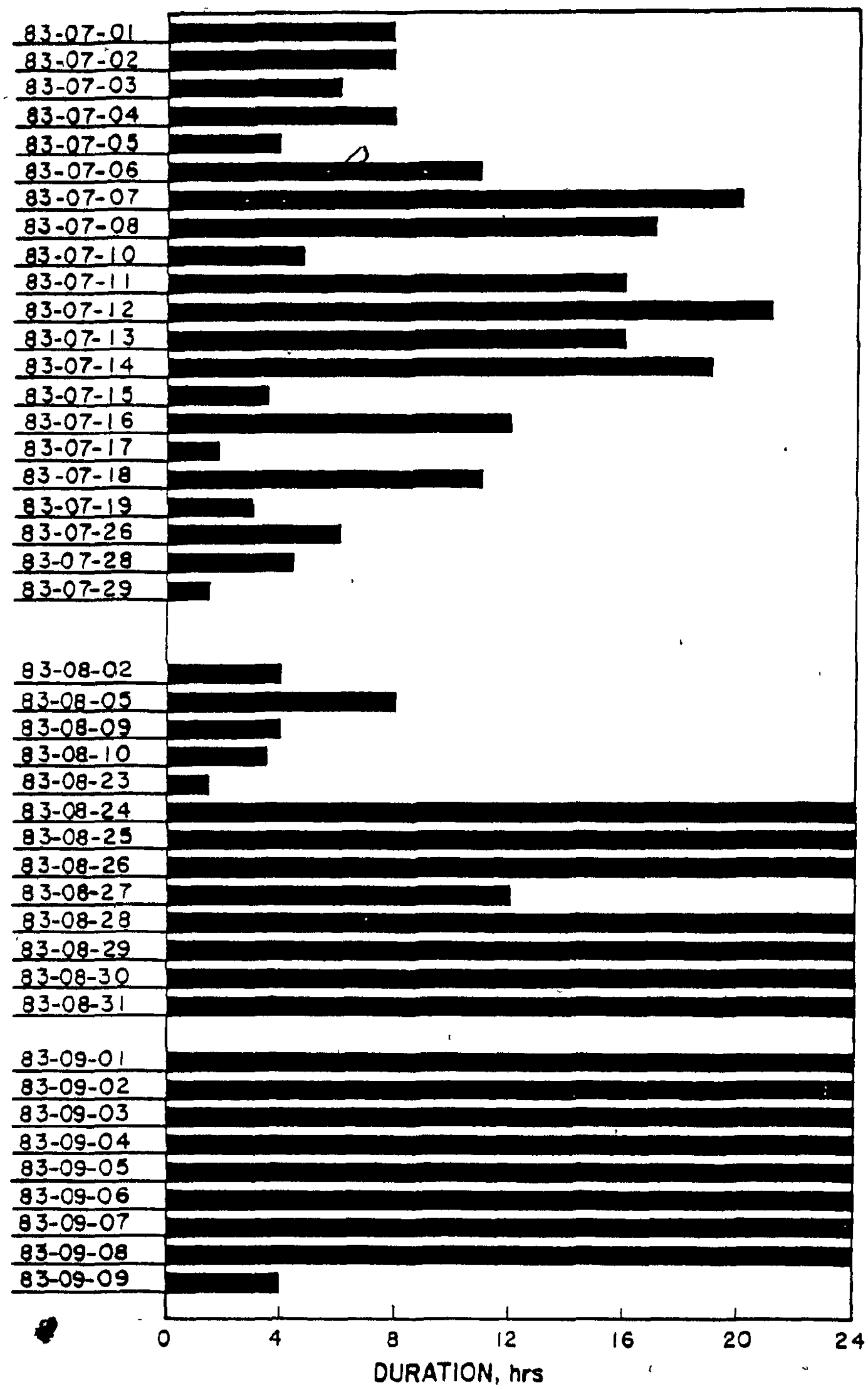

Figure B.2. Periods of irrigation in 1983.

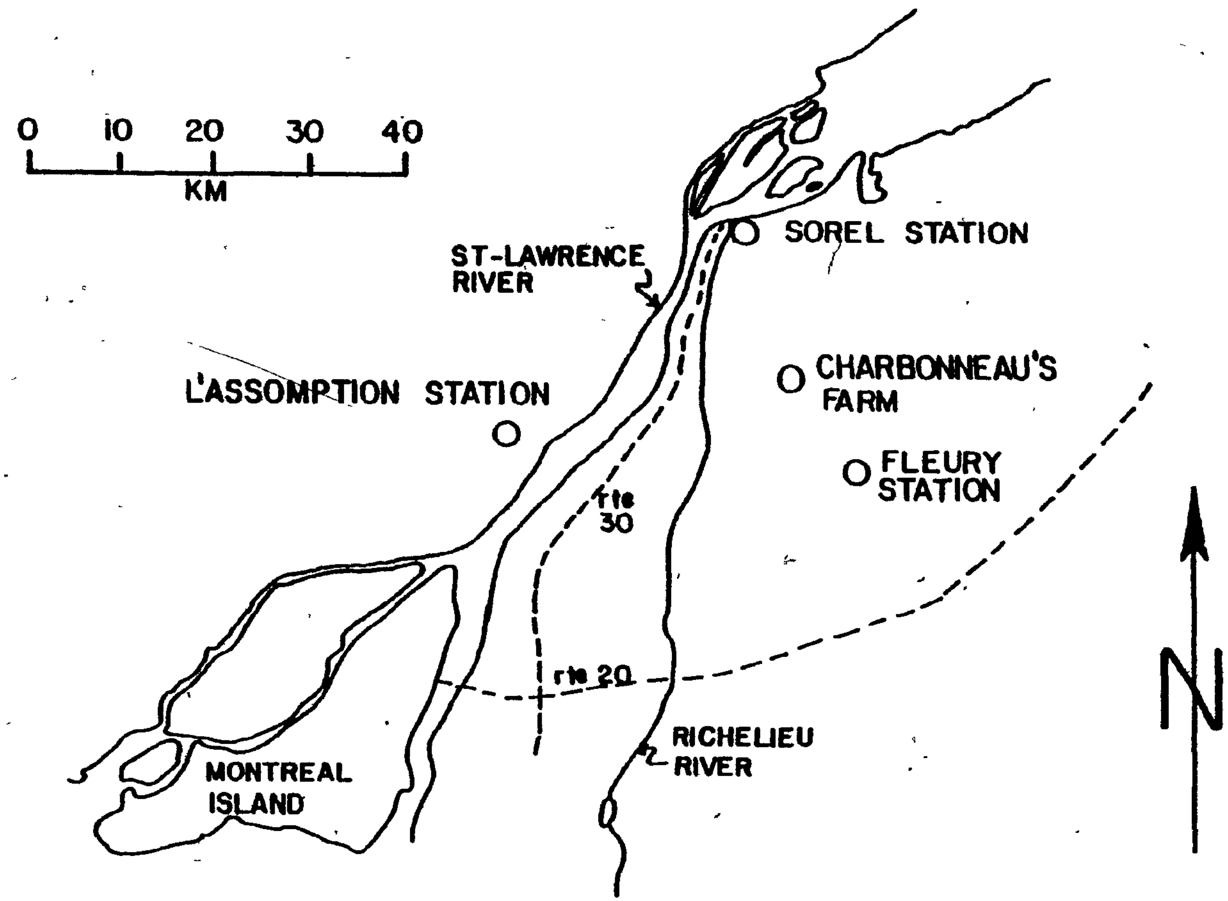

Figure B.3. Location of Charbonneau's farm and of meteorological stations.

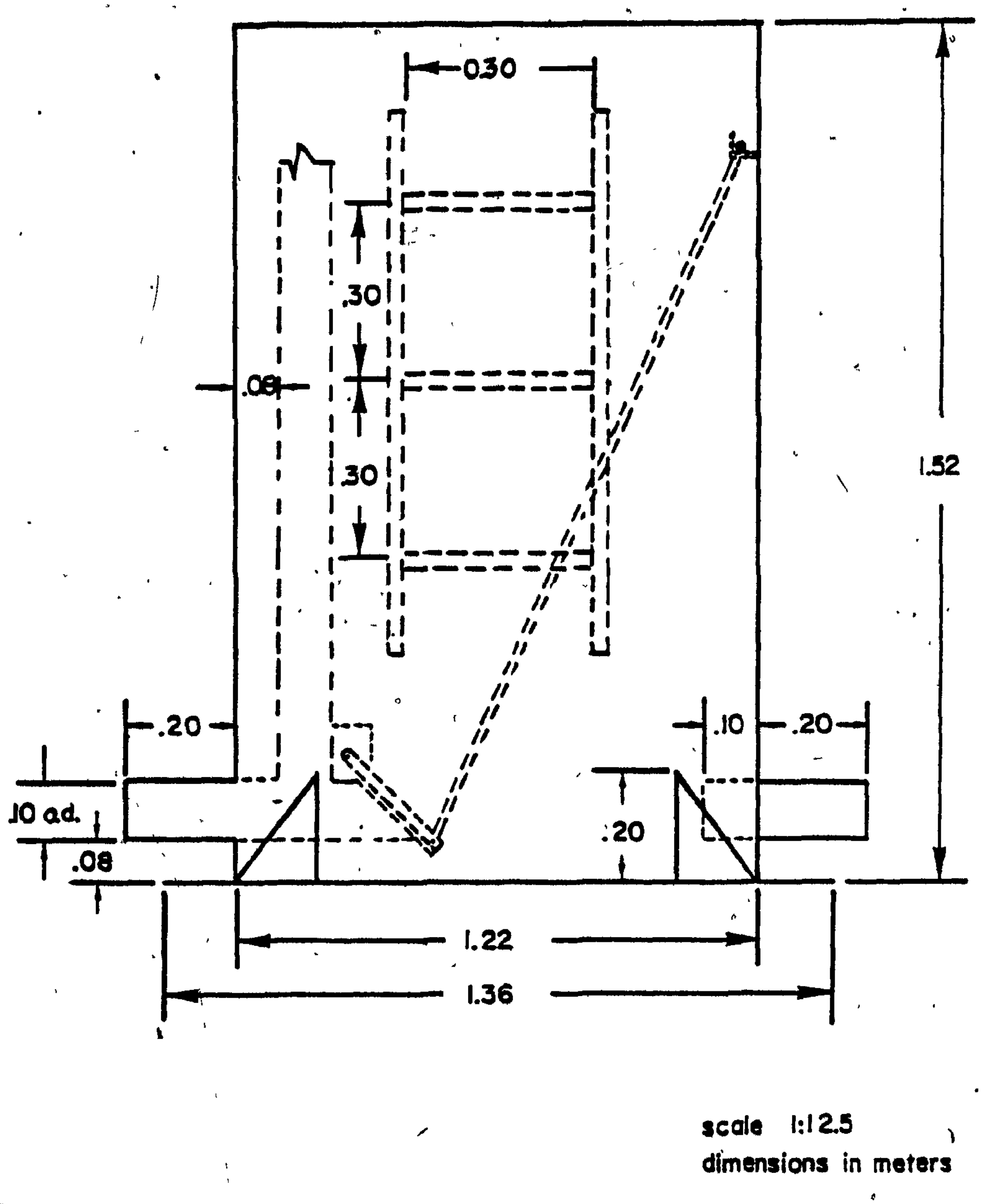

Figure B.4. Elevation view of the water table control chamber.

APPENDIX C

TABLE: C.1. Analysis of variance for dry bulk density with respect to treatment and depth.

Source	DF	Sum of sq.	Mean sq.	F	Pr>F	R	C.V
Model	9	1.4082	0.1565	33.70	0.001	0.569	4.46
Error	230	1.0678	0.0046	Root MSE		Density Mean	
Corr.Tot	239	2.4760		0.0681		1.53	

Source	DF	Anova SS	F	Pr>F
Treatment	1	0.000107	0.00	0.956
Depth	4	1.286792	10.22	0.022

TABLE:C.2. Pertinent soil properties of St. Samuel sandy loam soil.

Saturated moisture content percent by volume	Field capacity percent by volume	PWP percent by volume	Saturated hydraulic conductivity m/day
(1)	(2)	(3)	(4)
43.0	25.72	3.10	1.56

The values in columns 2,3 and 4 are obtained from Rashid-Noah (1981).

TABLE:C.3. Analysis of variance for yields of maize in the year 1983.

A. Grain yield

Source	DF	Sum of sq.	Mean sq.	F	Pr>F	R	C.V
Model	15	160081205	10672080	9.46	0.0001	0.689	28.65
Error	64	72165114	1127579	Root MSE		Grain Yield Mean	
Corr.Tot	79	232246319		1061		3705	

Source	DF	Annova SS	F	Pr>F
Block	7	28420836	0.90	0.5539
Treatment	1	100054301	22.16	0.0022

B. Ear yield

Source	DF	Sum of sq.	Mean sq.	F	Pr>F	R	C.V
Model	15	214451160	14296744	9.22	0.0001	0.684	28.35
Error	64	99226863	1550419	Root MSE		Ear Yield Mean	
Corr.Tot	79	313678023		1245		4392	

Source	DF	Annova SS	F	Pr>F
Block	7	38049104	0.89	0.5598
Treatment	1	133595389	21.85	0.0023

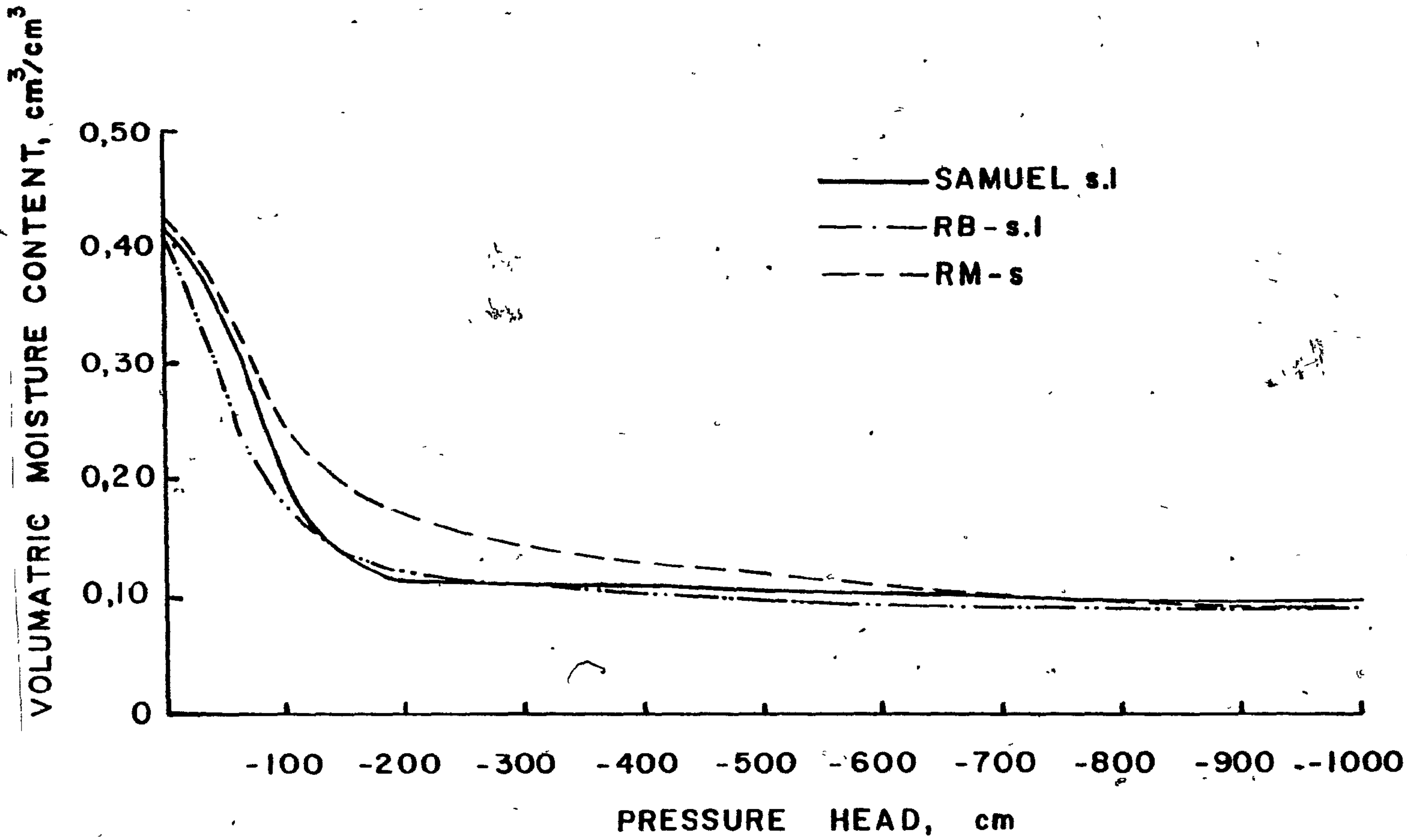

Figure C.1. Soil moisture characteristic curves for three sandy soils.

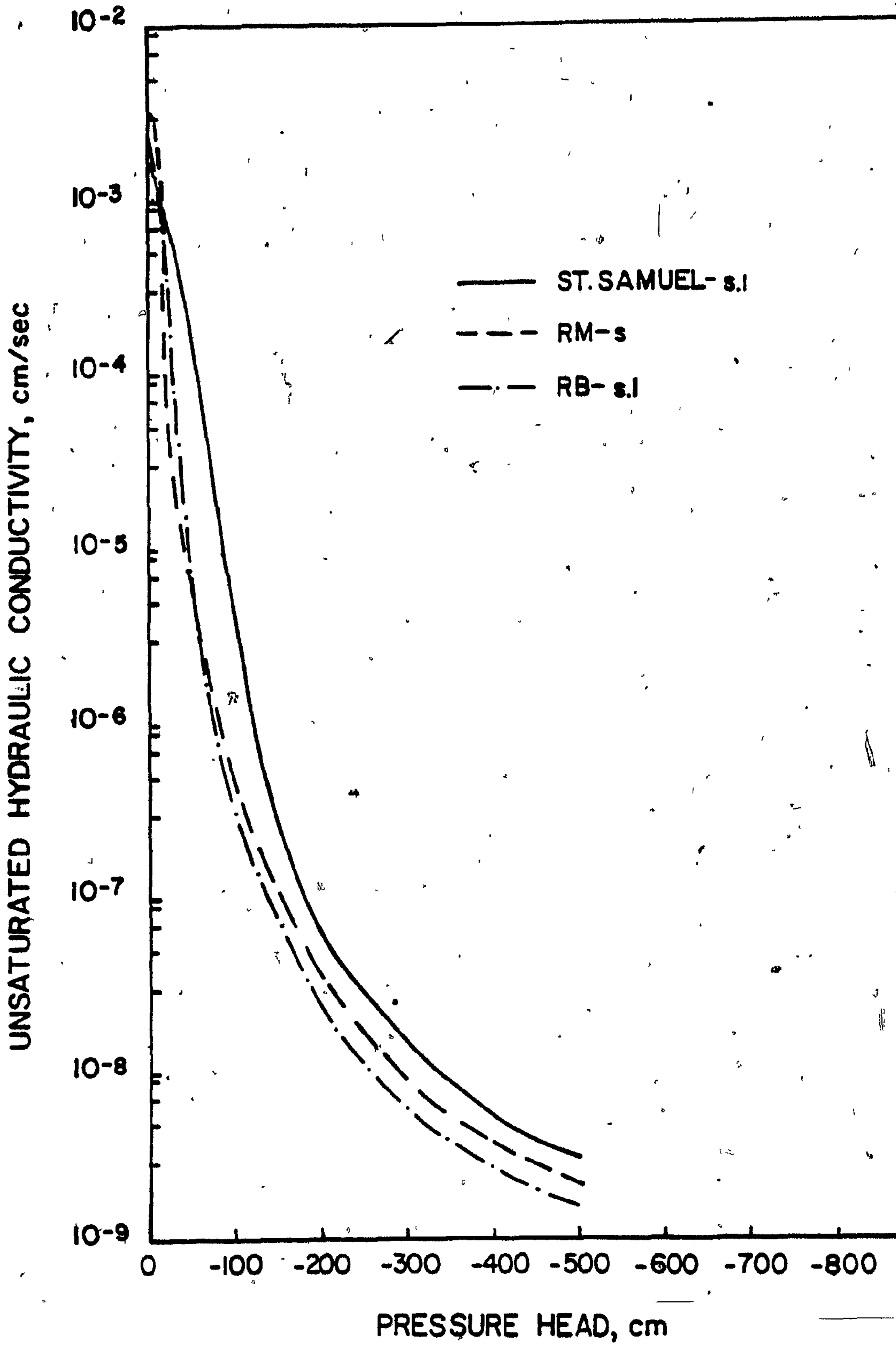

Figure C.2. Unsaturated hydraulic conductivity as a function of pressure head for three sandy soils.

APPENDIX D

TABLE: D.1. Exit and convergence head loss values in subsurface irrigation field (adopted from von Hoyningen Huene, 1984).

Date	Flow into lateral m^3/day	Exit head loss m	convergence head loss m
July 06	17.44	0.04792	0.06969
07	31.71	0.08712	0.12672
08	26.95	0.07405	0.10770
09	-	-	-
10	7.93	0.02178	0.03169
11	25.37	0.06970	0.10138
12	33.30	0.09148	0.13307
13	25.37	0.06970	0.10138
14	30.12	0.08276	0.12036
15	-	-	-
16	37.09	0.10192	0.14822
17	31.45	0.08641	0.12568
18	33.39	0.09174	0.13343
19	31.23	0.08581	0.12480

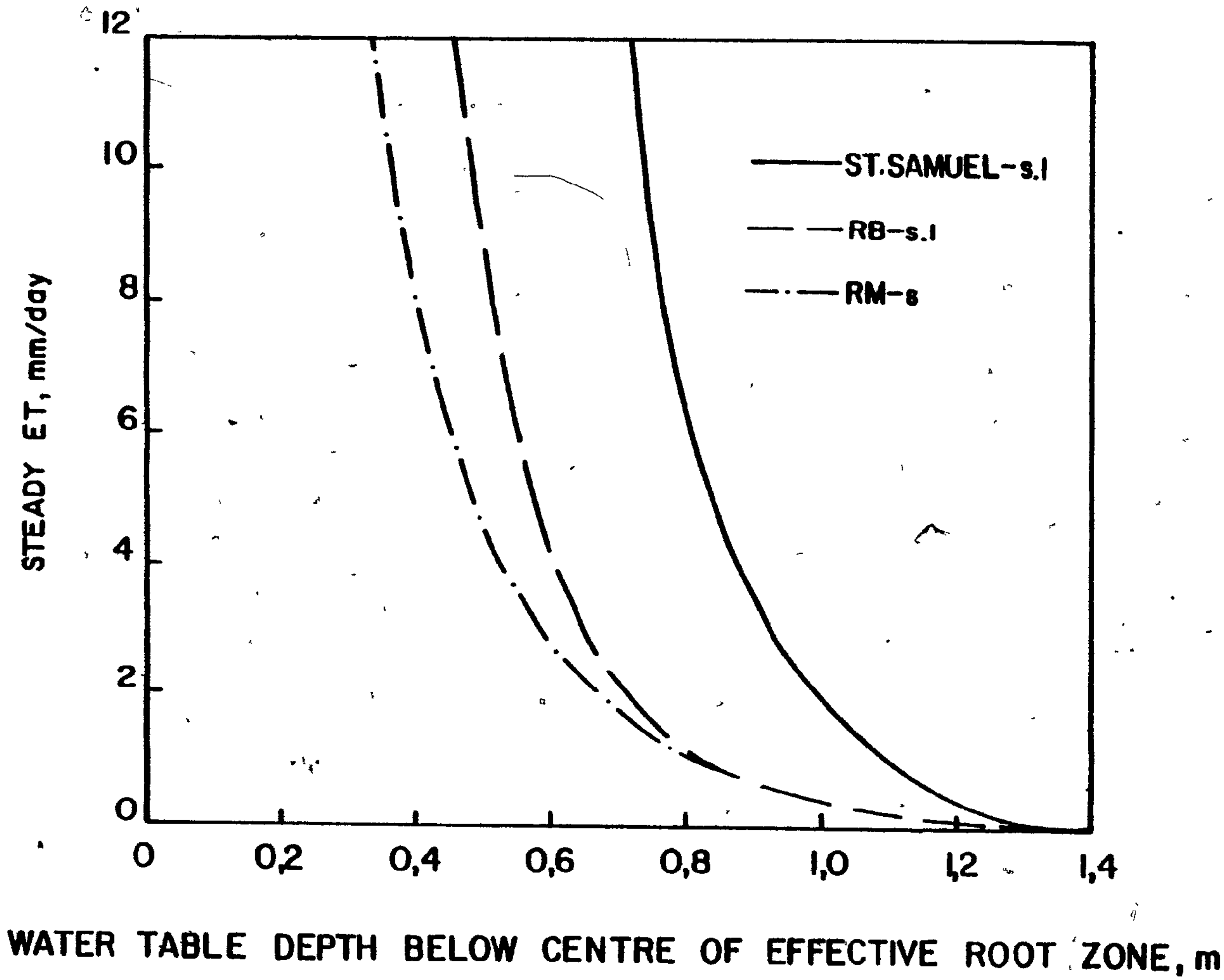

Figure D.1. Relationship between steady upward flux and watertable depth, using deterministic solution.

APPENDIX E

List of computer program of the water balance and integrated crop models

```
C ****************************************************
C
C           DESCRIPTION OF VARIABLES USED IN
C           WATER BALANCE MODEL FOR OPTMIZING
C            SUBSURFACE IRRIGATION/DRAINAGE
C                       SYSTEM
C
C                    DEVELOPED BY
C                 NISAR AHMED MEMON
C
C
C *****************
C   MAIN PROGRAM
C *****************
C
C AWC=AVAILABLE WATER CAPACITY, mm
C AERTZ=PARTIAL ACTUAL EVAPOTRANSPIRATION FROM ROOT ZONE, mm
C AEUP=PARTIAL EVAPOTRANSPIRATION FROM UPWARD FLUX, mm
C ASUBIR=AMOUNT OF SUBIRRIGATION, mm
C AETS=ACTUAL EVAPOTRANSPIRATION DURING SUBIRRIGATION, mm
C AET=ACTUAL EVAPOTRANSPIRATION DURING DRAINAGE, mm
C AYRDR=AVERAGE RELATIVE YIELD OF DRAINAGE SYSTEM
C AYRSUB=AVERAGE RELATIVE YIELD OF SUBIRRIGATION SYSTEM
C CSD=CROP SUSCEPTIBILITY FACTOR FOR DRY CONDITIONS
C CSW=CROP SUSCEPTIBILITY FACTOR FOR WET CONDITIONS
C DRWT=WATER TABLE DEPTH DURING DRAINAGE, mm
C DVOL=DRAINABLE VOLUME, mm
C DDZ=DRY ZONE DEPTH , mm
C PET=POTENTIAL EVAPOTRANSPIRATION, mm
C PDAY=PLANTING DAY
C PERC=DUMMY VARIABLE
C QDR=DRAINAGE FLUX, mm/day
C QDRS=DRAINAGE FLUX DURING SUBIRRIGATION, mm/day
C QSUB=SUBSURFACE IRRIGATION FLUX, mm/day
C RETDR=RATIO OF AE/PE FOR DRAINAGE CASE
C RETSUB=RATIO OF AE/PE FOR SUBIRRIGATION CASE
C RAW=REMAINING AVAILABLE WATER, mm
C RAWSUB=REMAINING AVAILABLE WATER FOR SUBIRRIGATION CASE, mm
C SPACE=DRAIN SPACING, mm
C SUBWT=WATER TABLE DEPTH DURING SUBIRRIGATION, mm
C THETAS=SOIL MOISTURE CONTENT AT SATURATION
C THETAW=SOIL MOISTURE CONTENT AT PERMENANT WILTING POINT
C TWT=TOTAL WATER TABLE, mm
C VOLSUB=VOLUME OF WATER ENTERING IN SUBIRRIGATION SYSTEM
C YRDR=RELATIVE YIELD OF MAIZE IN DRAINGE SYSTEM
C YRSUB=RELATIVE YIELD OF MAIZE IN SUBIRRIGATION SYSTEM
C
C *********************************
C         SUBROUTINE DRAIN
C *********************************
C
C ACTD=DEPTH OF THE IMPERMEABLE LAYER BELOW THE DRAIN, mm
C D=HIEGHT OF THE WATER TABLE ABOVE THE IMPRMEABLE LAYER AT THE DRAIN, m
C DD=DRAIN DEPTH, mm
C DE=EQUIVALENT DEPTH, mm
C DENOM=DUMMY VARIABLE
```

```
C DIFVOL=DUMMY VARIABLE
C DWT=DESIGN WATER TABLE DEPTH, mm
C EM=DEFLECTION OR PRESSURE HEAD, mm
C FACTOR=DUMMY VARIABLE
C HM=HEIGHT OF WATER TABLE ABOVE THE IMPERMEABLE LAYER
C    AT MIDSPACINGS, mm
C HO=HEIGHT OF WATER TABLE ABOVE THE IMPERMEABLE LAYER
C    AT THE DRAIN, mm
C OPTWT=DESIGN WATER TABLE DEPTH FOR SUBIRRIGATION SYSTEM, mm
C OPTVOL=DRAINABLE VOLUME AT 1000 mm SUCTION, mm
C QMAX=DRAINAGE COEFFICIENT,mm/day
C R=EFFECTIVE RADIUS FOR DRAIN PIPE, mm
C SATK=SATURATED HYDRAULIC CONDUCTIVITY, mm/day
C VOL1=DUMMY VARIABLE
C VOL2=DUMMY VARIABLE
C
C ***************************
C    SUBROUTINE EVAP
C ***************************
C
C WT=WATER TABLE DEPTH, mm
C UPFLUX=UPWARD FLUX, mm/day
C
C ***************************
C    SUBROUTINE ROOT
C ***************************
C
C INDAY=DAYS (INPUT)
C ROOTIN=ROOT DEPTH (INPUT),mm
C ROOTD=ROOT DEPTH (OUTPUT),mm
C
C ***************************
C    SUBROUTINE YIELD
C ***************************
C
C K=THE DAY CALCULATIONS START
C NP=NUMBER OF PERIODS IN GROWING SEASON
C NDP=NUMBER OF DAYS IN ONE PERIOD
C SDI=STRESS DAY INDEX
C SUMDI=SUMMATION OF SDI
C SDD=STRESS DAY FOR DEFICIT WATER CONDITIONS
C SUMD=SUMMATION OF SDD
C YY=RELATIVE YIELD OBTAINABLE DUE TO SOIL MOISTURE CONDITIONS
C
C **************************
C    SUBROUTINE YIELDW
C **************************
C
C SD=STRESS DAY FOR WET CONDITIONS
C SDIW=STRESS DAY INDEX DUE TO WET CONDITIONS
C WTD=WATER TABLE DEPTH, cm
C YW=RELATIVE YIELD OBTAINABLE DUE TO WET CONDITIONS
```

```
C ****************************************************
C                A WATER BALANCE MODEL
C            DEVELOPED BY NISAR AHMED MEMON
C           DEPT. OF AGRICULTURAL ENGINEERING
C                  MACDONALD COLLEGE
C             STE. ANNE DE BELLEVUE, QUEBEC
C                    FEBRUARY 1985
C                     -----------
C                       -------
C                        -----
C                         ---
C                          -
C
C ****************************************************
C THIS MODEL CALCULATES THE SOIL MOISTURE IN THE ROOT
C ZONE FOR BOTH SUBSURFACE IRRIGATION AND DRAINAGE
C SYSEMS. SUBSEQUENTLY THESE RESULTS ARE USED BY THE
C APPROPRIATE SUBROUTINES TO CALCULATE THE RELATIVE
C MAIZE YIELDS FOR DIFFERENT DESIGN ALTERNATIVES. THE
C MODEL ACCEPTS DAILY RAINFALL AND PE, SOME FIXED SYSTEM
C AND CROP PARAMETERS AS INPUT
C ****************************************************
C
C
C
C    *                                            *
C    *            THIS IS MAIN PROGRAMME          *
C    *                                            *
C    **********************************************
C
      INTEGER PDAY
      DIMENSION AWC(250),RETSUB(250),RETDR(250),ROOTD(250),RAIN(250),
     *SDD(20),SDI(30),CSD(20),SUMD(20),CSW(5),INDAY(50),ROOTIN(50),
     &SPACE(20),NMONTH(7),SUBWT(250),DRWT(250),SDIW(125),SD(125)
     &,YRDR(2,16),YRSUB(2,16)
      COMMON PET(250)
      DATA NMONTH/30,31,30,31,31,30,31/
C
C *************
C READ INPUT DATA
C *************
C
      READ(5,500)(CSD(I),I=1,17)
  500 FORMAT(14F5.2)
      READ(5,550)(CSW(I),I=1,3)
  550 FORMAT(3F5.2)
      READ(5,600)(INDAY(I),ROOTIN(I),I=1,13)
  600 FORMAT(I3,F9.1)
      READ(5,650)(SPACE(I),I=1,16)
  650 FORMAT(9F8.1)
      READ(5,655)THETAS,THETAW
  655 FORMAT(2F6.3)
      CALL ROOT(INDAY,ROOTIN,ROOTD)
      NYEAR=1981
      DO 10 I=1,2
      NYEAR=NYEAR+1
```

```
C
      READ(5,300)(RAIN(IDAY),PET(IDAY),IDAY=1,215)
  300 FORMAT(6(F6.1,F6.1))
      WRITE(6,660)NYEAR
  660 FORMAT('1',//,1X,'TABLE:  AN EXAMPLE OF COMPUTER OUTPUT OF PREDICT
     &ED RELATIVE YIELD FOR',/,9X,'DIFFERENT SPACINGS.',//,28X,'YEAR:  '
     &,I4,/,28X,7('-'),/,1X,75('*'),/,1X,'SPACING      SUBSURFACE DRAINA
     &GE  RELATIVE  SUBSURFACE IRRIGATION  RELATIVE',/,14X,19('-'),12X,2
     &1('-'),/,18X,'YRD      YRW      YIELD      YRD      YRW
     &YIELD',/,4X,'MM',12X,'(%)',6X,'(%)',8X,'(%)',8X,'(%)',7X,'(%)',9X,
     &'(%)',/,1X,75('*'),15X,'AMOUNT OF IRRIGATION',//)
      DO 20 ISP=1,16
      IDAY=1
      MONTH=3
C
C **************
C INITIALIZATION
C **************
C
      TWT=0.0
      DVOL=0.0
      WETWT=0.0
      DDZ=0.0
      PDAY=36
      TWTSUB=0.0
      VOLSUB=DVOL
C
C     CALCULATION OF AVAILABLE CAPACITY ON DAY FIRST
C
      AWC(1)=ROOTD(1)*(THETAS-THETAW)
      RAW=AWC(1)
C ******
C     START OF WATER BALANCE CALCULATIONS FROM DAY ONE
C ******
      DO 21 J=1,7
      MONTH=MONTH+1
      N=NMONTH(J)
      WRITE(6,700)MONTH,NYEAR
  700 FORMAT('1',//,1X,'TABLE :  AN EXAMPLE OF COMPUTER OUTPUT FOR DAILY
     & PREDICTED VALUES OF VARIABLES FROM RECORDED DAILY RAINFALL AND PE
     & VALUES.',//,1X,28('*'),12X,35('*'),12X,14('*'),10X,14('*'),/,1X,'
     &* STATION NUMBER :  7014160 *',11X,'* STATION NAME : L ASSOMPTION-
     &CDA',13X,'* MONTH :',I3,12X,'* YEAR: ',I4,/,1X,28('*'),12X,35('*')
     &,12X,14('*'),10X,14('*'),//,1X,127('*'),/,33X,'SUBSURFACE DRAINAGE
     &',37X,'SUBSURFACE IRRIGATION',/,18X,51('-'),3X,56('-'),/,' DAY  RA
     &IN  PE   AWC',5X,'RAW   AET   DR AIRVOL   DDZ   WETWT    TWT   A
     &ETS    RAWSUB  DZ  AIRVOL  QDRS  WETSUB  TWTSUB  ASUBIR',/,7X,'MM
     &  MM     MM     MM     MM    MM     MM       MM       MM      MM      MM
     &      MM     MM     MM     MM      MM      MM      MM',/,1X,127('*'),
     &//)
C
C
      DO 22 K=1,N
      IDAY=IDAY+1
      CALL DRAIN(TWT,VOLSUB,TWTSUB,SPACE,ISP,IDAY,QDR,QSUB,QDRS)
      WT=WETWT
```

```
      CALL EVAP(WT,UPFLUX)
C *************
C WATER BALANCE CALCULATIONS FOR SUBSURFACE DRAINAGE
C *************
C
      IF(UPFLUX.LT.PET(IDAY)) GO TO 35
      AEUP=PET(IDAY)
      AERTZ=0.0
      IF(DDZ.GT.0.0) GO TO 30
      DVOL=DVOL+AEUP+QDR-RAIN(IDAY)
      IF(DVOL.LE.0.0) GO TO 45
      AWC(IDAY)=ROOTD(IDAY)*(THETAS-THETAW)
      RAW=AWC(IDAY)
      DDZ=0.0
   25 WETWT=32.41*DVOL**0.619
      TWT=WETWT+DDZ
      AET=AEUP+AERTZ
      GO TO 70
C
C
   30 AWC(IDAY)=ROOTD(IDAY)*(THETAS-THETAW)
      RAW=AWC(IDAY)-AWC(IDAY-1)+RAW
      RAW=RAW+0.5*RAIN(IDAY)
      IF(RAW.GT.AWC(IDAY)) GO TO 50
      DDZ=(AWC(IDAY)-RAW)/(THETAS-THETAW)
      GO TO 60
C
C
   35 DEMAND=PET(IDAY)-UPFLUX
      AEUP=UPFLUX
      AWC(IDAY)=ROOTD(IDAY)*(THETAS-THETAW)
      RAW=AWC(IDAY)-AWC(IDAY-1)+RAW
      PERC=RAW/AWC(IDAY)
      IF(PERC.GE.0.5) GO TO 55
      RATIO=PERC*2.
      AERTZ=RATIO*DEMAND
      RAW=RAW-AERTZ+0.5*RAIN(IDAY)
      IF(RAW.GT. AWC(IDAY)) GO TO 50
   40 DDZ=(AWC(IDAY)-RAW)/(THETAS-THETAW)
      GO TO 60
C
C
   45 RUNOFF=ABS(DVOL)
      DVOL=0.0
      WETWT=0.0
      TWT=0.0
      AET=AERT+AEUP
      GO TO 70
C
C
   50 EXCESS=RAW-AWC(IDAY)
      RAW=AWC(IDAY)
      DDZ=0.0
      DVOL=DVOL-EXCESS+AEUP+QDR-0.5*RAIN(IDAY)
      IF(DVOL.LE.0.0) GO TO 45
      GO TO 25
```

```
C
C
   55 AERTZ=DEMAND
      RAW=RAW-AERTZ+0.5*RAIN(IDAY)
      IF(RAW.GT.AWC(IDAY)) GO TO 50
      GO TO 40
C
C
   60 DVOL=DVOL+AEUP+QDR-0.5*RAIN(IDAY)
      IF(DVOL.LE.0.0) GO TO 45
      GO TO 25
C
C
C
C
C     *******************************************************
C     *                                                     *
C     * WATER BALANCE CALCULATIONS FOR SUBSURFACE IRRIGATION *
C     *                                                     *
C     *******************************************************
C
   70 IF(IDAY.EQ.PDAY) GO TO 75
      IF(IDAY.GT.PDAY) GO TO 80
      ASUBIR=0.0
      AETS=AET
      TWTSUB=TWT
      WTSUB=WETWT
      GO TO 120
C
C
   75 ASUBIR=0.0
      ASUBIR=ASUBIR+QSUB
      DVOL1=DVOL-QDR
      VOLSUB=DVOL1-ASUBIR
      IF(VOLSUB.LE.0.0) GO TO 110
      WTSUB=32.51*VOLSUB**0.619
      TWTSUB=WTSUB+DDZ
      AETS=AET
      RAWSUB=RAW
      GO TO 120
C
C
   80 ASUBIR=ASUBIR+QSUB
      WT=WTSUB
      CALL EVAP(WT,UPFLUX)
      IF(UPFLUX.GE.PET(IDAY)) GO TO 95
      ETUP=UPFLUX
      DEMAND=PET(IDAY)-UPFLUX
      RAWSUB=AWC(IDAY)-AWC(IDAY-1)+RAWSUB
      PERC=RAWSUB/AWC(IDAY)
      IF(PERC.GE.0.5) GO TO 100
      RATIO=PERC*2.
      AERT=DEMAND*RATIO
      RAWSUB=RAWSUB-AERT+0.5*RAIN(IDAY)
   85 VOLSUB=VOLSUB+ETUP+QDRS-QSUB-0.5*RAIN(IDAY)
      IF(VOLSUB.LE.0.0) GO TO 110
```

```
      IF(RAWSUB.GT.AWC(IDAY)) GO TO 105
      DZ=(AWC(IDAY)-RAWSUB)/(THETAS-THETAW)
   90 WTSUB=32.41*VOLSUB**0.619
      TWTSUB=WTSUB+DZ
      AETS=AERT+ETUP
      GO TO 120
C
C
   95 ETUP=PET(IDAY)
      AERT=0.0
      RAWSUB=AWC(IDAY)-AWC(IDAY-1)+RAWSUB+0.5*RAIN(IDAY)
      GO TO 85
C
C
  100 AERT=DEMAND
      RAWSUB=RAWSUB-AERT+0.5*RAIN(IDAY)
      GO TO 85
C
C
  105 EXCESS=RAWSUB-AWC(IDAY)
      DZ=0.0
      VOLSUB=VOLSUB-EXCESS
      RAWSUB=AWC(IDAY)
      IF(VOLSUB.LE.0.0) GO TO 110
      GO TO 90
C
C
  110 RUNOF=ABS(VOLSUB)
      VOLSUB=0.0
      TWTSUB=0.0
      WTSUB=0.0
      RAWSUB=AWC(IDAY)
      AETS=AERT+ETUP
  120 IF(PET(IDAY).EQ.0.0) GO TO 125
      RETDR(IDAY-1)=AET/PET(IDAY)
      RETSUB(IDAY-1)=AETS/PET(IDAY)
      GO TO 130
  125 RETDR(IDAY-1)=1.0
      RETSUB(IDAY-1)=1.0
C
C
  130 NDAY=IDAY-1
      SUBWT(NDAY)=TWTSUB
      DRWT(NDAY)=TWT
      WRITE(6,750)K,RAIN(IDAY),PET(IDAY),AWC(IDAY),RAW,AET,QDR,DVOL,DDZ,
     &WETWT,TWT,AETS,RAWSUB,DZ,VOLSUB,QDRS,WTSUB,TWTSUB,ASUBIR
  750 FORMAT(I4,2X,F4.1,2X,F3.1,2X,F5.1,3X,F5.1,2X,F3.1,2X,F4.1,2X,F5.1,
     &2X,F5.1,2X,F6.1,2X,F6.1,2X,F3.1,3X,F5.1,2X,F5.1,2X,F5.1,2X,F4.1,2X
     &,F6.1,2X,F6.1,2X,F5.1)
      IF(NDAY.EQ.130) TSUBIR=ASUBIR
   22 CONTINUE
      WRITE(6,800)
  800 FORMAT(/,1X,125('*'))
   21 CONTINUE
      CALL YIELD(RETDR,CSD,YRDDR)
      CALL YIELD(RETSUB,CSD,YRDSUB)
```

```
      CALL YIELDW(DRWT,CSW,YRWDR)
      CALL YIELDW(SUBWT,CSW,YRWSUB)
      YRDR(I,ISP)=(YRDDR*YRWDR)/100.
      YRSUB(I,ISP)=(YRDSUB*YRWSUB)/100.
      WRITE(6,995)SPACE(ISP),YRDDR,YRWDR,YRDR(I,ISP),
     &YRDSUB,YRWSUB,YRSUB(I,ISP),TSUBIR
  995 FORMAT(1X,F7.1,9X,F6.2,3X,F6.2,5X,F6.2,5X,F6.2,4X,F6.2,6X,F6.2,21X
     &,F6.2)
   20 CONTINUE
      WRITE(6,999)
  999 FORMAT(/,1X,75('*'))
   10 CONTINUE
      WRITE(6,950)
  950 FORMAT('1',25X,'TABLE:    AN EXAMPLE OF COMPUTER OUTPUT',
     &/,36X,'OF AVERAGE RELATIVE YIELD AT VARIOUS
     &',/,36X,'DRAIN SPACINGS.',////,25X,38('*'),//,25X,
     &'SPACING',4X,'AVERAGE RELATIVE MAIZE YIELD',/,
     &36X,26('-'),/,38X,'SUBSURFACE',4X,'SUBSURFACE',/,
     &39X,'DRAINAGE',5X,'IRRIGATION',/,27X,'MM',13X,
     &'(%)',10X,'(%)',//,25X,38('*'),/)
C
C **********
C CALCULATE THE AVERAGE RELATIVE YIELD
C **********
C
      DO 96 JJ=1,16
      SUMDR=0.0
      SUMSUB=0.0
      DO 98 KK=1,2
      SUMDR=SUMDR+YRDR(KK,JJ)
      SUMSUB=SUMSUB+YRSUB(KK,JJ)
   98 CONTINUE
      AYRDR=SUMDR/2
      AYRSUB=SUMSUB/2
      WRITE(6,960)SPACE(JJ),AYRDR,AYRSUB
  960 FORMAT(25X,F7.1,9X,F6.2,7X,F6.2)
   96 CONTINUE
      WRITE(6,970)
  970 FORMAT(/,25X,38('*'))
      STOP
      END
C
C
C
C
C
C
C
C
```

```
C     ******************************************************
C     *                                                    *
C     *              S U B R O U T I N E S                 *
C     *                                                    *
C     ******************************************************
C
C
C     THIS SUBROUTINE CALCULATES THE DRAINAGE AND SUBIRRIGATION
C                          FLUXES
C                     *****************
C                         ********
      SUBROUTINE DRAIN(TWT,VOLSUB,TWTSUB,S,ISP,IDAY,QDR,QSUB,QDRS)
C
      DIMENSION S(ISP)
      INTEGER PDAY
      COMMON PET(250)
C
C     INITIALIZATION
C
C
      OPTWT=1000.
      OPTVOL=252.00
      PDAY=36
      QMAX=10.
      DD=1050.
      SATK=1560.
      HO=910.
      DWT=400.
      D=1510.
      ACTD=550.
      R=5.1
C
C
      FACTOR=(4.*SATK)/S(ISP)**2.
      DENOM=1+((ACTD/S(ISP))*((ALOG(ACTD/R)-3.4)*(8./3.142)))
      DE=ACTD/DENOM
C
C
      IF(TWT.GE.DD) GO TO 11
      H=DD-TWT
      QDR=FACTOR*(2.*DE*H+H**2.)
      IF(QDR.GE.QMAX)QDR=QMAX
   15 IF(IDAY.GE.PDAY) GO TO 12
      QSUB=0.0
      RETURN
C
C
   11 QDR=0.0
      GO TO 15
C
C
   12 IF(TWTSUB.LT.OPTWT) GO TO 13
      HM=D-TWTSUB
      EM=HO-HM
      QSUB=FACTOR*(2*DE*EM+EM**2)
      IF(QSUB.GE.QMAX)QSUB=QMAX
```

```
      QDRS=0.0
      RETURN
C
C
   13 H=DD-TWTSUB
      QDRS=FACTOR*(2.*DE*H+H**2.)
      IF(QDRS.GE.QMAX)QDRS=QMAX
      VOL1=((TWTSUB/32.41)**(1./0.619))
      DIFVOL=OPTVOL-VOL1
      IF(QDRS.GT.DIFVOL) GO TO 14
      VOL2=QDRS+PET(IDAY)
      IF(VOL2.GT.DIFVOL) GO TO 16
      QSUB=0.0
      RETURN
C
C
   14 QDRS=DIFVOL
   16 HM=D-TWTSUB
      EM=HO-HM
      QSUB=FACTOR*(2.*DE*EM+EM**2.)
      IF(QSUB.GE.PET(IDAY))QSUB=PET(IDAY)
      RETURN
      END
C
C     *****************************************************
C     *                                                   *
C     *   THIS SUBROUTINE INTERPOLATES THE VALUES OF UPWARD *
C     *   FLUX OF GIVEN VALUES OF WATER TABLE POSITION.    *
C     *                                                   *
C     *****************************************************
C
      SUBROUTINE EVAP(XX,F)
      DIMENSION WT(29),UPFLUX(29),A(29),B(29),C(29),R(29),FDP(29)
      DATA WT/0.,50.,100.,150.,200.,250.,300.,350.,400.,450.,500.,
     &550.,600.,650.,700.,750.,800.,850.,900.,950.,1000.,1050.,1100.,
     &1150.,1200.,1250.,1300.,1350.,1400./
      DATA UPFLUX/12.0,12.0,12.0,12.0,12.0,12.0,12.0,12.0,12.0,12.0,
     &12.0,12.0,12.0,12.0,12.0,9.10,6.25,4.50,3.30,2.60,1.90,1.45,1.10,
     &0.70,0.37,0.25,0.03,0.02,0.01/
C
C
      N=29
      ALAMDA=1
      NM2=N-2
      NM1=N-1
      C(1)=WT(2)-WT(1)
      DO 1 I=2,NM1
      C(I)=WT(I+1)-WT(I)
      A(I)=C(I-1)
      B(I)=2.0*(A(I)+C(I))
      R(I)=6.0*((UPFLUX(I+1)-UPFLUX(I))/C(I)-
     &     (UPFLUX(I)-UPFLUX(I-1))/C(I-1))
    1 CONTINUE
C
C
      B(2)=B(2)+ALAMDA+C(1)
```

```
      B(NM1)=B(NM1)+ALAMDA*C(NM1)
C
      DO 2 I=3,NM1
      T=A(I)/B(I-1)
      B(I)=B(I)-T*C(I-1)
      R(I)=R(I)-T*R(I-1)
    2 CONTINUE
      FDP(NM1)=R(NM1)/B(NM1)
C
      DO 3 I=2,NM2
      NMI=N-I
      FDP(NMI)=(R(NMI)-C(NMI)*FDP(NMI+1))/B(NMI)
    3 CONTINUE
C
      FDP(1)=ALAMDA*FDP(2)
      FDP(N)=ALAMDA*FDP(NM1)
C
C
      DO 4 I=1,NM1
      IF(XX.LE.WT(I+1)) GO TO 5
    4 CONTINUE
C
C
    5 DXM=XX-WT(I)
      DXP=WT(I+1)-XX
      DEL=WT(I+1)-WT(I)
      F=FDP(I)*DXP*(DXP*DXP/DEL-DEL)/6.0
     &   +FDP(I+1)*DXM*(DXM*DXM/DEL-DEL)/6.0
     &   +UPFLUX(I)*DXP/DEL+UPFLUX(I+1)*DXM/DEL
      RETURN
      END
C
C
C
C     *******************************************************
C     *                                                     *
C     * THIS SUBROUTINES INTERPOLATE THE EFFECTIVE ROOT ZONE *
C     * FOR EACH DAY THROUGHOUT THE GROWING SEASSON OF CORN  *
C     * CROP. IT STORES THE RESULTS AND SEND THE RESULTS TO  *
C     * THE CALLING PROGRAM.                                 *
C     *                                                     *
C     *******************************************************
C
C
      SUBROUTINE ROOT(INDAY,ROOTIN,ROOTD)
      DIMENSION ROOTD(250),INDAY(50),ROOTIN(50)
C
      J=2
      ROOTD(1)=ROOTIN(1)
      DO 10 I=2,215
      AI=I
      IF(I.GT.INDAY(J)) J=J+1
      ROOTD(I)=ROOTIN(J-1)+((AI-INDAY(J-1))/
     &(INDAY(J)-INDAY(J-1)))*(ROOTIN(J)-ROOTIN(J-1))
   10 CONTINUE
      RETURN
```

```
      END
C
C
C     ***********************************************************
C     *                                                         *
C     *  THIS SUBROUTINE CALCULATES THE YIELD REDUCTION USING AE/PE*
C     *  RATIO AND CROP SUCEPTABLITY FACTOR FOR DEFICIENT WATER   *
C     *  CONDITIONS.                                            *
C     *                                                         *
C     ***********************************************************
C
C
      SUBROUTINE YIELD(XX,CSD,YY)
      DIMENSION XX(250),SDD(20),SDI(30),CSD(20),SUMD(20)
C
C
      NP=17
      NDP=5
      SUMSDI=0.0
      SUMD(1)=0.0
      K=77
      WRITE(6,200)
  200 FORMAT('1',40X,'CROP MODEL CALCULATIONS',//////)
C
C
      DO 20 I=1,NP
      SUMDD=0.0
      L=I+1
      DO 10 J=1,NDP
      K=K+1
      SDD(J)=1.-XX(K)
      SUMDD=SUMDD+SDD(J)
      SUMD(L)=SUMDD
      WRITE(6,201)SDD(J),XX(K),SUMDD,SUMD(L)
  201 FORMAT(2X,4F10.3)
   10 CONTINUE
      IF(SUMD(L).LT.4.5) GO TO 11
      IF(SUMD(L).GE.SUMD(L-1)) GO TO 15
   11 SDI(I)=SUMDD*CSD(I)
      SUMSDI=SUMSDI+SDI(I)
      WRITE(6,202)SDI(I),CSD(I),SUMSDI
      GO TO 20
C
C
   15 SDI(I)=SUMDD*CSD(I)*1.5
      SUMSDI=SUMSDI+SDI(I)
      WRITE(6,202)SDI(I),CSD(I),SUMSDI
  202 FORMAT(//,50X,3F10.3)
   20 CONTINUE
      YY=100-1.22*SUMSDI
      WRITE(6,203)YY
  203 FORMAT(2X,F10.4)
      RETURN
      END
C
C
```

```
C ***********************************************************************
C *                                                                     *
C * THIS SUBROUTINE CALCULATES THE YIELD OF CORN DUE TO EXCESSIVE SOIL*
C * MOISTURE CONDITION.                                                 *
C *                                                                     *
C ***********************************************************************
C
      SUBROUTINE YIELDW(WT,CSW,YW)
C
      DIMENSION WT(250),CSW(5),SD(125),SDIW(125)
      INTEGER PDAY
C
C******* INITIALIZATION ***********
C
      PDAY=35
      SUMSDI=0.0
C
      DO 50 I=1,120
      WTD=WT(PDAY+I)/10.
      IF(WTD.GT.30.) GO TO 40
      SD(I)=30.-WTD
      IF(I.GT.80) GO TO 20
      IF(I.GT.42) GO TO 30
      SDIW(I)=SD(I)*CSW(1)
      SUMSDI=SUMSDI+SDIW(I)
      GO TO 50
C
   20 SDIW(I)=SD(I)*CSW(3)
      SUMSDI=SUMSDI+SDIW(I)
      GO TO 50
C
   30 SDIW(I)=SD(I)*CSW(2)
      SUMSDI=SUMSDI+SDIW(I)
      GO TO 50
   40 SD(I)=0.0
   50 CONTINUE
C
      IF(SUMSDI.LE.8.) GO TO 60
      IF(SUMSDI.GE.245.) GO TO 70
      YW=103.-0.42*SUMSDI
      GO TO 80
C
   60 YW=100.
      GO TO 80
C
   70 YW=0.0
      WRITE(6,200)SUMSDI,YW
  200 FORMAT(//////,5X,2F10.2)
   80 RETURN
      END
```

TABLE:E1 AN EXAMPLE OF COMPUTER OUTPUT OF PREDICTED RELATIVE YIELD FOR DIFFERENT SPACINGS.

YEAR 1982

SPACING MM	SUBSURFACE DRAINAGE YRD (%)	SUBSURFACE DRAINAGE YRW (%)	RELATIVE YIELD (%)	SUBSURFACE IRRIGATION YRD (%)	SUBSURFACE IRRIGATION YRW (%)	RELATIVE YIELD (%)
5000.0	53.52	100.00	53.52	100.00	100.00	100.00
10000.0	53.60	100.00	53.60	100.00	100.00	100.00
15000.0	53.89	100.00	53.89	100.00	100.00	100.00
20000.0	54.23	100.00	54.23	100.00	100.00	100.00
25000.0	54.62	100.00	54.62	100.00	100.00	100.00
30000.0	55.13	100.00	55.13	100.00	100.00	100.00
35000.0	55.63	100.00	55.63	99.87	100.00	99.87
40000.0	56.17	100.00	56.17	98.49	100.00	98.49
45000.0	56.61	100.00	56.61	96.03	100.00	96.03
50000.0	57.28	100.00	57.28	92.87	100.00	92.87
55000.0	58.12	100.00	58.12	89.95	100.00	89.95
60000.0	59.13	100.00	59.13	87.34	100.00	87.34
65000.0	60.22	100.00	60.22	84.79	100.00	84.79
70000.0	61.37	100.00	61.37	83.03	100.00	83.03
75000.0	62.55	100.00	62.55	81.83	100.00	81.83
80000.0	63.76	100.00	63.76	80.79	100.00	80.78

TABLE:E2 AN EXAMPLE OF COMPUTER OUTPUT OF PREDICTED RELATIVE YIELD FOR DIFFERENT SPACINGS.

YEAR: 1983

SPACING MM	SUBSURFACE DRAINAGE YRD (%)	SUBSURFACE DRAINAGE YRW (%)	RELATIVE YIELD (%)	SUBSURFACE IRRIGATION YRD (%)	SUBSURFACE IRRIGATION YRW (%)	RELATIVE YIELD (%)
5000.0	30.96	100.00	30.96	100.00	100.00	100.00
10000.0	32.41	100.00	32.41	100.00	100.00	100.00
15000.0	33.69	100.00	33.69	100.00	100.00	100.00
20000.0	35.56	100.00	35.56	100.00	100.00	100.00
25000.0	37.96	100.00	37.96	100.00	100.00	100.00
30000.0	40.82	100.00	40.82	100.00	100.00	100.00
35000.0	43.98	100.00	43.98	98.43	100.00	98.43
40000.0	47.22	99.24	46.86	94.84	95.67	90.73
45000.0	50.31	92.67	46.62	91.34	87.49	79.91
50000.0	53.18	84.58	44.98	88.06	82.58	72.72
55000.0	55.72	77.37	43.11	85.43	74.78	63.88
60000.0	57.97	66.03	38.28	83.31	64.54	53.77
65000.0	59.88	50.99	30.53	81.52	49.63	40.46
70000.0	61.01	39.69	24.21	79.53	38.45	30.57
75000.0	62.00	28.50	17.67	78.22	27.36	21.40
80000.0	62.86	17.99	11.31	76.89	16.94	13.03