MODELING OF WATER TABLE PROFILE FOR A SUBIRRIGATION SYSTEM

AND

EVALUATION OF RELIABILITY OF DRAINMOD FOR THE LOWER FRASER VALLEY

By

Shipra Agarwala

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ABSTRACT

Subsurface drainage and subirrigation were simulated in the Lower Fraser Valley of British Columbia under different water regimes with DRAINMOD and the results were compared with data obtained from conventional subsurface drainage and subirrigation field experiment at Boundary Bay in the Lower Fraser Valley. Predicted and measured water table depth were compared for 4 years (1985, 1986, 1987 and 1988), where 1986 was a normal year from the total rainfall standpoint. Model simulations of water table depth were closer to the actual value of wet season. The model overestimated water storage capacity of the soil profile. For the drier than normal year, 1985, water table depth was over predicted as evapotranspiration was over predicted by the model. When rooting depth for the dry year was increased, soil water withdrawal by ET increased and predictions for water table depth were significantly improved.

Laboratory experiment was performed to evaluate the shape of the water table under subirrigation and the time required for the profile to attain a stable state from a steady recharge. A slow transition from semi elliptical water table at the initiation of irrigation to a nearly flat water table profile at a stable state was observed. A linear relationship between capillary rise and water table elevation was observed.

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Chapter 1

INTRODUCTION

1.1 Background

The increasing need for crop production for the growing population is causing a rapid expansion and rehabilitation of irrigation and drainage throughout the world. Without the large areas of land that drainage and irrigation have made productive, it would not be possible to feed the present population. Irrigation and drainage influence the availability of water for plants and control the water content of the soil. The effective manipulation of soil moisture by proper irrigation and drainage management at the field level allows soil moisture to be brought to optimum effectiveness.

In some parts of the world, natural precipitation and drainage can maintain suitable soil moisture content, but most parts of the world are not so favorable. In semi-humid and humid areas due to uneven distribution of rainfall agricultural lands suffer both waterlogging and drought. They may have excess precipitation during a part of the year requiring drainage and on the other hand it may undergo drought requiring artificial irrigation. In recent years, an innovative method of improving the soil water environment by using subirrigation for crop production has emerged. Agricultural producers are installing or modifying subsurface drainage systems that are designed for drainage and used for subirrigation in the dry periods.

Subirrigation is one of the irrigation methods where the water supply for the crop comes from underneath the ground surface. Subirrigation involves the establishing and maintaining a water table near the bottom of the crop root zone from which water moves by capillary into the root zone. This process involves the continuous supply of readily available moisture to the crop roots. The type of subirrigation

treated herein is that of water table management for which the objective is to raise and maintain the water table at a depth sufficient to supply the water needs by the crop. Since subirrigation is dependent upon controlling the position of the water table, there must be some provision of getting water into the soil as needed. Subsurface drainage systems can sometimes be designed to perform both drainage and irrigation functions.

Subirrigation has been practiced in various scattered locations for many years (Clinton, 1948; Renfro, 1955). In recent years subirrigation has begun to be used on field scale in North and South Carolina and Florida in the U.S.A. (Kriz and Skaggs, 1973; Skaggs et al., 1972; Doty et al., 1975; Doty and Christenbury, 1979; Doering et al., 1982). Chieng et al., (1987) observed that successful irrigation can be practiced through a subsurface drainage system, however, no significant increase in yield was observed in the coastal area of British Columbia.

Several computer simulation models have been developed for simulating the performance of drainage systems (Feddes et al., 1978; Kanwar et al., 1983; Skaggs, 1978; Workman and Skaggs, 1991). The most difficult task facing the users of these models is to determine the accuracy of the models to estimate the changes in soil water regime brought about by drainage. Model validation involving field testing and evaluation of the existing models over a wide range of agricultural and climatic conditions is an essential element in modeling.

A water management computer model (DRAINMOD) was developed by Skaggs (1975), and it is still under improvement. It was developed for soils with shallow water tables and approximate methods are used to quantify hydrologic components: subsurface drainage, subirrigation, infiltration, evapotranspiration and surface runoff. It can be used to simulate various water management systems, namely - conventional drainage, controlled drainage, subirrigation and sprinkler irrigation (waste water irrigation). Conventional drainage in this study was defined as the drainage provided by evenly spaced parallel drains with a free (not submerged) outlet. Controlled drainage is used to conserve water and reduce pollutant loading from the drained lands, which is implemented by placing a control structure in the drainage outlet such that the water level in the outlet must rise to a set level or weir elevation before drainage can occur. Subirrigation

or water table management is similar to the controlled drainage mode. During periods of heavy rainfall the outlet water level may be lowered to facilitate rapid drainage and prevent crop damage due to excessive soil water and during dry period water is pumped into the drainage outlet to maintain the outlet water level at the set point or weir elevation. Surface or sprinkler irrigation is an option for the model which was originally intended to analyze drainage for wastewater irrigation.

Model simulation, can be used to determine the effectiveness of the proposed water-management scheme, effect of various water management alternatives and to select the optimum facility design. The model can be used for the comprehensive analysis of soil water movement on a field scale where most water management facilities are designed and installed as a single unit. The model has been verified for various regions in the U.S. and has subsequently been adopted by Soil Conservation Service, U.S. Department of Agriculture, for analyzing water management alternatives for soils subject to shallow water tables in humid regions.

The most important design parameters for a dual function subsurface drainage and subirrigation system are drain spacing and drain depth necessary to supply water during dry periods and remove excess water during wet periods. The drain depth depends on the soil profile, the discharge outlet and the availability of excavation equipment. The determination of drain spacing is based on soil properties, site parameters, crop requirements and climatological conditions.

Several theories have been developed for drain spacing calculations. They can be grouped into steady state and transient state flow conditions. A steady state exists when the boundaries and the flow rates of the system do not change with time, otherwise a transient state exists. Steady state seldom occurs under actual field conditions. Transient or non-steady conditions occur when groundwater table fluctuates with time, therefore, the hydraulic head is changing constantly. Due to their simplicity, steady state theories are commonly used in agricultural drainage design. In cases where soil water table fluctuation are to be considered, more realistic non-steady state theories should be used.

Richards equation (Equation 2.1) for two dimensional saturated and unsaturated flow was solved numerically (Tangs and Skaggs, 1977). Skaggs (1991) modeled water table response to drainage and subirrigation by solving Boussinesq equation subject to radial flow condition near the drain (Equation 2.4). While there have been numerous theoretical solutions for subsurface drainage and subirrigation, no experimental evaluation of the water table shape has been done.

This study will assess the feasibility of the model to be used in the LFV to simulate subsurface drainage and subirrigation. The simulated results will be compared to the measured data from the field experiments. The shape of the water table under subirrigation and the time to attain a stable state will be investigated by using a drainage soil tank.

1.2 Objectives

Specifically the objectives of the study are :

(1) To evaluate the shape of the water table profile and the time needed to obtain a flat or stable water table profile using a laboratory experimental setup. The study will focus on the transient response of the water table during the initial period of subirrigation, for a initially horizontal water table profile.

(2) To develop a mathematical relationship between capillary rise and water table elevation.

(3) To simulate subsurface drainage and subirrigation in the Lower Fraser Valley (LFV) of British Columbia under different water management regimes with DRAINMOD and compare the results with data obtained from full scale field experiment.

(4) To evaluate the reliability of using DRAINMOD for estimating the performance of subsurface drainage and subirrigation in the LFV through comparison of simulated and actual data.

Chapter 2

REVIEW OF LITERATURE

Water movement in the soil is probably the most complicated process in the hydrologic cycle. Much research on both saturated and unsaturated flow has been conducted by hydrologists and soil scientists over the past few decades. Until recent years, principles, possibilities and limitations of subirrigation had not been studied intensely. Nevertheless, investigations show that subirrigation systems do work satisfactorily under certain conditions (Criddle and Kalisvaart, 1967).

Subirrigation depends on creating an artificial water table and maintaining it at some predetermined depth below the ground surface. Subirrigation is drainage in reverse. Moisture reaches the plant roots through capillary movement upward from the water table (Fox et al., 1956). This process provides a continuous supply of readily available moisture to the crop roots. Subirrigation requires a rigid control over the depth of water, otherwise the depth can become too small or too great and either retard growth or stop it completely. Raising the water table too soon or controlling the water table at a shallow depth below the soil surface will also discourage root growth, an effect which can make the crop more susceptible to drought later. For good control over the water table and to reduce downward water movement, a shallow impermeable layer below the rooting depth is desirable. High water table and poor drainage creates excessive soil water conditions and severely limits field equipment activities, restricts crop root growth and subsequent growth. Holding the water table too high will also encourage denitrification which could result in a nitrogen deficiency later in the season or increase the use of fertilizer.

The most critical factor in the design of subirrigation system is the determination of drain spacing and depth necessary to supply water during dry periods. Required drain spacing depends on soil parameters such as hydraulic conductivity, profile depth and on water table depth that should be maintained

during the growing season. The optimum water table depth is a function of the soil properties, crops to be grown and the climatological factors which are a function of location. The best crop response for a drainage and subirrigation system will be realized with the system that is specifically designed to serve both purposes. A system whose design is focused on drainage alone is not adequate to function in both modes.

Many researchers including Fox et al., (1956) and Cheing (1983) pointed out that in order for a subirrigation system to be practical, certain natural conditions must exist. Since the practice involves actual management of water table, either an impermeable layer or a permanent water table should exist at rather shallow depth to prevent excessive loss. Further, it is necessary that the topography be nearly flat. Another important requirement is that the soil should have a high hydraulic conductivity so that a reasonable spacing of drains will be provide for both drainage and subirrigation.

2.1 Subirrigation Water Movement

Water movement is a basic process occurring in the soils. It is involved in almost every other process, e.g., water movement from surrounding soils to roots to maintain a constant supply of water to the crops.

The water table position and shape during subirrigation are shown schematically in Figure 2.1. The drains are located at distance d above the impermeable layer and distance L apart. The hydraulic head in the drain is maintained at h_0 above the impermeable layer so that the water level in the ditch or the pressure head in the drain is y_0 above the drain.

Water moves laterally from a drain tube or open ditch to replenish the water lost vertically from the profile by evapotranspiration. The zone above the water table is unsaturated except the small capillary fringe which may exist in some soils. As hydraulic conductivity decreases with water content, there is little lateral movement above the water table, most of the lateral movement occurs in the saturated zone. Thus it maybe stated that water moves laterally into the profile by saturated flow, then vertically from the water

table by unsaturated flow to the root zone or to the surface where it leaves the profile as evapotranspiration. Water movement in the unsaturated zone occurs both in liquid and vapor phases.

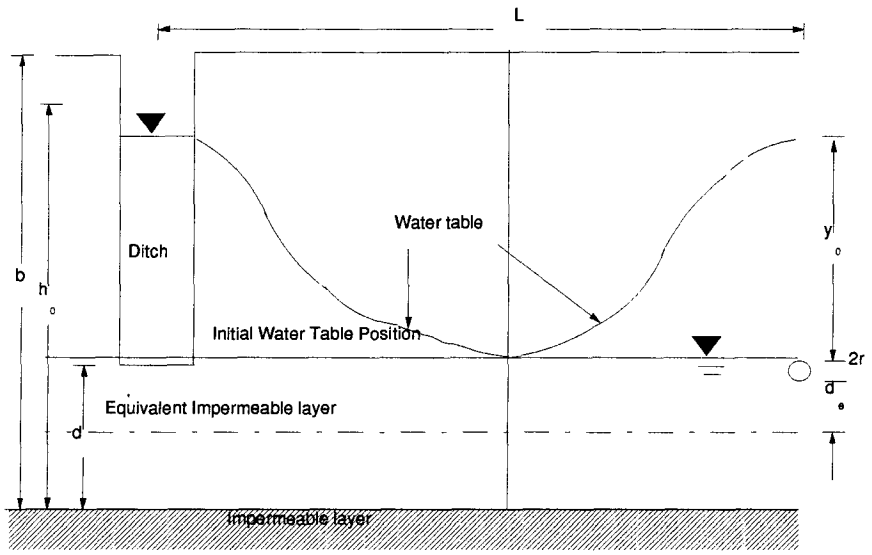

Figure 2.1 Schematic of subirrigation from lateral ditch and drain.

Conditions of steady two-dimensional unsaturated flow of moisture in soil that maybe of importance to agricultural engineering are encountered in problems of subsurface drainage, subirrigation, canal seepage, ground water recharge, etc. In the past, not much attention has been paid to the unsaturated flow phases, perhaps mainly because of the complicity of their quantitative evaluation. As steady state seldom exists under actual field conditions, solutions using transient state condition should be used.

Under surface and sprinkler irrigation systems, soil water in the root zone is continually varying. Immediately following irrigation, the soil is at or near field capacity. Under subirrigation the water content above the ground water table in the same soil will vary as shown schematically by line *a* and *b* in Figure 2.2 and Figure 2.3.

Two-dimensional water movement for subirrigation in a uniform soil can be characterized by the relationship proposed by Richards (1931) and given in Equation 2.1:

$$c(h)\frac{\partial h}{\partial t}=\frac{\partial}{\partial z}\left[k(h)\frac{\partial h}{\partial z}\right]+\frac{\partial}{\partial x}\left[k(h)\frac{\partial h}{\partial x}\right]+\frac{\partial k(h)}{\partial z}-s(h) \tag{2.1}$$

where,

h	=	soil water pressure head, which is negative in unsaturated soils,
k(h)	=	hydraulic conductivity function,
t	=	time,
C(h)	=	d (θ)/dh, the soil water capacity which is determined from soil water characteristics,
θ	=	volumetric water content, and
S	=	water uptake by roots (by volume).

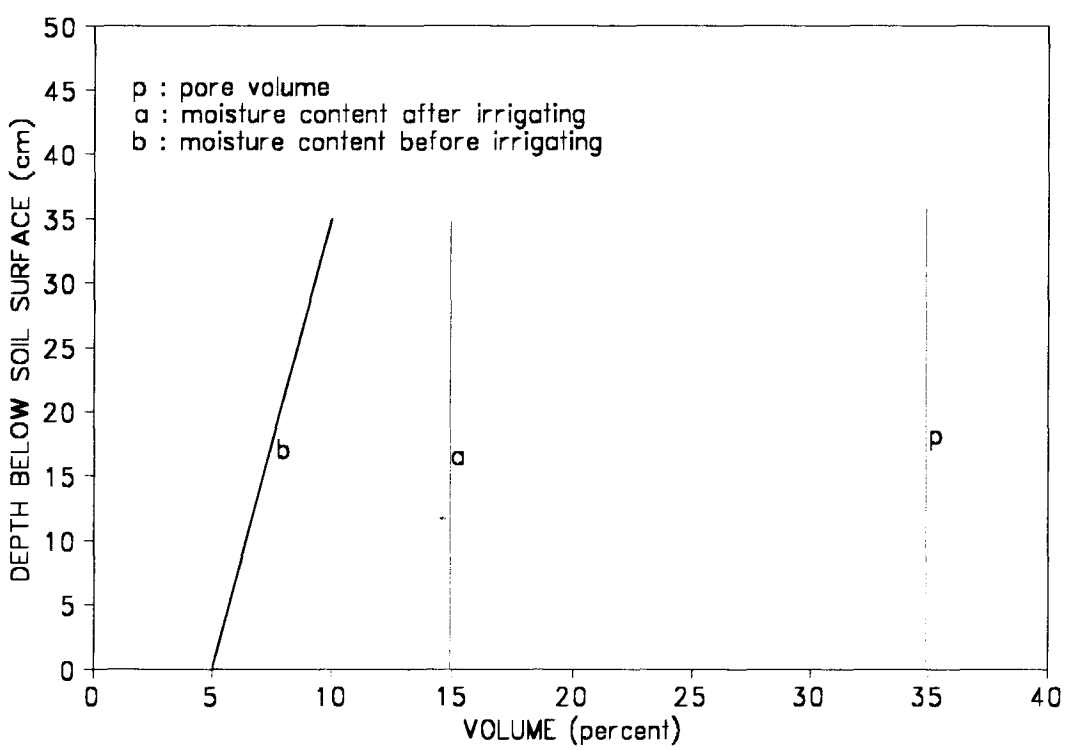

Figure 2.2 Water content in a surface irrigated coarse sandy soil (Criddle and Kalisvaart, 1967).

For saturated conditions it reduces to Laplace equation given in Equation 2.2:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial z^2} = 0 \tag{2.2}$$

Richards equation can be used to describe the soil moisture changes during short periods of time, when standard meteorological, soil, and plant parameters are known.

Many single event models have been developed over the past 40 years for determining depth and spacing of drainage ditches or tubes. These models or design equations have been derived for both steady and transient conditions (Van Schilfgaarde, 1974). While some are based on potential flow theory (e.g., Kirkham, 1964), the most frequently used equations employ the Dupuit-Forcheimer (D-F) assumptions.

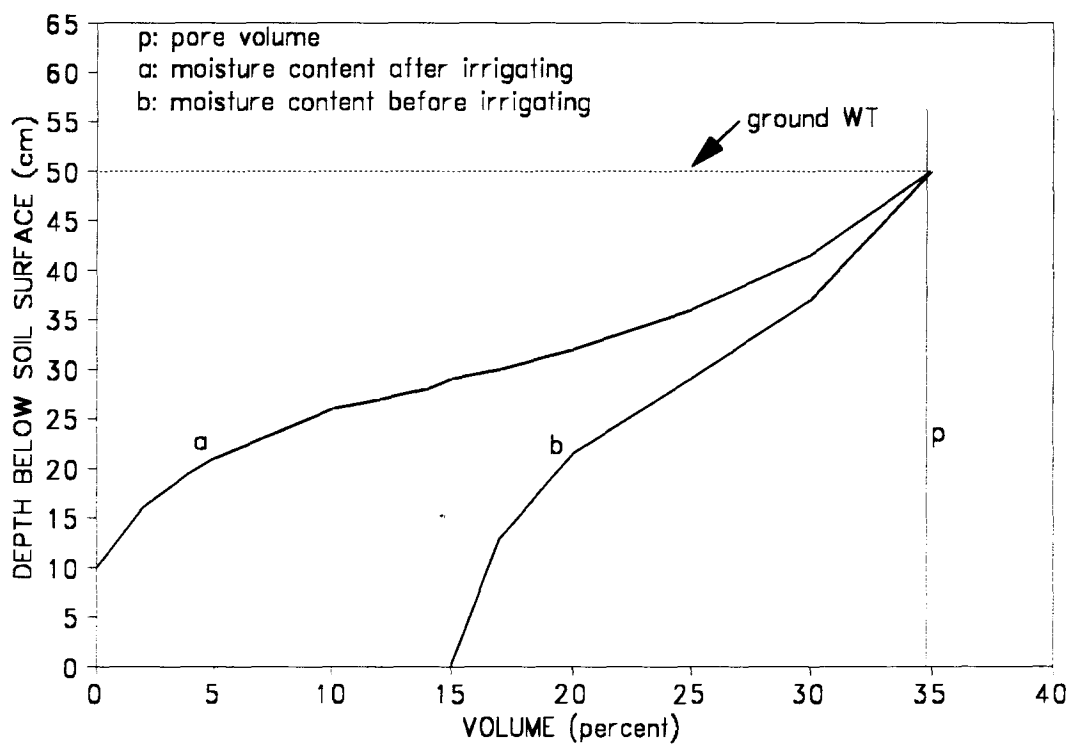

Figure 2.3 Water content above the groundwater table in subirrigated coarse sandy soil (Criddle and Kalisvaart, 1967).

Examples for steady state are the equations of Hooghoudt (Van Schilfgaarde, 1974), Donnan (1959), Ernst (1978) and Wu and Cheing (1991). Van Beers (1976) reviewed several modifications of Hooghoudt and Ernst equations.

Equations for transient conditions include those developed by Glower (Dumm 1954, 1964), Van Schilfgaarde (1963), Guyon (1962), Uziak and Chieng (1988) and Uziak and Chieng (1989). Similar equations have also been derived for subirrigation by Fox et al., (1956) and Ernst (1975) for steady state and Skaggs (1973) for transient conditions.

2. 2 Water Table Movement and Profile

Design of subirrigation and drainage systems for water table control requires characterization of water table under various initial and boundary conditions. There are hydraulic head losses due to convergence and divergence which must be accounted for in characterizing water movement during subirrigation and drainage. Most of the methods used for characterization of the water table movement make an implicit assumption that water movement above the water table can be neglected (Skaggs, 1973). Vachaud et al., (1972) demonstrated experimentally that for drainage the outflow volume was over predicted and the water table drawdown rate was under predicted when all the flow was assumed to occur below the water table.

Experimental study by Tang and Skaggs (1977) have shown that Richards equation can be used to describe water table movement and inflow rate for subirrigation in a uniform soil.

Tang and Skaggs (1980), reported that Richards equation could be used for transient two dimensional saturated-unsaturated flow in two layered soil for subirrigation. However, these methods required D-F assumptions, neglected unsaturated flow and were limited to homogenous soils.

Approximate methods for predicting the water table rise during subirrigation were presented by Skaggs (1973). Galganov (1991) concluded that under subsurface irrigated conditions, in a sandy soil, the shape of the water table above the subsurface drains is similar to the initial shape of the water table where the initial shape is the water table shape under controlled drainage prior to the initiation of irrigation.

Field studies (Skaggs, et al., 1972) have shown that for initially draining profiles the water table elevation midway between the drain continues to recede even after subirrigation conditions have been applied. Lag time of as much as two and a half days before the water table begins to rise at the midpoint between the lateral drain lines have been observed.

Skaggs, et al., (1972) reported that the upward flux was not uniform during the initial period of subirrigation when the water table at the midpoint was stationary or still moving down. Neither was it uniform for the large times when water table directly above the drains has reached the control water level in the outlet ditch, but is still rising at the outlet.

Skaggs, et al., (1972) derived the equation given as Equation 2.3 using methods of Bouwer and Van Schilfgaarde (1963) for the upward movement of water table during subirrigation.

$$\frac{dm}{dt} = \frac{u}{f} \tag{2.3}$$

where,

m	=	the height of water table above the center of the drain at the midpoint between the drains,
t	=	time,
u	=	instantaneous subirrigation rate, and
f	=	drainable porosity.

Except for initial lag period, the equation can be used to accurately predict the water table rise midway between the drains.

The exact description of the water table would require solving the Laplace equation for combined saturated and unsaturated flow by analog or numerical methods (e.g., Bouwer or Sewell and Van Schilfgaarde). However, Fox et al., (1956) used the D-F assumption to derive an approximate algebraic expression describing the water table.

Assuming steady state conditions, drain spacing was found not to be the cause for water table elevation variation when distance between subsurface drain pipes is sufficiently small. The major reason for water table elevation variations was shown to be the increase in the water table elevation along the laterals longitudinally (Galganov, et al., 1989).

Wells and Skaggs (1976) developed an equation for one-dimensional (vertical) water movement for subirrigation in layered soil columns. However, subirrigation as practiced in the field involves two-dimensional flow so a one dimensional approach is not sufficient for designing field systems.

Probably Boussinesq equation is the most frequently used methods for describing subirrigation and drainage under transient conditions. Boussinesq equation neglects flow in unsaturated zone and is based on continuity, Darcy's law and D-F assumptions. D-F assumptions do not hold good in the vicinity of the drains due to the convergence of streamlines near the drain. Water drained from the unsaturated zone was assumed to be instantaneously released as water table falls. Boussinesq equation is given as Equation 2.4.

$$\frac{\partial h}{\partial t} = k \frac{\partial}{\partial x} + \left[h \frac{\partial h}{\partial \mathrm{x}} \right] + e \qquad (2.4)$$

where,

h = height of water table above impermeable layer,

x = horizontal position,

t	=	time,
k	=	lateral saturated hydraulic conductivity,
f	=	drainable porosity, and
e	=	rate of vertical infiltration into saturated soil.

Skaggs (1991) predicted water table profile as shown in Figure 2.4 using solutions to Boussinesq equation with the equivalent depth and radial flow boundary conditions for drain tubes with re = 5 mm, L = 15 m, d = 1 m and ET = 4.8 mm/day.

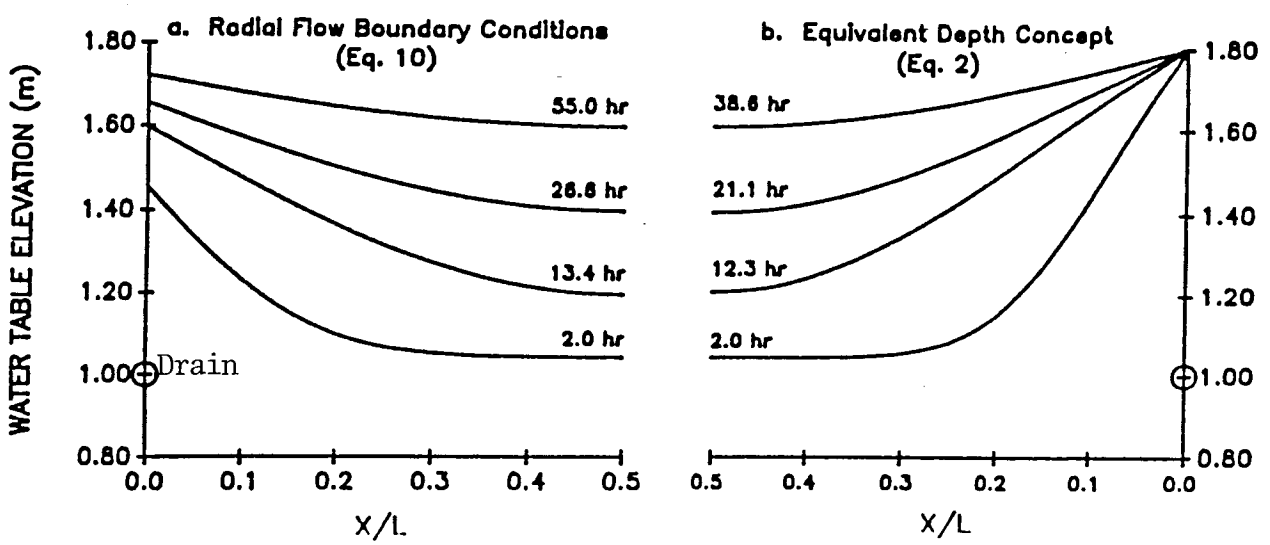

Figure 2.4 Subirrigation water table profiles predicted by solutions to Boussinesq equation. Values on the curves are time after subirrigation was initiated.

Conventional methods of predicting water table draw down due to drainage usually assume that the drain tube is completely permeable and offers no resistance to entry of water. However, the reduction of inflow due to finite openings in the drains has long been recognized.

Prasher et al., (1989) found that divergent head loss is the most significant head loss in a subirrigation system and suggested that water in the lowest chamber in the subirrigation system should be

kept higher than the desirable water level in the soil to counteract the divergent and other head losses. This extra height will depend on the type of soil, soil profile, hydraulic conductivity of the soil, location of the impermeable layer, etc.

Soultani (1985) attributed the increase in water table elevation to the decrease in saturated hydraulic conductivity with increase in soil depth.

2.3 Upward Water Movement from The Water Table

Capillary flow is an important factor affecting subsurface drainage and subirrigation. Soil capillary action and diffusion draw water upward from the water table to provide a zone with suitable soil moisture for root growth.

The rise of water in the soil from the free water surface has been termed as capillary rise. This term is derived from the capillary model which regards soil analogous to a bundle of capillary tubes predominantly wide in case of sandy soils and narrow in case of a clay soil. The capillary fringe is commonly defined as the soil zone in which pores are saturated, but water pressure is less than atmospheric. The free water surface here being the water table. The importance of unsaturated flow in the upper soil profile in case of subsurface drainage is demonstrated by Bouwer (1959) where capillary fringe extended into the permeable top soil.

Silin-Bekchurin (1958) suggested a capillary rise of 2 - 5 cm in coarse sand, 12 - 35 cm in medium sand, 35 - 70 cm in fine sand, 70 - 150 cm in silt and more than 200 cm in clay soil. Physical factors determining the extent of capillary rise include soil pore size and conformation, degree of saturation, surface tension and pressures in the water relative to atmospheric pressure (Spangler, 1960).

The thickness of capillary fringe can be estimated by the formula given by Polubarinova-Kochina (1952):

$$h_c = \frac{0.45}{d_{10}} \frac{1-n}{n} \tag{2.5}$$

where,

h_c	=	height of capillary fringe in cm,
d_{10}	=	effective particle diameter in cm, and
n	=	total porosity

The rate at which water can be transferred upward from the watertable depends on the unsaturated hydraulic conductivity function, the soil water pressure heads in the root zone or at the soil surface and the water table depth.

Assuming vertical flow in the unsaturated zone, the flux q_Z maybe expressed as Equation 2.6:

$$q_z = k(h)\frac{dh}{dz} + k(h) \tag{2.6}$$

where,

k(h)	=	unsaturated hydraulic conductivity function,
z	=	vertical distance from soil surface and
h	=	height of water table above impermeable layer (function of the horizontal position).

The steady rate of capillary rise and evapotranspiration depend on the depth of the water table and the suction at the soil surface. The height of capillary rise in experimental fields has been observed to be approximately 20 cm (Chieng, 1987). For any given water table depth, the rate of upward movement will increase with soil water suction at the upper boundary. The soil surface and average root depth has been taken as the upper boundary for fallow periods and during the growing season, respectively. A

subirrigation system should be so designed that this suction in the root zone does not exceed the limiting value.

The actual height of capillary rise from the water table can vary widely depending on the textural and humus content differences in the soil profile and on the depth of the water table (Bloeman, 1980).

Field experiments and theoretical analysis have been carried out by many researchers to investigate the behavior of dual-function systems. However, no work has been done to predict the height of capillary rise and its relation to the height of ground water table as well as the stable capillary response time.

2.4 DRAINMOD

DRAINMOD is a computer simulation model for describing the performance of drainage system on a continuous basis over a long period of climatological record. The model predicts, on a day to day or hour by hour basis surface runoff, water table position, drainage outflow, soil water content and evapotranspiration in response to a given input climatological data, soil and crop properties and design parameters for a given water management system. DRAINMOD was developed for soils with shallow water tables and is proposed as a tool for optimizing the design of surface and subsurface drainage systems which may include subirrigation or irrigation water applied to the surface. Approximate methods are used to quantify hydrologic components: subsurface drainage, subirrigation, infiltration, evapotranspiration and surface runoff. Equations developed by Hooghoudt (Luthin, 1978), Kirkham (1957) and Ernst (1975) are used to calculate drainage and subirrigation rates and infiltration rates are predicted by Green and Ampt (1911) equation.

Briefly the model is based on a water balance for a thin section of the soil with a unit surface area which extends from the impermeable layer to the surface and is located midway between the adjacent drains.

The same principle has been used by other investigators to analyze subsurface drainage systems (Chieng et al., 1978; Holsambre and Sinai, 1980). The water balance is computed on an hourly basis by using approximate methods to calculate infiltration, drainage, subirrigation and evapotranspiration. The technical basis of the model is described in the DRAINMOD reference report: Methods for design and evaluation of drainage - water management systems for soils with high water tables, prepared for the USDA, Soil Conservation Service by Dr. R. W. Skaggs, North Carolina State University, Raleigh, North Carolina, U.S.A.

The simulation maybe used to determine the effectiveness of the proposed water management scheme by evaluating trafficability and adverse moisture conditions during the crop growing season, effect of various water management alternatives and to select the optimum facility design. DRAINMOD has been used as a tool for optimizing the design of surface and subsurface drainage systems, including a routine for irrigation, which maybe either surface or subsurface.

It can be used for the comprehensive analysis of soil water movement on a field scale where most water management facilities are designed and installed as a single unit.

DRAINMOD can be used to simulate the performance of a given system design and evaluate the appropriate objective functions such as number of working days, number of dry days, stress factor, such as soil excess water (SEW_{50}) for each simulation year.

DRAINMOD has been verified for different regions of the U.S. some of which are humid, from field scale drainage experiments in North Carolina (Skaggs, 1982), Ohio (Skaggs et al., 1981), Florida (Rogers, 1985), Louisiana (Gayle et al., 1985; Fouss et al., 1987), Virginia (McMahan et al., 1988), Michigan (Belcher and Merva, 1987) Indiana (Skaggs, 1982) and Belgium (Susanto et al., 1987).

Chang et al.,(1983) evaluated the model for irrigated agriculture for the semiarid climate in California and concluded that water table elevations predicted by DRAINMOD agreed reasonably well

with field situations and when the water table drawdown exceeded 150 cm, the model tended to overestimate the depth of the water table. Chang et al.,(1983) reported a standard error of 6 to 23 cm and an average deviation of 4 to 19 cm for the comparison of predicted and measured water table elevations.

Skaggs (1982) reported that in North Carolina, comparison of the predicted and measured water table elevations were in excellent agreement with the daily water table depths having standard errors of estimate ranging from 7.5 to 19.6 cm and an absolute deviation of only 8.1 cm.

Fouss et al., (1987) simulated subsurface drainage in the lower Mississippi valley with DRAINMOD and concluded that the simulations were more accurate for years with above normal rainfall and frequent shallow water table, than for years with below normal rainfall and water table depth below drain depth for extended periods.

Skaggs et al., (1981) evaluated DRAINMOD for north central Ohio and concluded that predicted surface runoff and subsurface drainage volumes were in good agreement with measured values. He reported a coefficient of determination of 0.94 between measured and predicted outflow volumes.

Workman and Skaggs, (1991) reported an average deviation of 14.4 cm between the simulated and observed water table depths and an excellent agreement between the simulated and observed water table depths.

Snow, snow melt and the effect of frozen conditions on soil water processes are not considered in DRAINMOD. Therefore the application is confined to periods when soil is not frozen.

Chapter 3

EXPERIMENTAL LAYOUT

3.1 Background

The field experiment was carried out in the Lower Fraser Valley (LFV) of the province of British Columbia. The LFV is a very important agricultural area. Although it makes up less than one tenth of the improved land in B.C., it generates more than half the dollar values of the farm sales (de Vries, 1983). The lowland makes up 90% of the total improved farmland area in the valley.

The LFV is a humid region with an annual precipitation of about 1100 mm (Hare and Thomas, 1974). The annual evapotranspiration is about 550 mm. The annual water surplus is about 550 mm with most of the precipitation during the winter season which results in a water surplus from October to April, and water deficit from May to September as shown in Figure 3.1. Therefore, removing excess water from the field is the systems most important role. The topography of the land is low and flat with poor natural drainage conditions. Thus artificial land drainage is the traditional water management approach for profitable crop production.

Subirrigation is the most recently adopted irrigation method and is receiving more and more attention due to low labor cost, low energy requirements and possible low leaching of (fertilizer) nutrients. Thus many researchers and farmers have been trying to use the existing subsurface drainage system for irrigation.

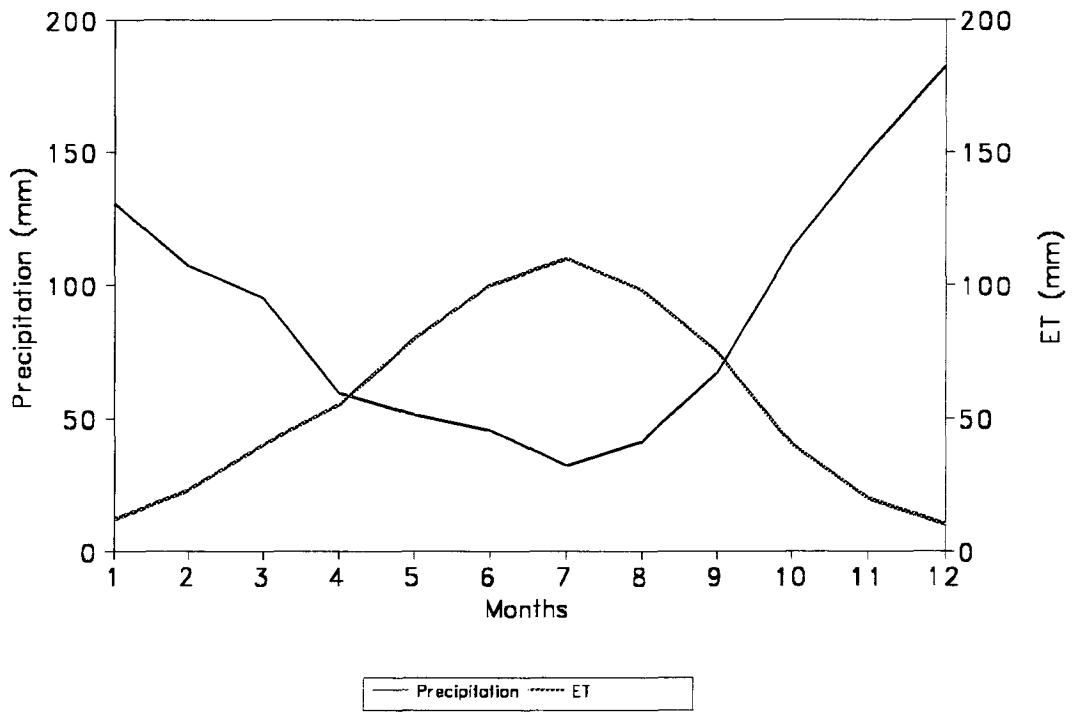

Figure 3.1 Mean monthly precipitation and evapotranspiration (based on 30 years of data).

3.2 Experimental Layout

3.2.1 Laboratory Experiment Layout

The laboratory experiment was carried out at the Soil and Water Engineering Laboratory at The University of British Columbia. The experiment setup is shown in Figure 3.2 and Figure 3.3. A drainage soil tank was designed and built to make an experimental study of the water table profile, elevation and the capillary rise of the subsurface drainage system in the subirrigation mode.

The dimensions of the tank were 4.88 m (16 ft) long, 1.22 m (4 ft) wide, and 1.22 m (4 ft) high. One side of the tank was made of Plexiglas to facilitate the visual observation of the water table profile and 8 peizometric tubes were placed on the other long side to observe the water table elevation. Lateral drain tubes (100 mm nominal diameter corrugated polyethylene plastic) were located 0.9 m below the soil surface

and at a spacing of 2.0 m. The laterals were installed on a 1 percent slope along the laterals and there was no side slope. A ditch was simulated by connecting a reservoir to the drain inlets. The water level in the reservoir was controlled during subirrigation by means of an overflow pipe fitted into the reservoir.

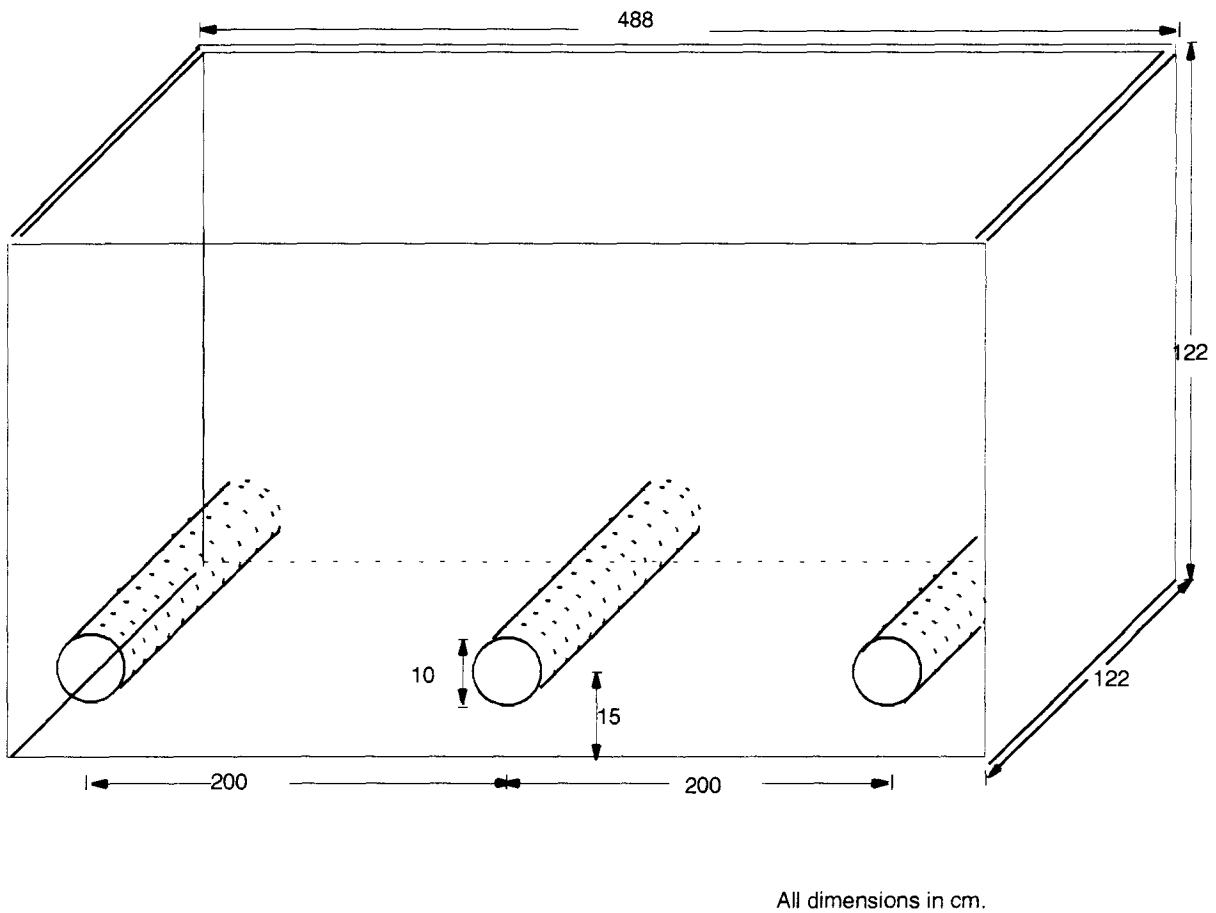

Figure 3.2 Laboratory experiment setup (front view).

The setup can be used to run different spacings. A 2 m spacing was obtained with all the three drains in the subirrigation mode. The 4 m spacing combination was obtained by using only the two drains at the ends. The 4.88 m spacing was obtained by using only the center drain and a 8 m spacing was obtained by using only one of the drains at the end. The unused drains were closed and no subirrigation or drainage was allowed to occur.

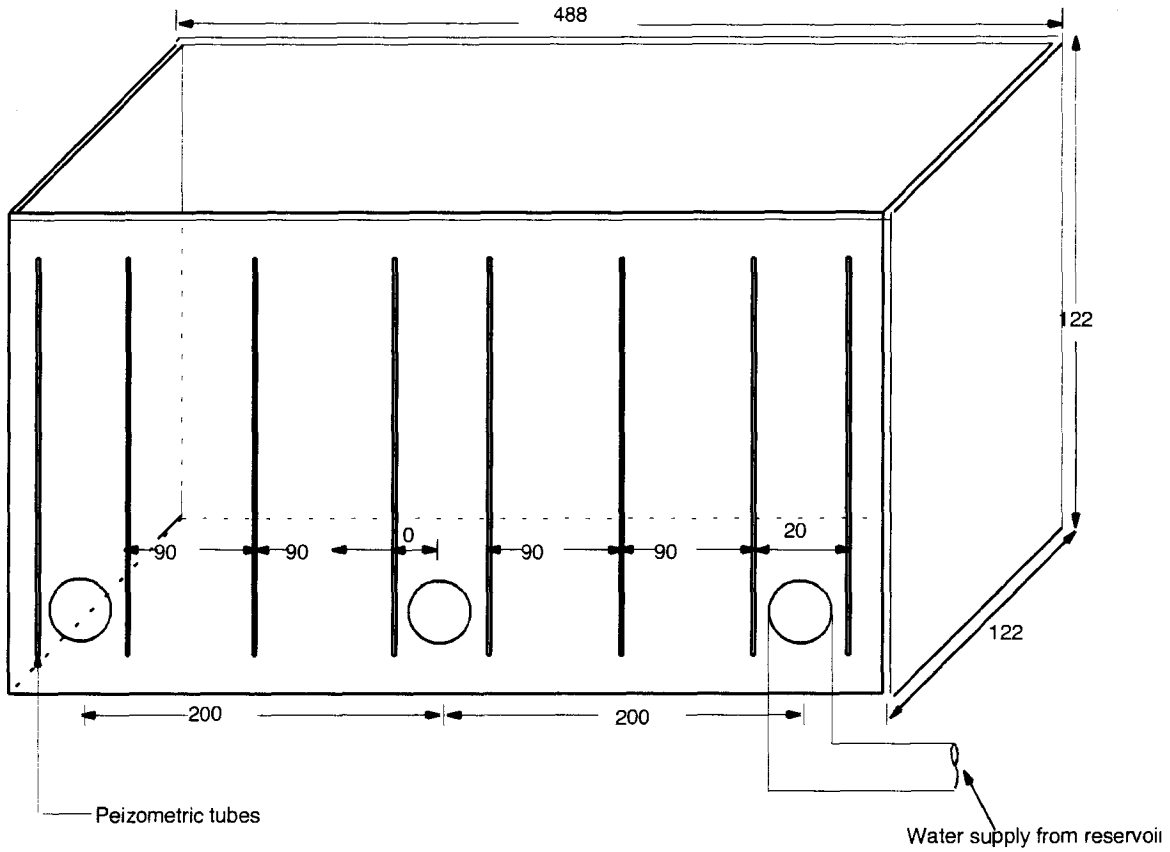

Figure 3.3 Laboratory experiment setup (rear view).

Fine sand was used as the soil medium to conduct the experimental study. Experiment was conducted for fallow conditions. A constant hydraulic head was used to force water from the laterals into the soil profile. Experiment was conducted for various combinations of drain spacing and water table elevations as listed in Table 3.1. Soil physical and hydraulic properties (i.e., hydraulic conductivity, soil water characteristics, bulk density and particle size distribution) were evaluated for developing the model. The transient response of the water table was studied during the initial period of subirrigation when the water level is raised in the outlet for a horizontal water table profile.

An additional Plexiglas soil column as shown in Figure 3.4 was used to determine the capillary rise above the water table as capillary rise could not be easily observed visually in the soil tank. The

dimensions of the column were 1.8 m high with an internal diameter of 14.5 cm. The column was placed in a tank of water with a layer of gravel at the bottom to allow the movement of water into the sand column. The height of sand in the column was 1.0 m to simulate the same conditions as in the soil tank. Dry fine sand was used as the soil medium to observe the capillary rise. Capillary rise for different water table heights was observed.

Table 3.1 Combinations of drain spacing and hydraulic head.

Drain spacing	2 m	4 m	4.88 m	8.88 m
Hydraulic head	70 cm	70 cm	70 cm	80 cm
Hydraulic head	85 cm	85 cm	75 cm	95 cm
Hydraulic head	95 cm	95 cm	90 cm	105 cm

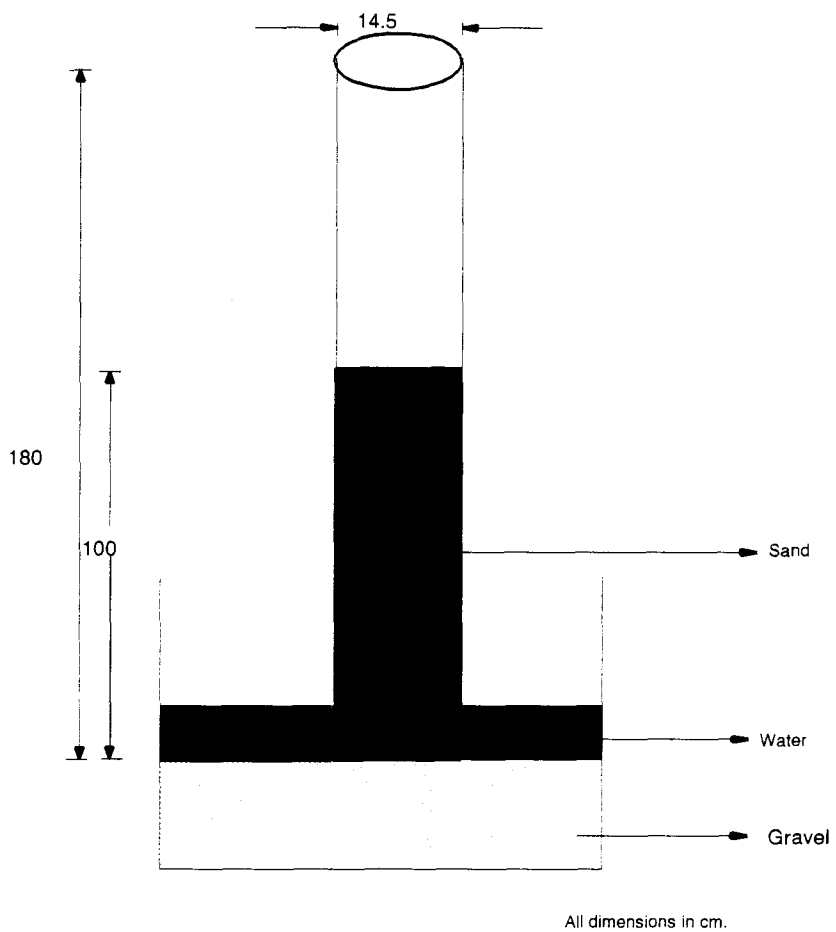

Figure 3.4 Experimental Setup for Capillary Rise

3.2.2 Field Experimental Layout

The experimental site was located at Boundary Bay, Delta, British Columbia in the LFV. The field had a low-lying topography with an elevation of 1.2 m above the mean sea level. The soil was classified as Ladner series, a humic gleysol. The soil developed on moderately fine to fine textured deposits of both marine and fresh water origin, overlying sandy deposits at a depth of over 100 cm (Luttmerding, 1981). Surface and subsurface soil textures varied from silty clay loam to silty loam. The particle size distribution curve for the soil was generated from data reported by Chao (1987) and is shown in Figure A.3 in Appendix A The particle size distribution curve shows a weathered uniform soil. The drainage condition of the land was moderately poor to poor (Driehuyzen, 1983).

Four water management regimes were studied. The size of each treatment plot was 4200 m^2 , 100 m long and 42 m wide. The drainage setup for each plot consisted of three parallel drain pipes installed at an average depth of 1.1 m from the soil surface. Corrugated and perforated polyethylene drains of 100 mm nominal diameter were installed with a spacing of 14 m and length of 100 m. The drains were installed on a parallel pattern in east-west direction emptying into a nonlined earthen ditch at the east end. The experimental research plot layout is shown in Figure 3.5.

A non-lined ditch was used as drain collector. The drainage ditch was divided into three segments and each segment was interconnected with plastic pipes at the bottom. The water table in each segment could be controlled separately with overfow standpipes for subirrigation. The collector ditch is emptied into the main ditch, the highway ditch along 72nd street, using a pump. The water control system is shown in Figure 3.6

The four water management regimes were:

1. **Regime A**: subsurface drainage at all times (i.e., water table was controlled at or below the drains).

2. **Regime B**: subsurface drainage during periods of excess precipitation and subirrigation during periods of moisture deficit by maintaining the water table at 60 cm below the soil surface.

3. **Regime C**: subsurface drainage during periods of excess precipitation and subirrigation during periods of moisture deficit by maintaining the water table at 30 cm below the soil surface.

4. **Regime D**: no subsurface drainage and subirrigation at anytime of the year (i.e., control plot).

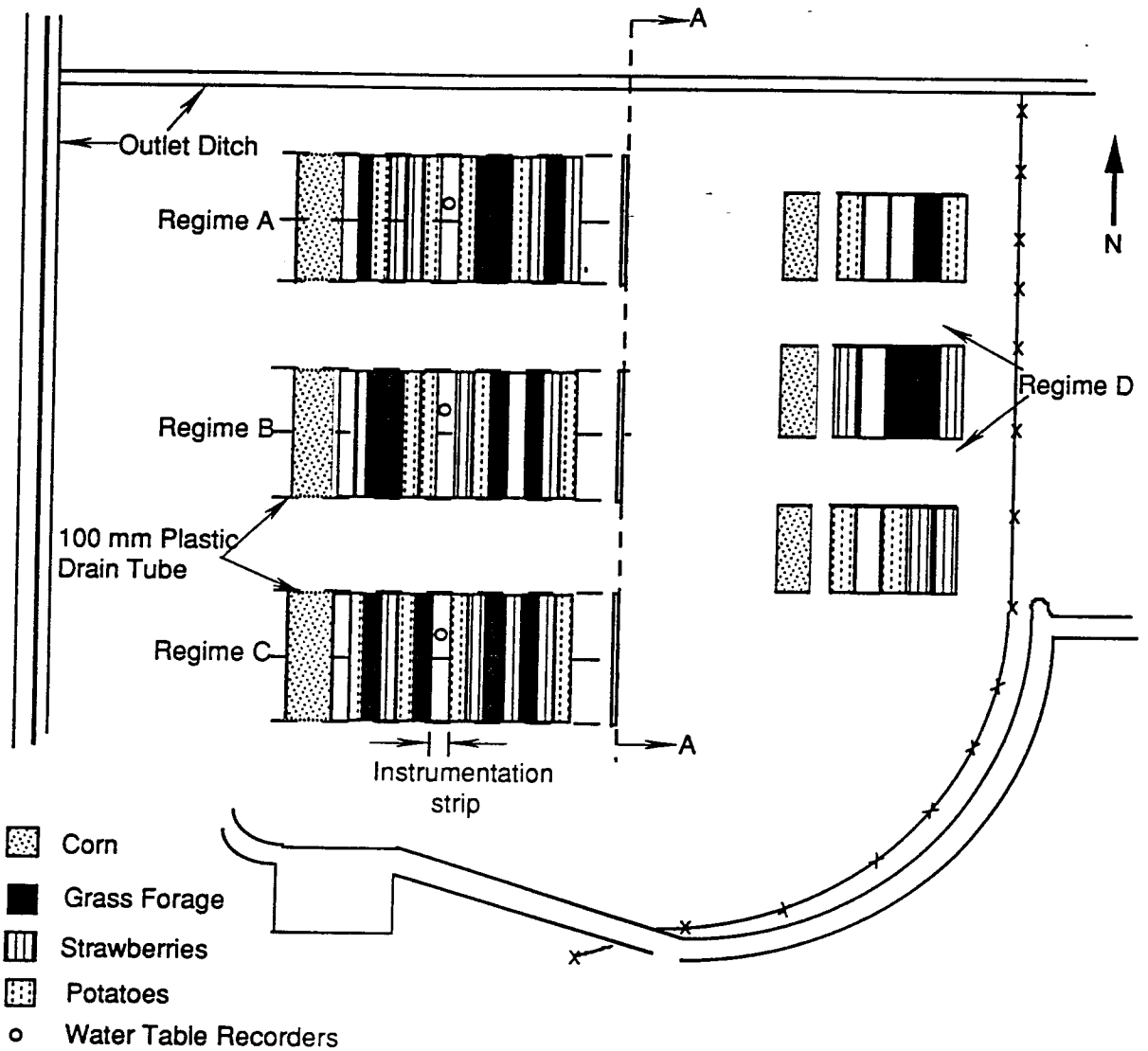

Figure 3.5 Experimental plot layout.

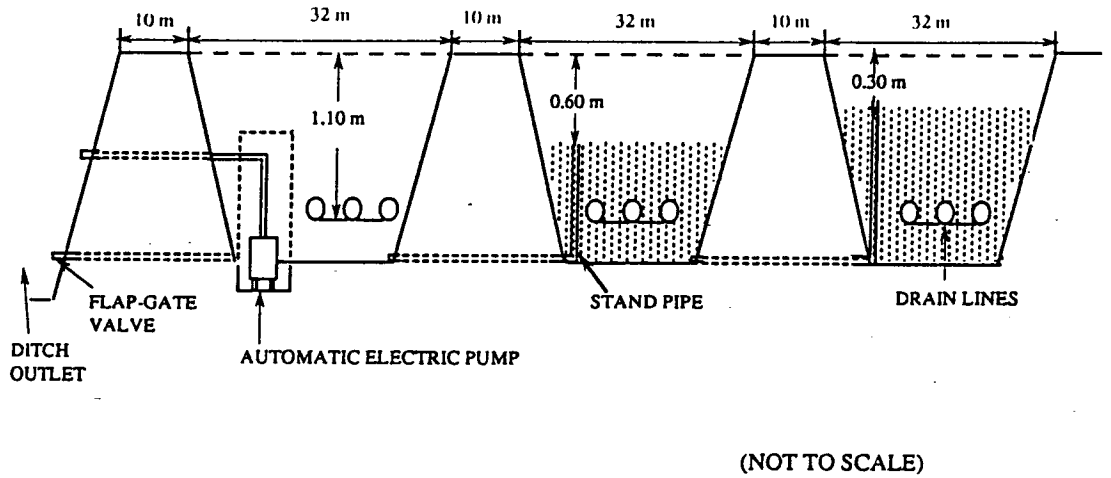

Figure 3.6 Water control system for the field experiment.

From different studies done in the Fraser Valley it has been determined that the water table must be at least 50 cm below the soil surface within 48 hours after a storm rainfall event has ceased so that crop and soil structure damages are minimized (B.C. Agricultural Drainage Manual, 1986).

Based on the above guidelines, the water tables in the study were maintained at 30 and 60 cm below the soil surface respectively in the two soil regimes to cover the lower and upper ranges of minimum water table depths to avoid reduction in crop yield and trafficability. Subirrigation operations were maintained throughout the summer and early fall months when periods of water deficit were prevalent.

Two basic criteria were considered for operating the water control system. Primarily the criterion for subsurface drainage was to keep the water table low enough such that the "sum of excess water" (SEW_{50}) value did not exceed 200 cm during the period from 1st of November to the 31st of March. The second criterion was to obtain trafficability of the land during early spring from 31st of March to 1st of May. Wooley (1965) concludes that most agricultural crops grow well if the upper 37.5 cm of the soil is well drained. SEW_{50} is calculated by Equation 3.2:

$$SEW_{50} = \sum_{i=1}^{N} (X - x_i) \tag{3.2}$$

where,

X	=	water table depth to be maintained, cm,
x_i	=	water table depth on day i, cm and
N	=	number of days in the growing season.

Negative terms in the summation are ignored; i.e. no wet stress calculated for water table depths greater than 50 cm as the summation is the measure for the exceedence of the 50 cm level. Large SEW values generally indicate poor drainage conditions.

Four different crops were planted on each plot, namely grass forage, corn, potatoes, and strawberries. The crops were randomly arranged in the plots with corn being planted on the left side to prevent shading effects on other adjacent crops (Chao, 1987).

3.3 Data Collection and Analysis

3.3.1 Laboratory Data Collection and Analysis

Soil physical and hydraulic properties (i.e., hydraulic conductivity, soil water characteristics, bulk density and particle size distribution) were evaluated. Various combinations of drain spacing and water table elevations were studied. The drain spacings were 2 m, 4 m, 4.44 m and 8.88 m. Although the actual model length was 4.88 m a spacing of 8.88 m was also obtained by assuming symmetry with the axis of symmetry (i.e., the midspan of the drains) at the box wall. A hydraulic head was built up in the reservoir connected to the to the drain inlets. The water level in the reservoir was controlled during subirrigation by means of an overflow pipe fitted into the reservoir. The transient response of the water table was studied during the initial period of subirrigation when the water level is raised in the outlet for a horizontal water table profile .

The transient water table profile was traced on Plexiglas and the water table height was observed simultaneously from the peizometric tubes. The profile observed was not actually the water table profile but was the shape of the advancing wetting front. For all practical purposes, the water table profile was assumed to match exactly with the shape of the advancing water front during subirrigation because the shape of the water table from the peizometric readings was same as the shape of the advancing wetting front. However, as the saturated zone could not be differentiated from the unsaturated zone the height of capillary rise could not be observed..

The height of capillary rise was observed using the soil column. Dry fine sand was used as the soil medium to observe the capillary rise as the unsaturated zone can be visually differentiated in dry sand. The soil column was placed in the reservoir with the desired water table height and water was allowed to rise into the column for a period of 24 to 72 hours. The capillary rise for different water table heights was observed. The setup has been described in Section 3.2.1

3.3.2 Field Data Collection and Analysis

The physical and hydrological characteristics of the soil, including satiated hydraulic conductivity, bulk density, particle size distribution, moisture retention curve, etc. were analyzed by Chao (1987).

The water table heights at the midpoint between the laterals were recorded using automatic water table recorders. The daily rainfall were recorded by rainfall recorders. The charts from the recorders were traced into the computer by Talos CYBERGRAPH digitizer at the Computing Center of The University of British Columbia. The data produced from the digitizer then can be used for studying water table fluctuation patterns and some other analysis by using programs such as LOTUS 123 (Release 2), TELL-A-GRAF (mainframe), etc.

Maximum and minimum temperatures were obtained from Vancouver International Airport Weather Station (VIA). Global radiation was measured at the UBC weather station. VIA and UBC weather stations are 10 and 20 km from the experimental site and the latitudes being $49^0 11'$ and $49^0 15'$, respectively. Thus it can be assumed that the climatological data collected at VIA and UBC weather stations can be used in this study.

The potential evapotranspiration for this site was computed by Penman method by Gao (1990).

3.4 Model Evaluation

3.4.1 Simulation Input Data And Procedure

Four years of experimental data from subsurface drainage and subirrigation field study was used to evaluate the reliability of using DRAINMOD for simulating subsurface drainage and subirrigation in the Lower Fraser Valley. The inputs to the model include weather data, soil properties, crop variables and site parameters.

3.4.1.1 Climatological data

Daily evapotranspiration (PET) and hourly precipitation are the required climatological input data for water balance calculation in this model.

Precipitation

DRAINMOD uses hourly rainfall data for simulation purposes, but only daily rainfall data was collected. The daily rainfall data was interpolated into hourly rainfall data using the SCS rainfall distribution (Chow et al., 1988) pattern for 24 hour storm duration storms as given in Table 3.2. The type IA distribution which is for Pacific Maritime climate with wet winters and dry summers was used. The rainfall input data was hourly amounts in hundreths of an inch.

PET

The daily maximum and minimum air temperature data files were used to estimate the PET as simulated by DRAINMOD. DRAINMOD uses Thornthwaite's equation to estimate PET, which uses latitude and heat index for the location along with the temperature data. The Thornthwaite PET estimates were adjusted on a monthly basis. The PET was calculated using Penman's method by Gao (1990). Gao(1990) reported a mean evaporation coefficient of 0.87. Thus Thornthwaite PET estimates were adjusted on a monthly basis by the coefficient of 0.87.

Table 3.2 SCS rainfall distribution for 24 hour **Type IA** storm.

Hour (t)	t/24	P_t/P_{24}*
0	0	0
2.0	0.083	0.050
4.0	0.0167	0.116
6.0	0.250	0.206
7.0	0.292	0.268
8.0	0.333	0.425
9.0	0.375	0.520
10.0	0.417	0.577
11.0	0.459	0.624
12.0	0.500	0.664
13.0	0.542	0.701
14.0	0.583	0.736
16.0	0.667	0.800
20.0	0.833	0.906
24.0	1.000	1.000

* P_t = accumulated precipitation at time t and

P_{24} = total precipitation in 24 hours.

3.4.1.2 Soil properties

The soil characteristic curves were available for upto 50 cm, 50 - 70 cm and 90 - 110 cm layers. The soil water content versus hydraulic potential and hydraulic conductivity data were taken from Chao (1987). Three undisturbed core samples (7.3 cm in diameter and 7.5 cm in height) were used to determine water retaining and transmitting properties. The satiated hydraulic conductivity has been reported to decrease progressively with increased subirrigation practices. The model outputs are very sensitive to saturated hydraulic conductivity values (Skaggs, 1975).

Table 3.3 Summary of satiated hydraulic conductivities for the years 1985 and 1986.

(layer depth)	Layer 1 (50 cm)	Layer 2 (70 cm)	Layer 3 (110 cm)
Regime A	0.23 m/day	0.11 m/day	0.07 m/day
Regime B	0.13 m/day	0.07 m/day	0.04 m/day
Regime C	0.08 m/day	0.04 m/day	0.03 m/day

The DRAINMOD soil preparation programs were used for estimating unsaturated hydraulic conductivities, volume drained and upward flux versus water table depth from soil water characteristics data and hydraulic conductivities. The soil was a three layered soil with hydraulic conductivities as shown in Table 3.3 and 3.4. These values were converted to cm/hr as DRAINMOD requires the input values in this unit. As reported by Chieng et al.,(1992) the hydraulic conductivity decreased progressively with increased subirrigation practices. Therefore, different hydraulic conductivities for each year were used for the simulation.

DRAINMOD uses the relationship between drained volume and water table depth to determine the rise and fall of the water table when a given amount of water is added or removed.

Table 3.4 Summary of satiated hydraulic conductivities for the years 1987 and 1988.

(layer depth)	Layer 1 (50 cm)	Layer 2 (70 cm)	Layer 3 (110 cm)
Regime A	0.22 m/day	0.11 m/day	0.07 m/day
Regime B	0.12 m/day	0.09 m/day	0.04 m/day
Regime C	0.09 m/day	0.07 m/day	0.03 m/day

3.4.1.3 Crop parameters

Crop input data to DRAINMOD include relationship between effective crop rooting depth, time, days to initiate and stop SEW_{50} and dry day computation as shown in Table 3.5. The effective rooting depth of the crop is the depth of soil from which a crop removes significant amounts of water. The crops grown on the research plot are corn, potatoes, forage grass and strawberries, DRAINMOD uses only one crop for the simulation hence a weighted average rooting depth was used as the effective rooting depth attained at different times of the calendar year.

Since the rooting depths in the selected field experiment was not measured, the maximum effective depth was estimated from the literature, and the relationship of the rooting depth to time was approximated by the crop growth stage coefficient (K_c) defined in Evapotranspiration and Irrigation Water Requirement (ASCE, 1990). For a given crop, the K_c value, which indicated the rate of water use by the crop, was defined in terms of percent of the growing season. For a given crop, the effective root depth at any time during a growing season is linearly related to the value of K_c.. As soil moisture will be removed from the surface layer by evaporation even when the field is fallow, a minimum rooting depth of 11 cm was assumed

for periods before and after the growing season. The maximum rooting depth for corn, grass forage and potatoes in this study were assumed to be 60, 40 and 50 cm, respectively. The maximum rooting depth for strawberry in this study was assumed to be 50 cm throughout the year as strawberry is a perennial plant. The effective crop rooting depth for the growing season is shown in Figure 3.7. A maximum crop root depth of 47 cm was used for soil data preparation.

Although the values assumed above were used for the simulation, normal root development could have been inhibited due to compaction of the surface soil, excessively coarse subsoil, impervious subsoil, poor soil drainage, high water tables, chemical and fertility problems and hence reduce the effective rooting depth.

The period between March 10 and May 31 was assumed for beginning and ending dates for spring planting, respectively and was used for SEW_{50}.

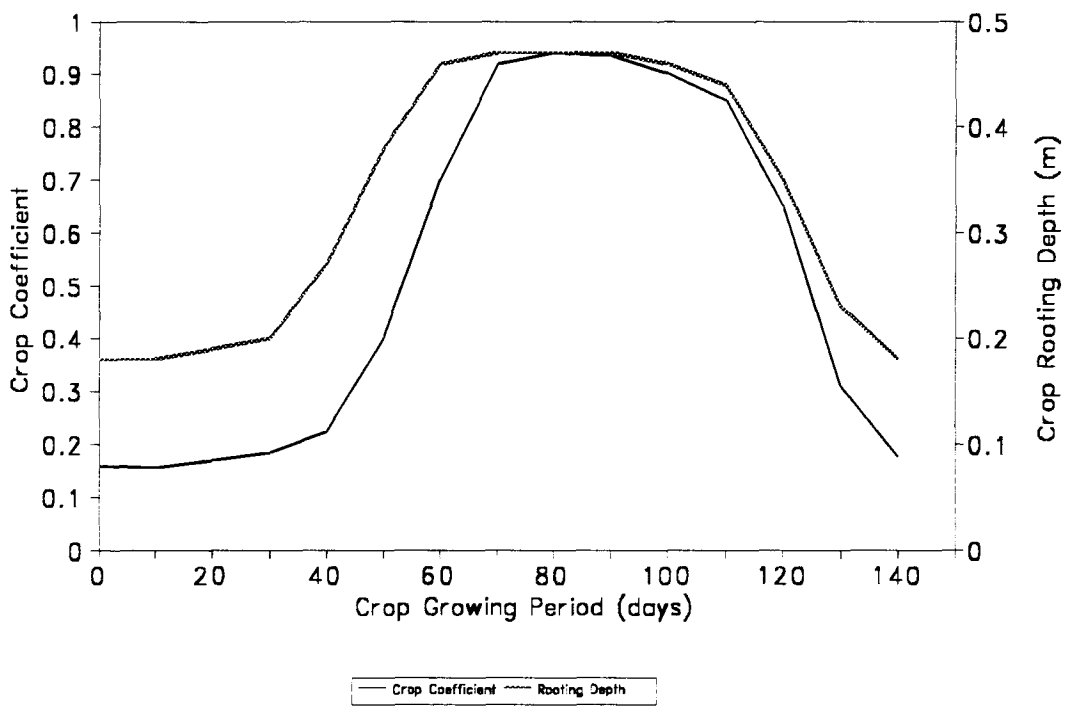

Figure 3.7 Generalized crop coefficient curve and effective crop rooting depth.

Table 3.5 Summary of input data for soil properties and crop parameters for the LFV.

Input Parameters	Program Variable Name	Value
Depth to restrictive layer	ADEPTH	180 cm
Water content at wilting point	WP	0.14 cm^3/cm^3
Initial water table depth	DTWT	50 cm
Minimum soil air volume required for tillage operations during spring	AMINA	4.7 cm
Minimum rain to stop field operations during seedbed preparation	ROUTA1	0.5 cm
Minimum time after rain before tilling work can start in spring	ROUTA2	1 Day
Starting and ending hour of work during spring	SWKHR1, EWKHR1	0800, 2000
Depth to which SEW calculations are made	SEWX	50 cm
Month and year simulation starts	IMST, IYST	January, 1985
Month and year simulation ends	IMED, IYED	December, 1988
Latitude for temperature index	LAT	$49^{o}11'$
Heat index	HIDX	37

3.4.1.4 Drainage System Design Input Data

A number of drainage system input parameters are required for each simulation. The drainage system input data are drain spacing, drain depth, effective depth of the impermeable layer and the depth of surface depression storage. Drains were assumed to be 100 mm nominal diameter, corrugated and perforated polyethylene pipes. The effective depth to the impermeable layer was calculated by using DRAINMOD, which depends on the depth, spacing and radius of the drains. The drainage system design input parameters are tabulated in Table 3.6.

Different subirrigation periods were used for the simulation for each year as the actual subirrigation period for each year was different in the field. The subirrigation periods for the simulation years were July 5 to August 19, 1985, July 30 to September 8, 1986, May 27 to August 27, 1987 and June 28 to September 19, 1988.

Table 3.6 Summary of drainage input parameters used in simulation for the LFV.

Input parameters	Program variable name	Value
Drain depth	DDRAIN	110 cm
Drain spacing	SDRAIN	1400 cm
Actual depth to impermeable layer	ADEPTH	180 cm
Effective drain radius	EFFRAD	0.51 cm
Surface depressional storage	STMAX	2.00 cm
Effective depth from drain to impermeable layer	HDRAIN	48.18 cm*

* These variables are not direct inputs to DRAINMOD, but are used to calculate other input parameters.

Chapter 4

RESULTS AND DISCUSSION

4.1 Soil Physical and Hydraulic Properties of Experimental Sand

The results of the soil physical characteristics and soil water retention characteristics are presented in Appendix A. The soil water retention characteristic was obtained by laboratory using tensiometers and porous plate extractors. Tensiometers were used for 0 to 60 cm and porous plate extractors for 300 to 15290 cm soil matric potential. Each analysis was replicated three times. The soil water characteristic curve is shown in Figure A.1. The particle size distribution curve is shown in Figure A.2. The textural classification is fine sand under the standards of the United States Department of Agriculture (USDA). The bulk density of the sand was 1.5 gm / cm^3.

The particle size analysis for the sand used for laboratory experiments exhibited a very steep curve, which indicates that the grains are nearly the same size and such a soil is termed as uniform. The uniformity coefficient C_u is defined by the relation

$$C_u = \frac{D_{60}}{D_{10}} \tag{3.1}$$

where,

D_{60} = Size corresponding to 60 percent on the grain size curve and

D_{10} = Size corresponding to 10 percent on the grain size curve

Soils with a C_u less than 4 is said to be uniform (Sowers and Sowers, 1970). The uniformity

coefficient for experimental sand was 3.

The effective particle size is defined as the size corresponding to 10 percent on the grain size curve. The effective particle size for experimental sand was 0.13 mm. The particle size distribution is important in determining the pore space and hence the distribution of air and water in the soil.

4.2 Water Table Profile

The time required to raise the water table to a height sufficient to supply crop evapotranspiration demands may be the limiting factor in the design of subirrigation systems. The shape of the water table during subirrigation and the time it takes for the water table to assume a flat shape should be an important criteria to be considered in the design and operation of subirrigation systems. The time taken by a horizontal water table profile to rise and assume a flat shape could be treated as the response time for a subirrigation system. The high response time will subject the crop to dry stress and if the water table does not assume a flat profile it shall be subjected to dry and wet stress in alternate strips, where the wet stress shall be above the drains and dry stress at the midpoint between the drains.

The effect of the drain spacing on the wetting front profile and on the water table rise for a subirrigation system is shown in Figures 4.1 - 4.4 and B.1 - B.7 in Appendix B. The drains are located 15 cm above the impermeable layer. As shown in Figure 4.1 - 4.4, observed wetting front profiles show a slow transition from a semi-elliptical shape (with a vertical major axis) around the drains to a nearly flat wetting front i.e., the initial shape of the water table. The initial water table was assumed to be horizontal at 15 cm below the drains. The initial semi - elliptical shape around the drain is more pronounced in case of 4 and 4.88 m drain spacing as seen in Figure 4.2 and 4.3. Similar results were also observed by Galgonov (1991). The study concluded that in a subirrigation system, the shape of the water table profile above the drain after subirrigation is similar to the shape of the water table prior to the initiation of irrigation.

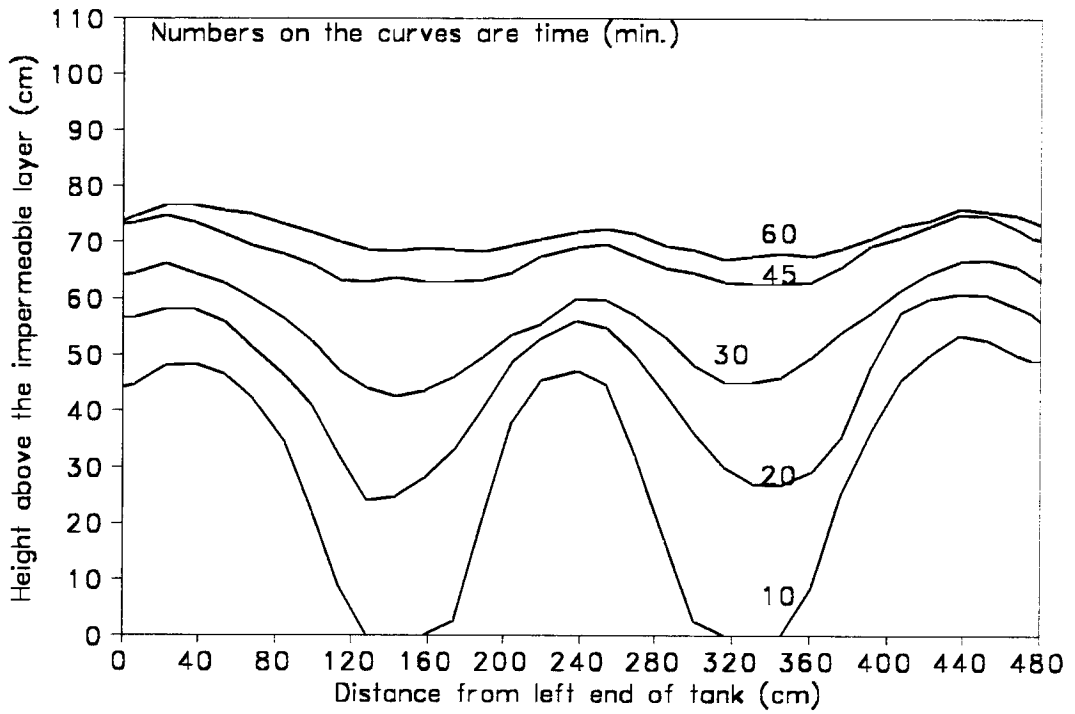

Figure 4.1 Wetting front profile for a 2 m drain spacing for a hydraulic head of 85 cm.

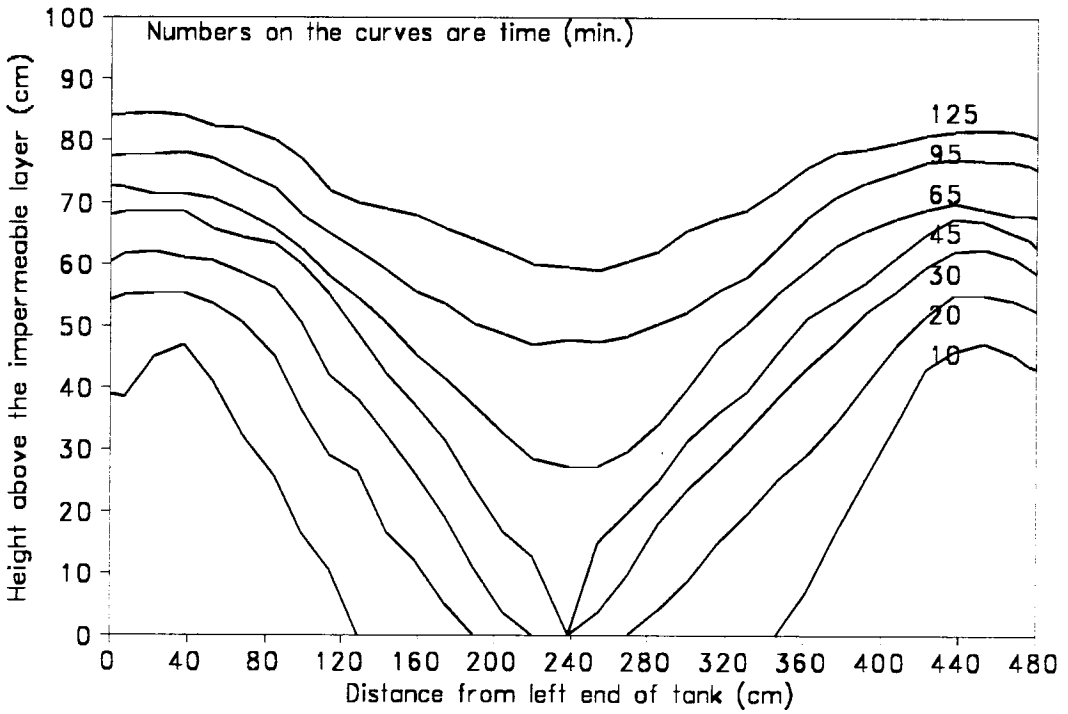

Figure 4.2 Wetting front profile for a 4 m drain spacing for a hydraulic head of 70 cm.

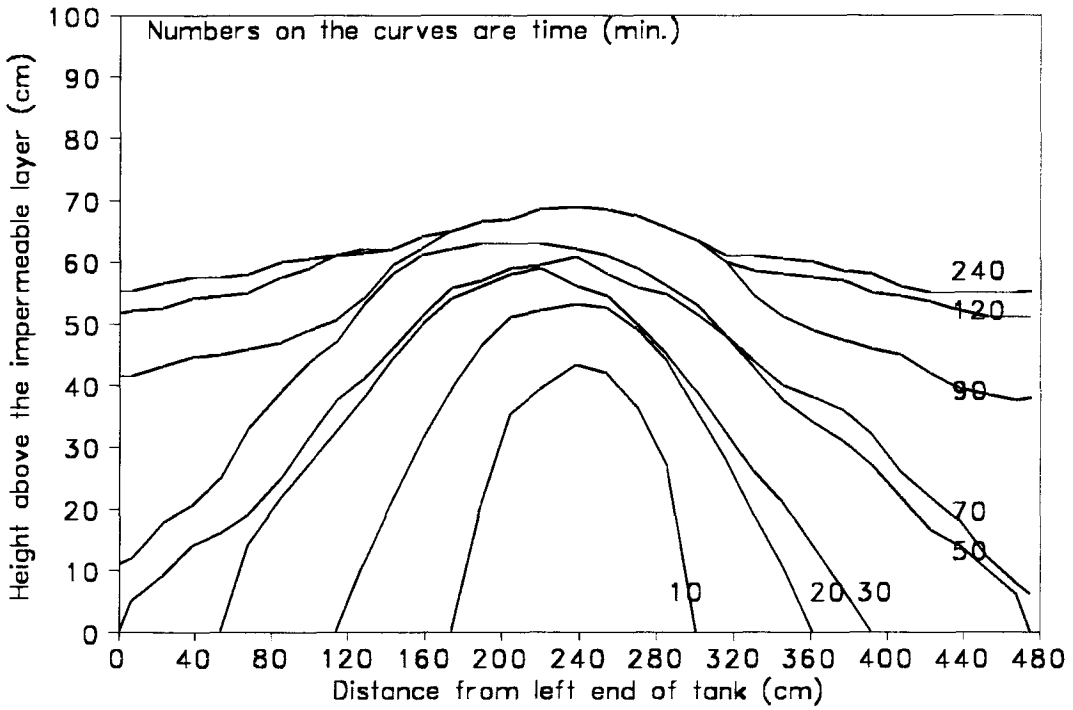

Figure 4.3 Wetting front profile for a 4.88 m drain spacing for a hydraulic head of 70 cm.

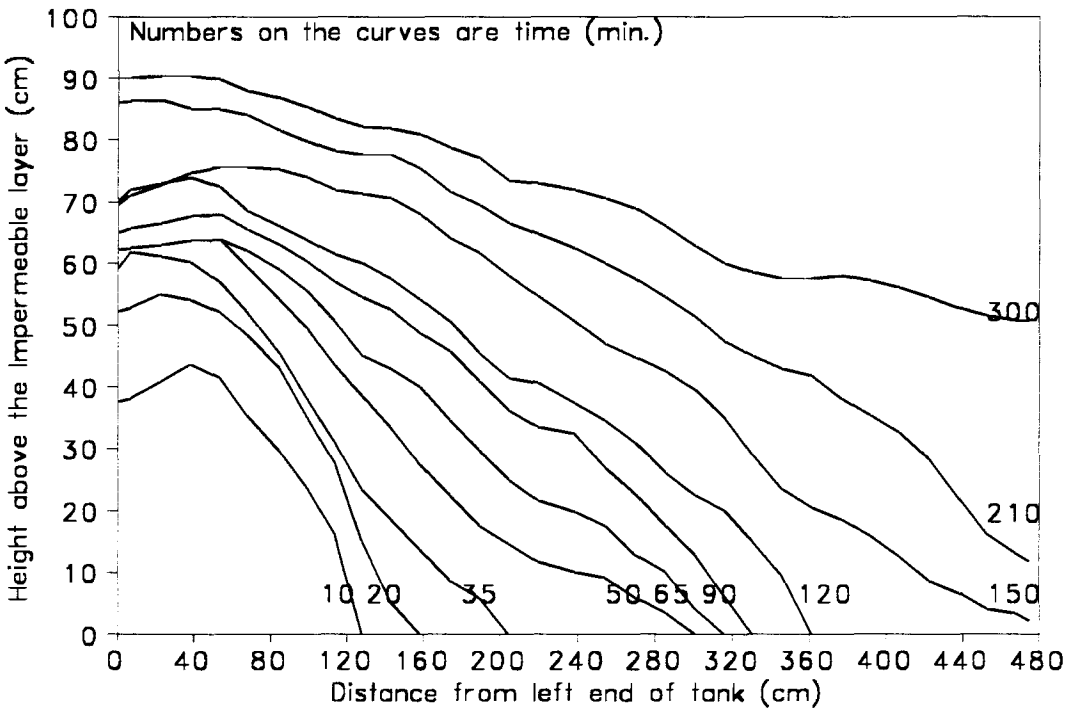

Figure 4.4 Wetting front profile for a 8.88 m drain spacing for a hydraulic head of 95 cm.

As shown in Figures 4.1 - 4.4, the water level in the water reservoir (i.e., hydraulic head) was higher than the water table in the soil due to divergent and other head losses in the subirrigation system. Thus, from the operational viewpoint, it follows that water level in the water reservoir in a subirrigation system should be kept higher than the desired water table in the soil to counteract divergent and other head losses in the subirrigation system. This extra height will depend upon the type of soil, soil profile, hydraulic conductivity and the location of the impermeable layer.

As shown in Figure 4.5 and Figure 4.6 the hydraulic head does not result in the change in the shape of the wetting front but only a change in the initial wetting front profile is observed as shown in Figure 4.5. Only the response time changes. As shown in Figure 4.6 the water table profiles for 2 m drain spacing with a hydraulic head of 70, 80 and 90 cm at time t = 60 minutes are nearly identical. The time taken to obtain a nearly flat wetting front profile is the same, irrespective of the hydraulic head for a given drain spacing as shown in Figure 4.6, where the wetting front assumed a nearly flat profile after t = 60 minutes. It was observed that the water table elevation increases with time reaching a steady state position at t = 24 hours.

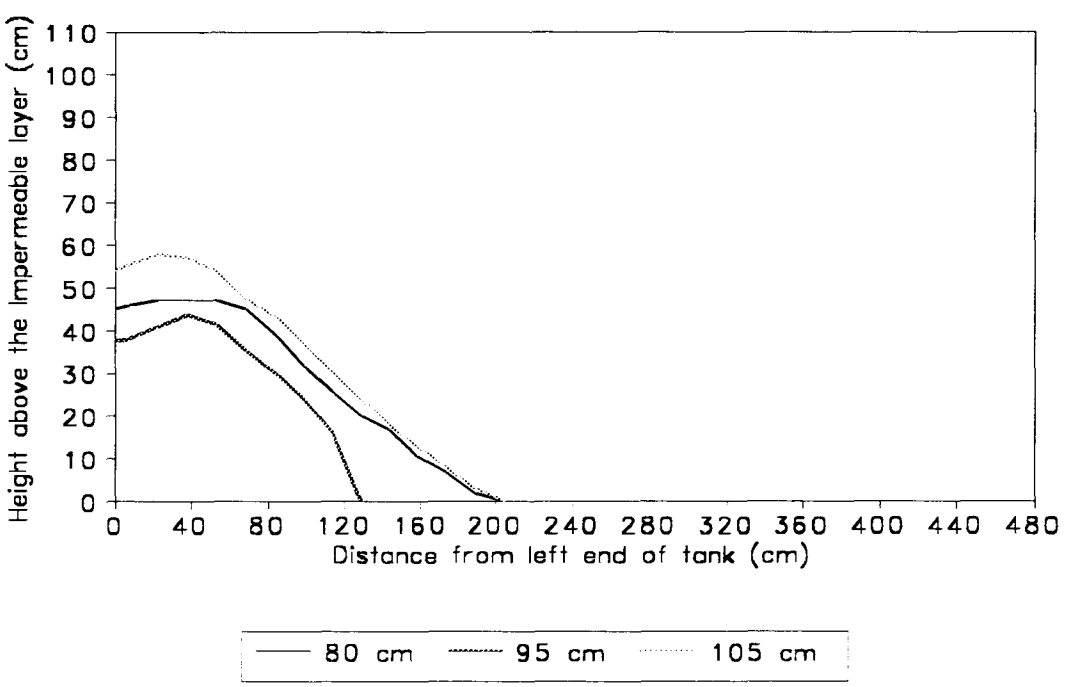

Figure 4.5 Wetting front profile for 2 m drain spacing at t = 10 minutes at different hydraulic heads.

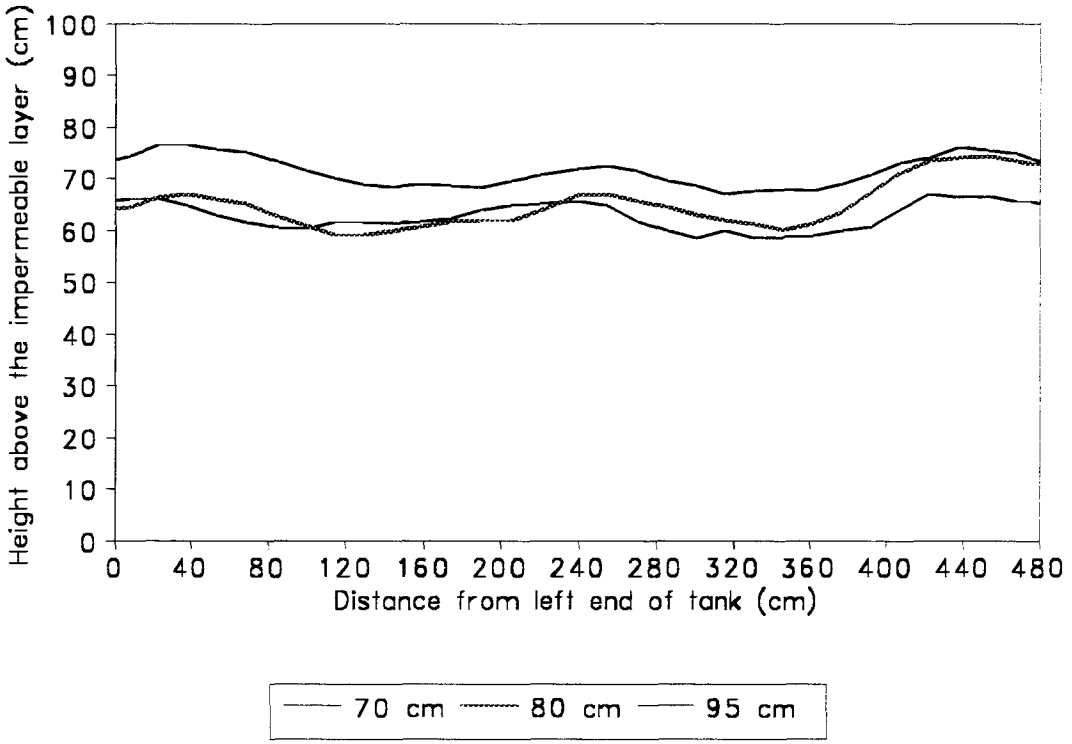

Figure 4.6 Wetting front profile for 8 m drain spacing at t = 60 minutes at different hydraulic heads.

Results for subirrigation show that water movement in the saturated zone was essentially horizontal. Figure 4.6 further exemplifies this phenomena. It was observed that in case of fine sand lateral movement of water was higher as compared to vertical movement, inspite of the hydraulic head. Because hydraulic conductivity increases rapidly with water content, there is very little lateral movement above the water table (i.e., most lateral movement occurs in the saturated zone).

As shown in Figure 4.7, the shape of the advancing wetting front is same as the water table profile during subirrigation. There is a difference in the height of the wetting front profile and the water table profile above the impermeable layer as the wetting front includes the saturated and unsaturated flow. The difference in the two profiles shows a capillary rise of about 24 cm.

Figure 4.8 shows the water table profile for a 2 m drain spacing is nearly flat or stable in 130

minutes after the initiation of subirrigation in case of fine sand. The shape of the water table compares closely to subirrigation water table profiles predicted by Skaggs (1991) shown in Figure 2.4.

As shown in Figure 4.9, the water table elevation above the drains at t = 60 minutes after initiation of subirrigation is nearly constant irrespective of drain spacing or hydraulic head, whereas at the midpoint between the drains it is a function of drain spacing and hydraulic head.

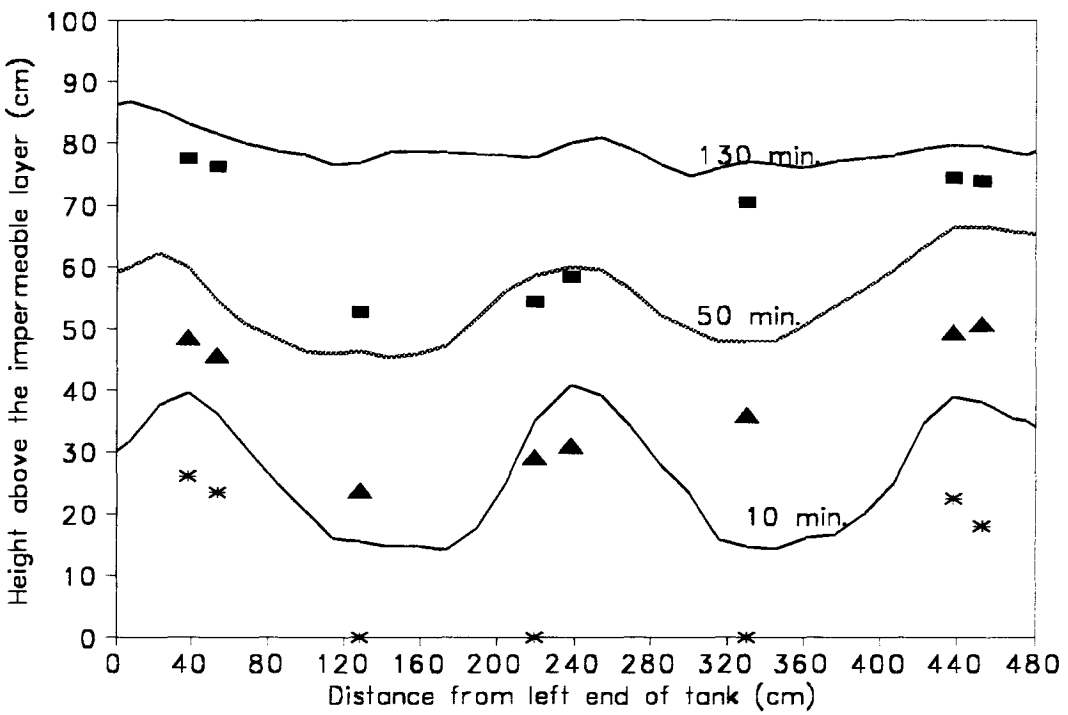

Figure 4.7 Wetting front profile and water table profile for a 2 m drain spacing for a hydraulic head of 95 cm.

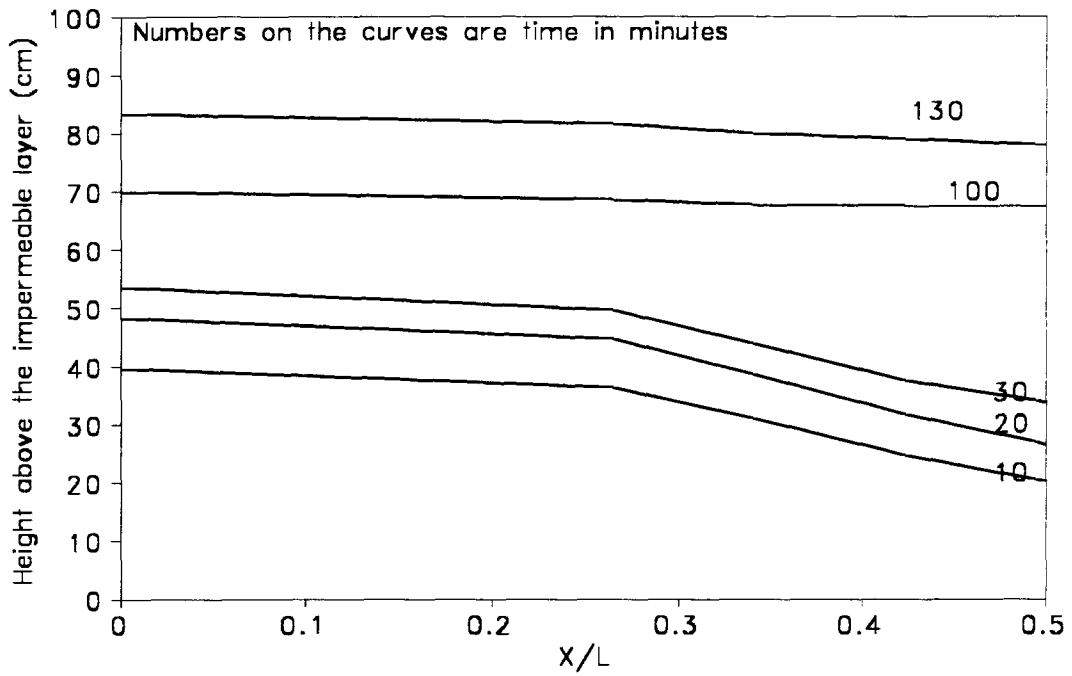

Figure 4.8 Subirrigation water table profile for 2 m drain spacing for 95 cm hydraulic head.

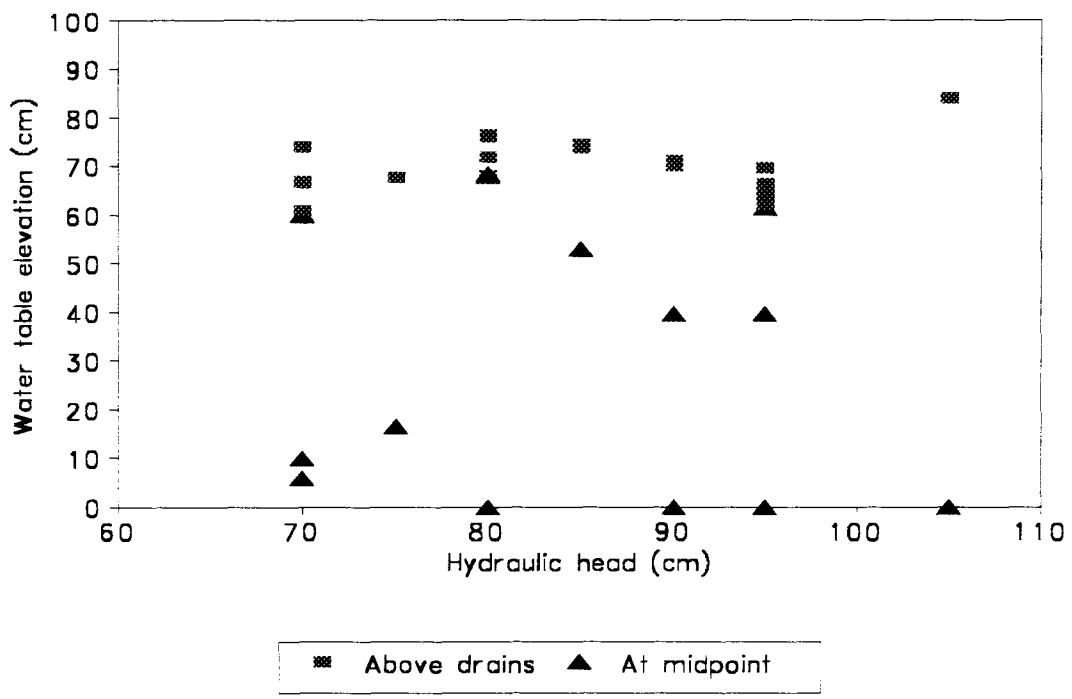

Figure 4.9 Water table elevation for various drain spacings at t = 60 min. (each symbol used in the figure represents hydraulic head for four different drain spacings i.e., 2 m, 4 m, 4.88 m and 8.88 m).

4.3 DRAINMOD

4.3.1 Simulations

The four year (1985-1988) conventional subsurface drainage and subirrigation experiment provided an excellent field data set to validate the simulation model, DRAINMOD, for silty clay loam soil and the climatic conditions in the LFV. A simulation was performed for years 1985, 1986, 1987 and 1988, which represent the dry, normal, dry and wet years, respectively from the total rainfall standpoint as compared to a 30 year average rainfall as shown in Figure 4.10. The initial water table height for each year was set to 50 cm below the soil surface at the beginning of the year for each simulation.

In comparison to the 30 year average rainfall for the Boundary Bay area, 1985 was a dry year and 1988 was a very wet year from the total rainfall standpoint. The year 1986 was a nearly normal year. The model predictions of drainage system performance compared best with the field observed parameters for the driest year (1985), when the water table depth was frequently deep. Simulation results for the driest growing period (1985) provided good example of the interactions of crop rooting depth and the increase of water table depth resulting from upward flux and ET.

The observed and simulated water table elevations are presented in Figs. 4.11 to 4.22 for years 1985-1988. The simulations for each year and regime was performed individually as each year had a different subirrigation period as well as saturated hydraulic conductivity. The drains laid at 1.1 m from the soil surface (i.e., at the 0 axis in Figures 4.11 - 4.22). The simulation was performed for conventional subsurface drainage and subirrigation (i.e., regimes A, B and C). However, no simulations could be done for undrained conditions (i e., regime D) as DRAINMOD is designed to simulate only for following management practices: conventional drainage, controlled drainage, subirrigation and surface irrigation (waste water irrigation). A simulation of the undrained conditions would provide a better comparison of the results and the advantage of the drainage or subirrigation system over undrained conditions.

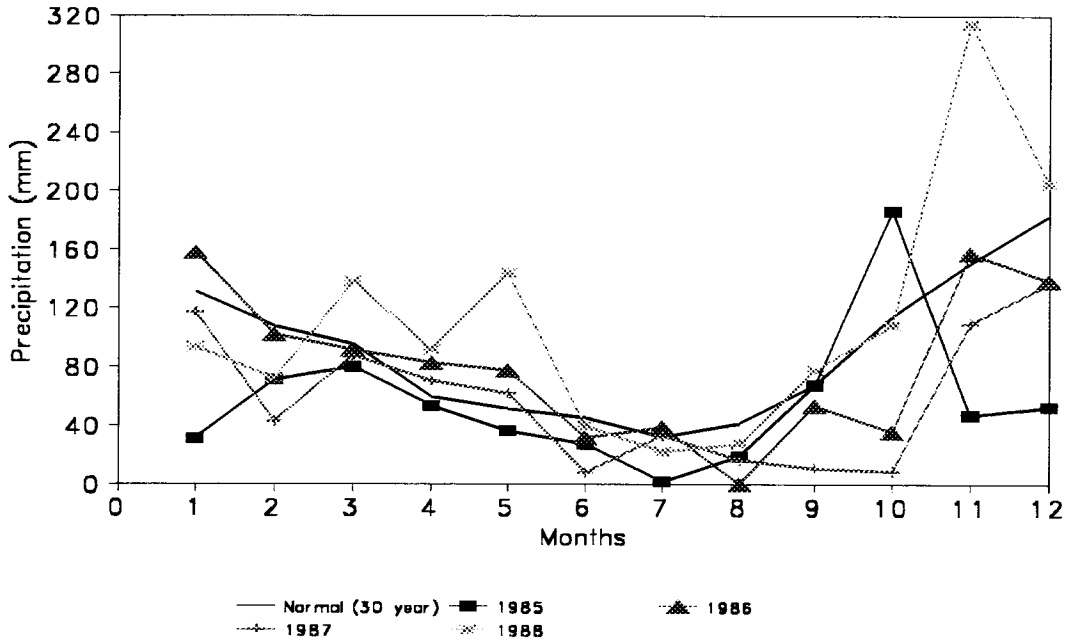

Figure 4.10 Comparison of monthly 1985, 1986, 1987 and 1988 to normal precipitation at Vancouver International Airport Weather Station.

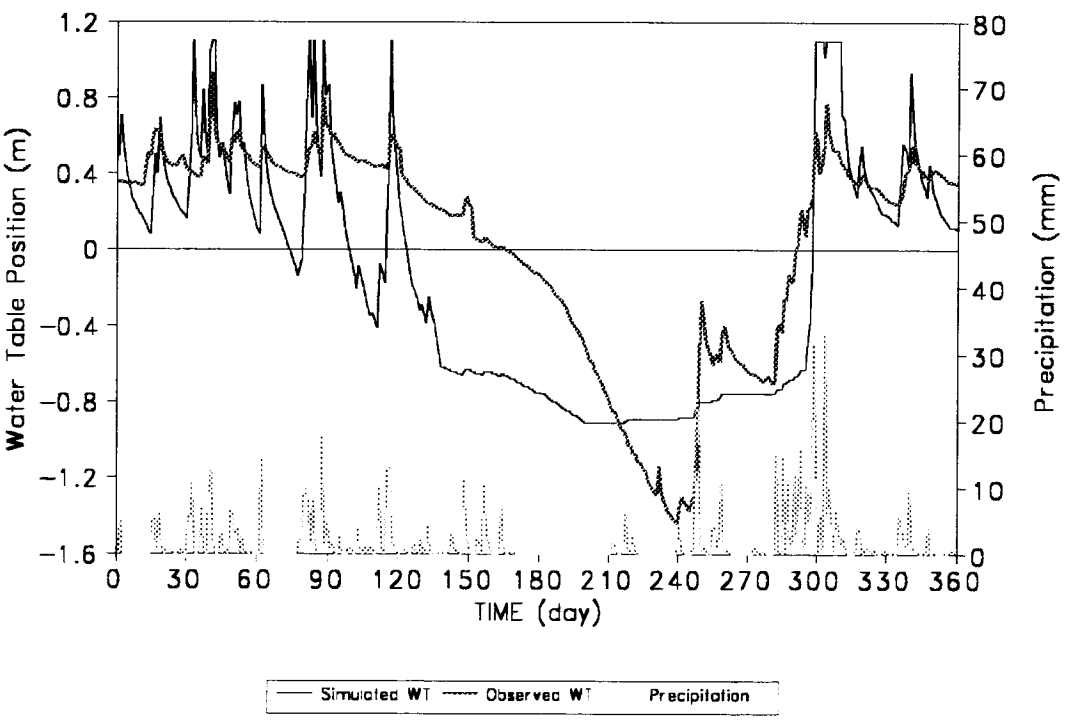

Figure 4.11 Simulated and observed water table profile for Regime A (1985).

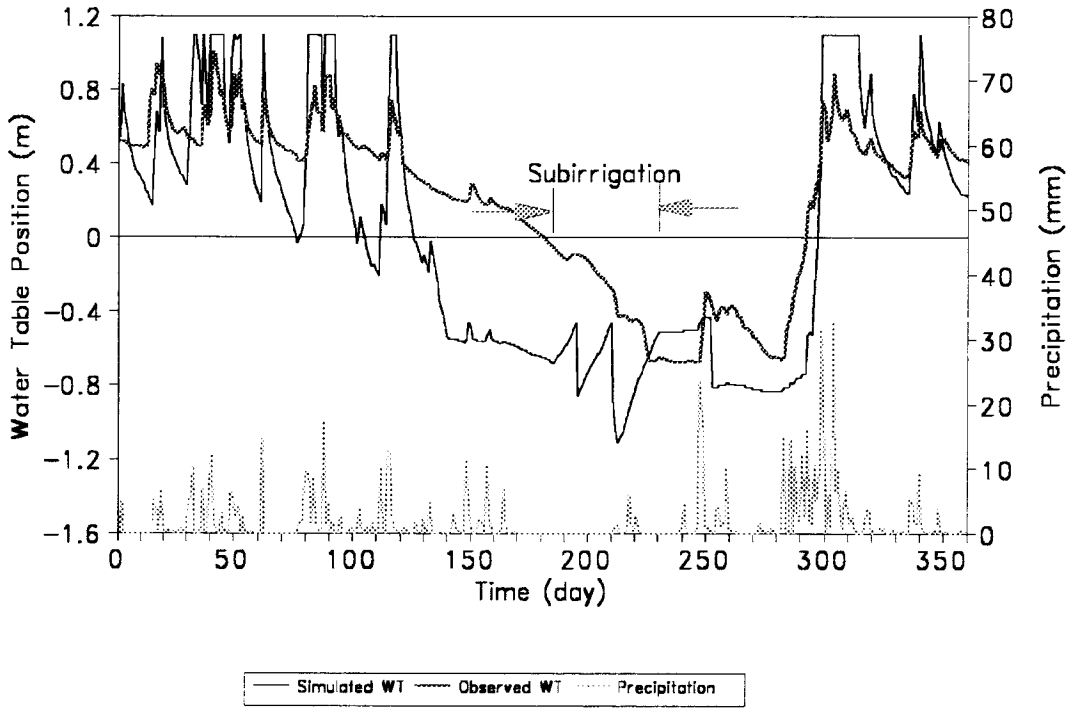

Figure 4.12 Simulated and observed water table profile for Regime B (1985).

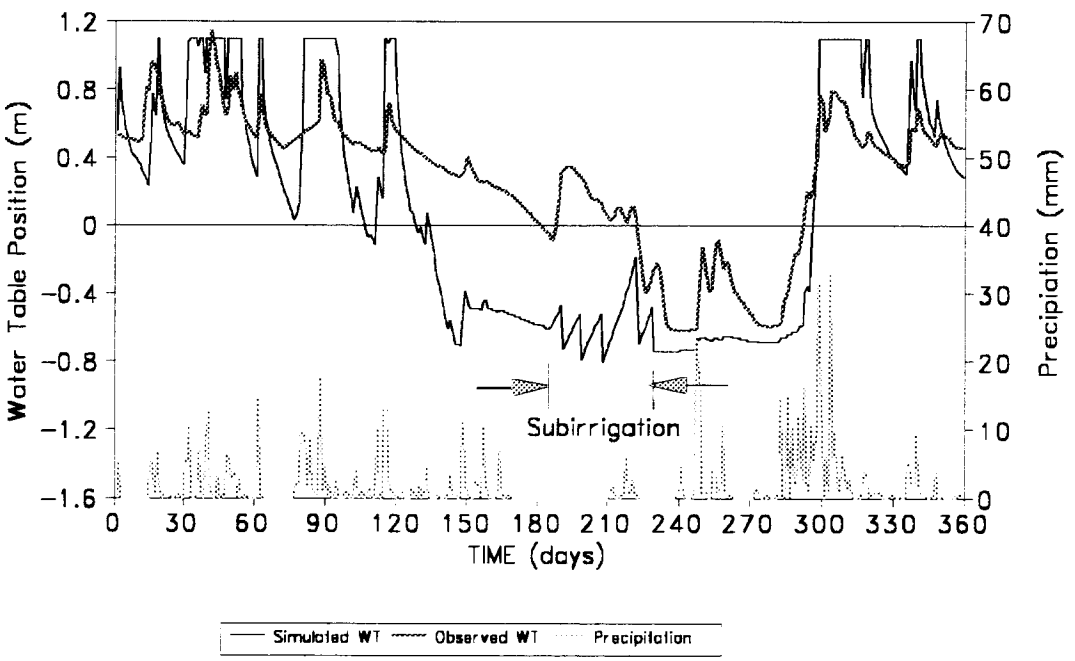

Figure 4.13 Simulated and observed water table profile for Regime C (1985).

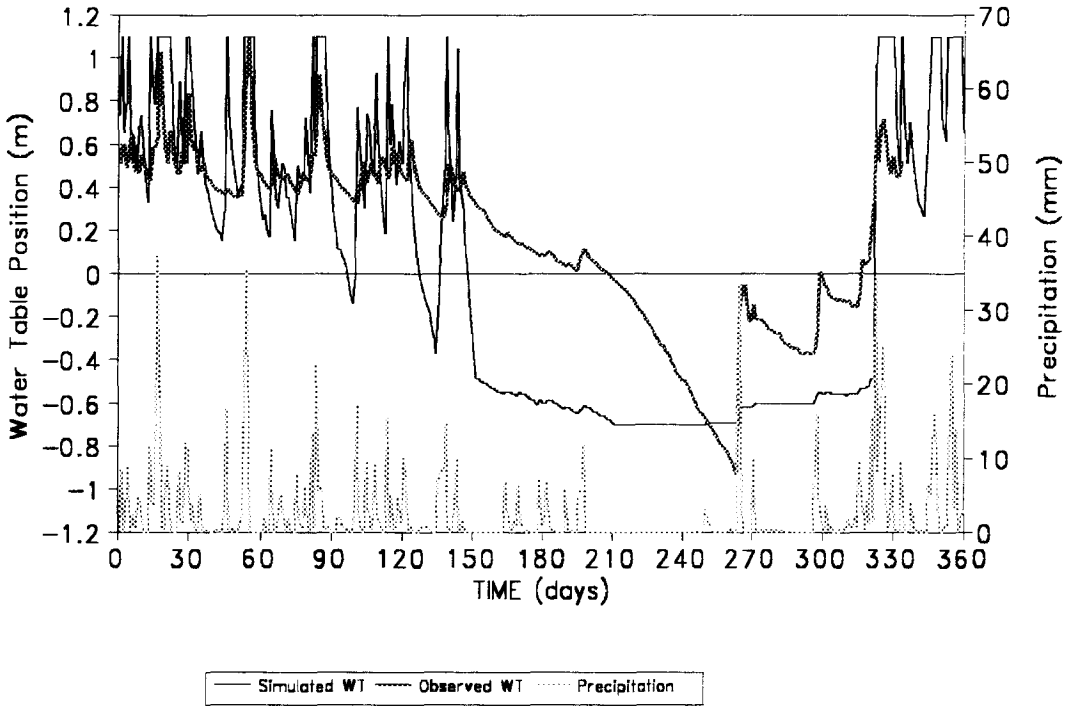

Figure 4.14 Simulated and observed water table profile for Regime A (1986).

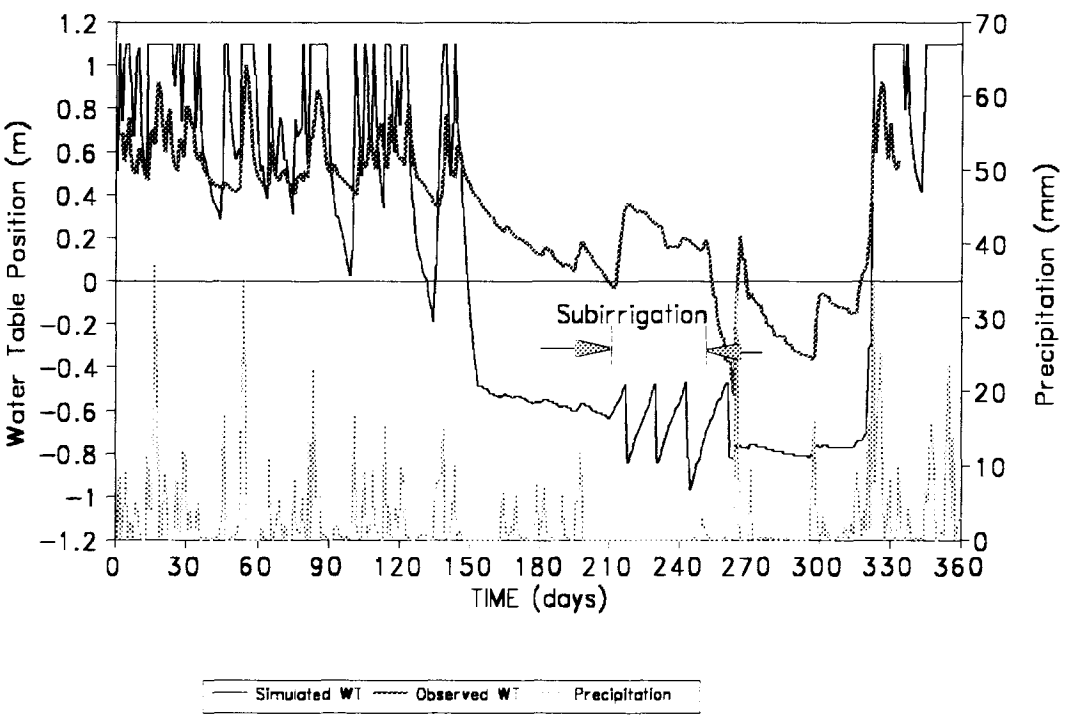

Figure 4.15 Simulated and observed water table profile for Regime B (1986).

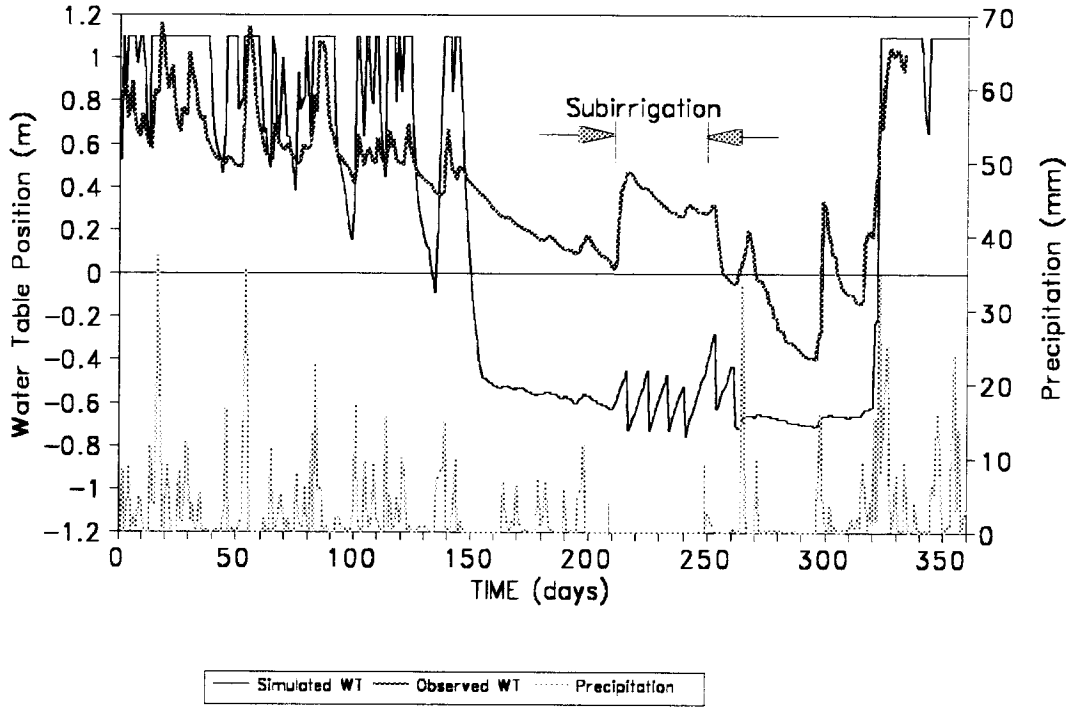

Figure 4.16 Simulated and observed water table profile for Regime C (1986).

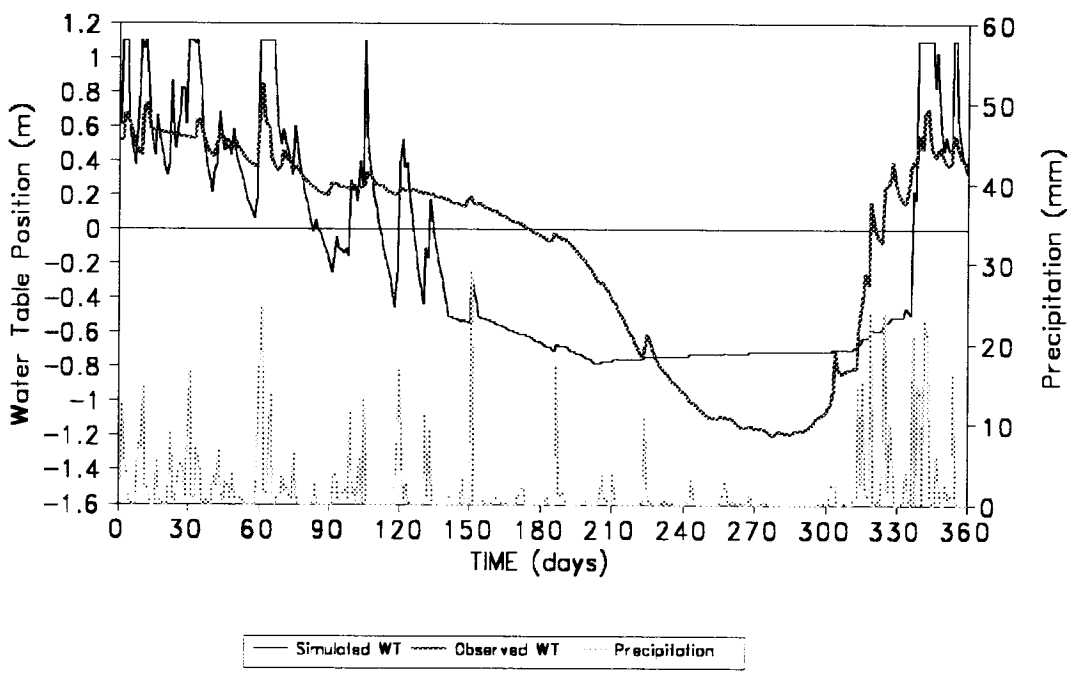

Figure 4.17 Simulated and observed water table profile for Regime A (1987).

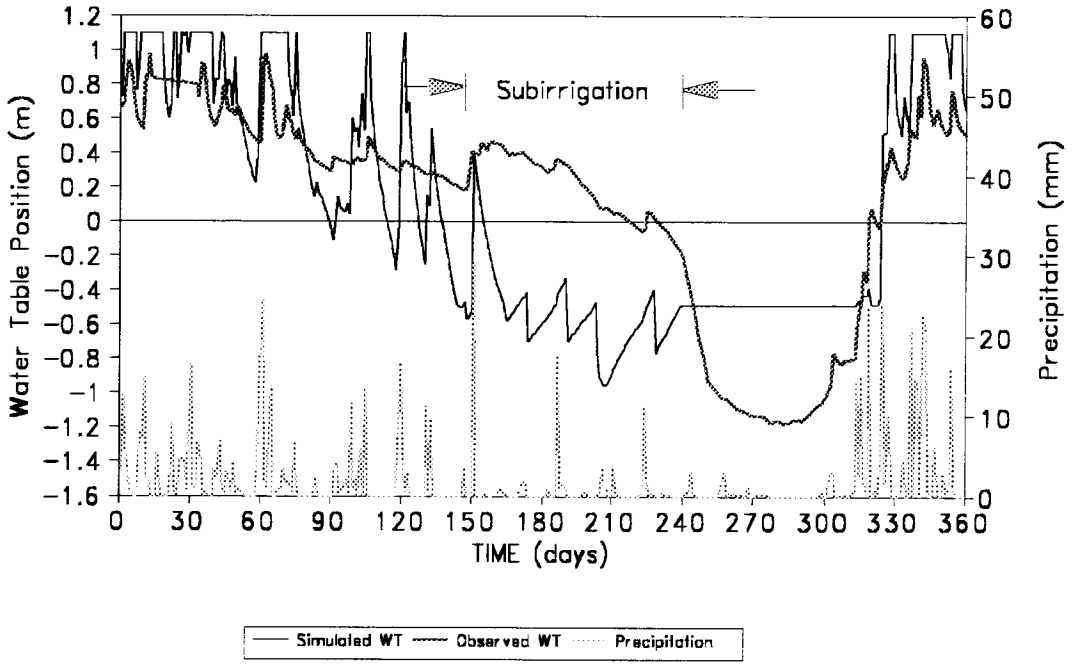

Figure 4.18 Simulated and observed water table profile for Regime B (1987).

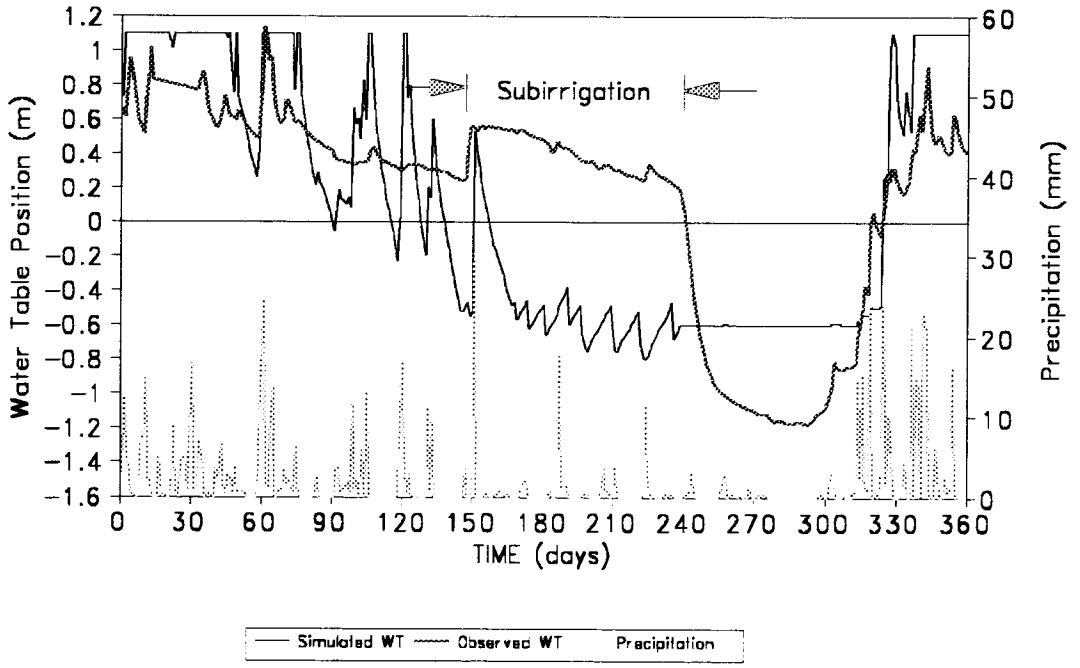

Figure 4.19 Simulated and observed water table profile for Regime C (1987).

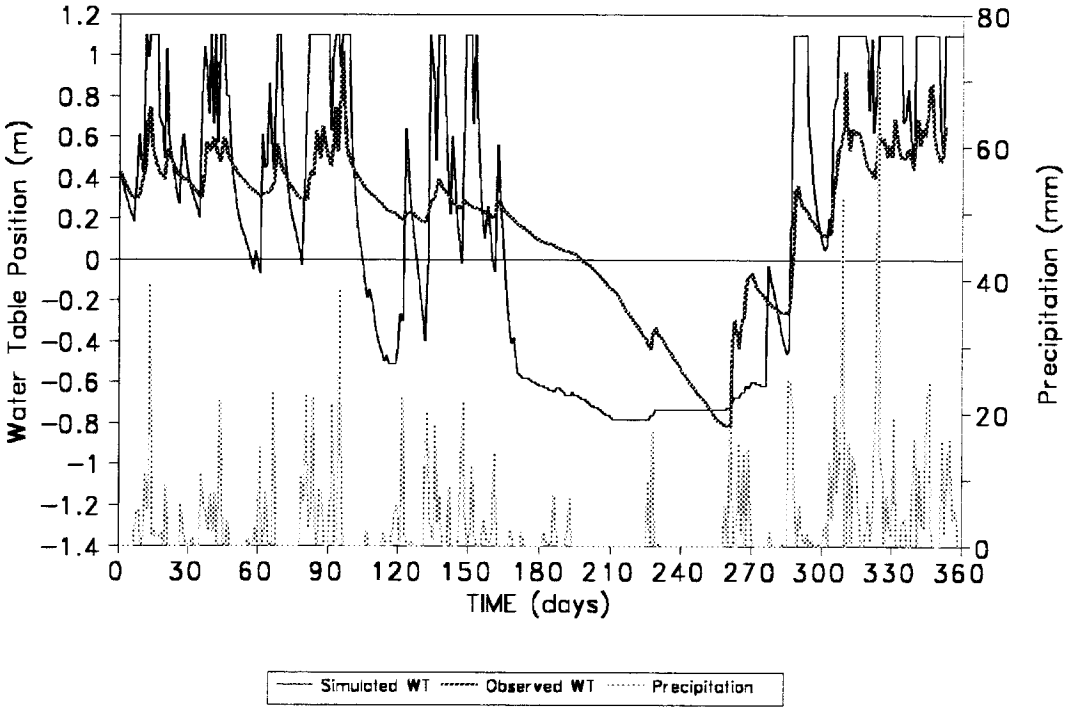

Figure 4.20 Simulated and observed water table profile for Regime A (1988).

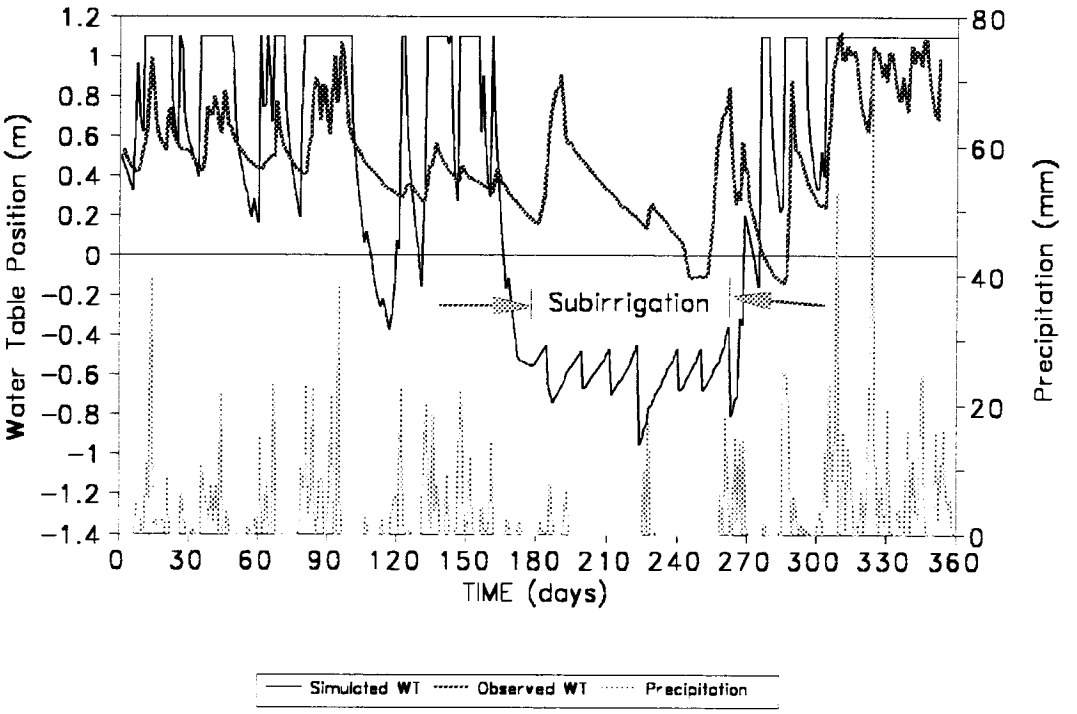

Figure 4.21 Simulated and observed water table profile for Regime B (1988).

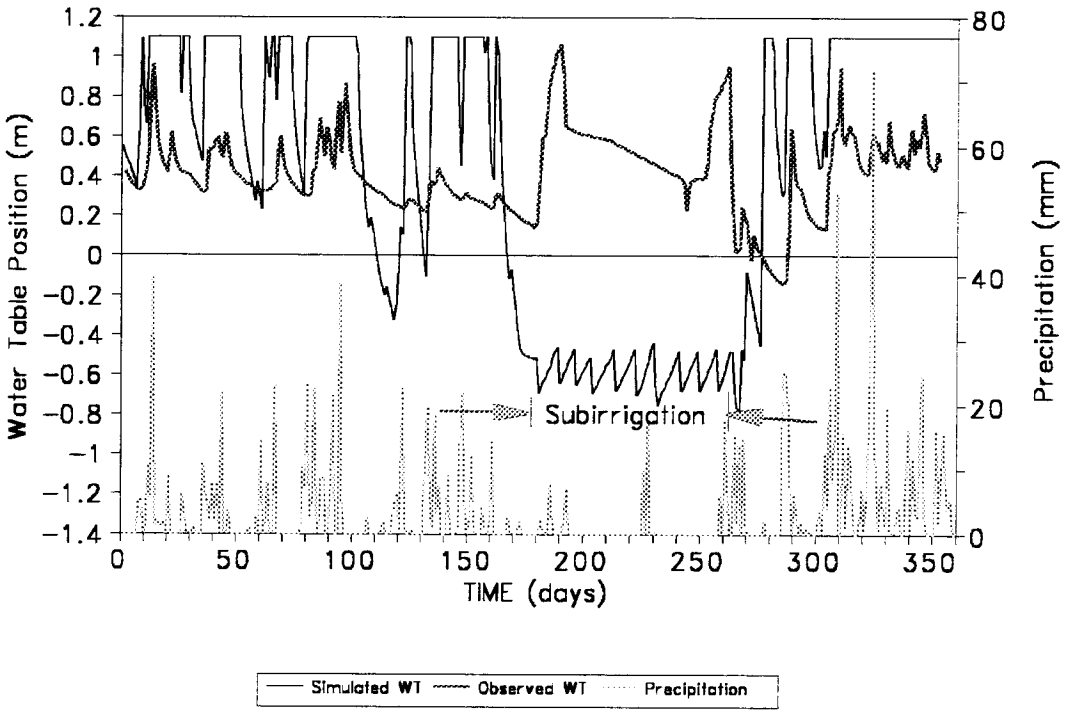

Figure 4.22 Simulated and observed water table profile for Regime C (1988).

For the Ladner series soil, water table should rise no closer to 50 cm below the soil surface as the capillary rise in the experimental field is about 20 cm as reported by Chieng et al. (1987) and an average rooting depth of 30 cm. In the LFV, March 1st to May 31st is the critical period for trafficability consideration therefore, SEW_{50} was calculated for this period and are given in Table 4.1. The SEW_{50} values as simulated by DRAINMOD for each year are given in Table 4.1.

The results indicate that the simulated water table shows a faster drainage and subirrigation of the soil profile which is evident from the sharp peaks and valleys. The model grossly overestimated the water storage capacity of the soil and hence the water table depth.

Table 4.1 SEW_{50} (March 1st to May 31st) values as simulated by DRAINMOD.

DRAINAGE REGIME	1985	1986	1987	1988
REGIME A	323.69	593.81	410.09	1419.19
REGIME B	828.02	1149.81	919.95	2407.17
REGIME C	1118.02	2251.42	1137.12	2710.89

As shown in Figure 4.15 and 4.16 (normal year) water table level were raised effectively with subirrigation but could not be simulated by DRAINMOD as the water table are below the drain depth. These results showed that subirrigation is effective in raising the water table but a 14 m drain spacing may be too wide for this soil to achieve complete control of the water table.

In being able to reasonably simulate the water table, the usefulness of the model DRAINMOD, lies in it's relationship to SEW_{50} criterion, trafficability and workdays. DRAINMOD could be used as a tool to design appropriate water management system for the Lower Fraser Valley.

4.3.2 Model Performance

The water table patterns were quite similar during the four year experimental period. The simulated water table fluctuation peaks matched with the observed water table fluctuation peaks. In general, the model simulated the trend of the observed water table fluctuation as the peak and the valleys did coincide as shown in Figures 4.11 to 4.22.

Ideally, the predicted and the measured water table elevations should be identical. However, the

model was limited by approximations made in assessing various components of water balance and the lack of some measured soil property data. Nevertheless, the agreement between simulated and observed water table elevations would indicate the suitability of the model for the intended application. For this study, the simulated and measured water table elevations were quantitatively compared by assuming that there was no error associated with the measured value. The standard error(s) of the simulated water table elevation was therefore calculated as:

$$S = \sqrt{\sum_{i=1}^{n} \frac{\left(Y_i - Y_i'\right)^2}{n}} \qquad 4.1)$$

where,

n	=	number of observations compared,
Y_i	=	measured water table elevation at the end of day i, and
Y'_i	=	simulated water table elevation at the end of day i.

Statistically, the standard error gave the measure of dispersion of the simulated water table elevations from the actual observations expressed in units of length. The average deviation (α), the arithmetic mean of the absolute differences between calculated and measured water table elevation was also computed for each test period as:

$$\alpha = \sum_{i=1}^{n} \frac{\left|Y_i - Y_i'\right|}{n} \qquad (4.2)$$

The standard error and average deviations of the simulated water table are summarized in Table 4.2.

The model tends to overestimate the water table depth when the drawdown exceeded 110 cm (i.e., the drain depth). Comparisons shown in Figure 4.18 and 4.19 indicate that the model tends to overestimate the water table depth when the drawdown exceeded 110 cm. This may have been caused by the assumption

in the model that the soil drains to hydrostatic equilibrium above the water table. Although, this assumption is reasonable for shallow water tables (Skaggs, 1974; Skaggs and Tangs, 1976) it introduces great error when the water table is deep. As the model uses Hooghoudt's equation which is valid only for prediction of water table height at or above the drain level the average deviation of the water table is higher when the water table is below the drain level. This affects the continuity principle as the mass balance is performed for the whole soil profile.

The standard error of estimate ranged from 0.410 m to 0.759 m for the predicted water table fluctuation. As noted previously the first two years show the best fit. Regime A shows the best fit for all the years, except 1985. The difference in simulated and measured water table fluctuations (0.410 m to 0.759 m for standard error and 0.34 to 0.67 m for average deviation) are acceptable when the numerous factors affecting the water table elevation in the field are considered.

Table 4.2 Standard error and average deviation for the comparison of simulated and observed water table elevation (m).

DRAINAGE REGIME	1985 S	1985 α	1986 S	1986 α	1987 S	1987 α	1988 S	1988 α
REGIME A	0.421	0.340	0.439	0.371	0.420	0.356	0.449	0.378
REGIME B	0.410	0.343	0.576	0.508	0.528	0.457	0.613	0.502
REGIME C	0.458	0.377	0.572	0.496	0.587	0.567	0.759	0.670

Table 4.3 shows that the standard error and average deviation for the wet season or the time when the drawdown was less 110 cm (i.e., the drain depth). For the wet period, the standard error of estimate ranged from 0.317 to 0.523 and the average deviation from 0.251 to 0.460 m. Among the three regimes, regime B shows the best fit for all the four years. The model predictions for the wet period are better than

for the dry period or the whole year.

Table 4.3 Standard error and average deviation for the comparison of simulated and observed water table elevation for the wet season (i e.,from January 1 st to May 31 st) (m).

DRAINAGE REGIME	1985 S	1985 α	1986 S	1986 α	1987 S	1987 α	1988 S	1988 α
REGIME A	0.440	0.359	0.317	0.251	0.456	0.410	0.414	0.337
REGIME B	0.382	0.320	0.347	0.290	0.629	0.572	0.418	0.355
REGIME C	0.418	0.344	0.342	0.288	0.693	0.617	0.523	0.463

A closer examination of the simulated water table elevation as shown in Figure 4.23 shows that the simulated water table responded faster to a precipitation event as compared to the measured values. On day 17, there was 37.3 mm of precipitation and simulated water table rose rapidly to peak on the same day whereas the observed water table showed a lag time of one day to peak. Similarly, the simulated water table reached the peak on the day of precipitation whereas the observed water table shows a lag time of one day to peak as seen in Figure 4.23 on days 26, 29, 35, 46 and 65.

A similar trend was also observed for draining water tables as well as seen in Figure 4.23 on days 22, 26, 30, 46, 57 and 65. The simulated water table drains rapidly whereas the observed water table drains at a slower rate. Overall the model appeared to respond well to a precipitation event. Following periods of rainfall the measured water table peaks tend to be higher than the predicted values. When the water table dropped below the level of the drain, the model predicted a deeper water table.

As shown in Figure 4.24, subirrigation started on day 211 and ends on day 251. The simulated and observed water table peaked on day 217 (i.e., six days after the initiation of subirrigation). The

observed and simulated water table rose by 0.375 m and 0.175 m, respectively. Thus the simulation water table profile had a lower porosity than the field.

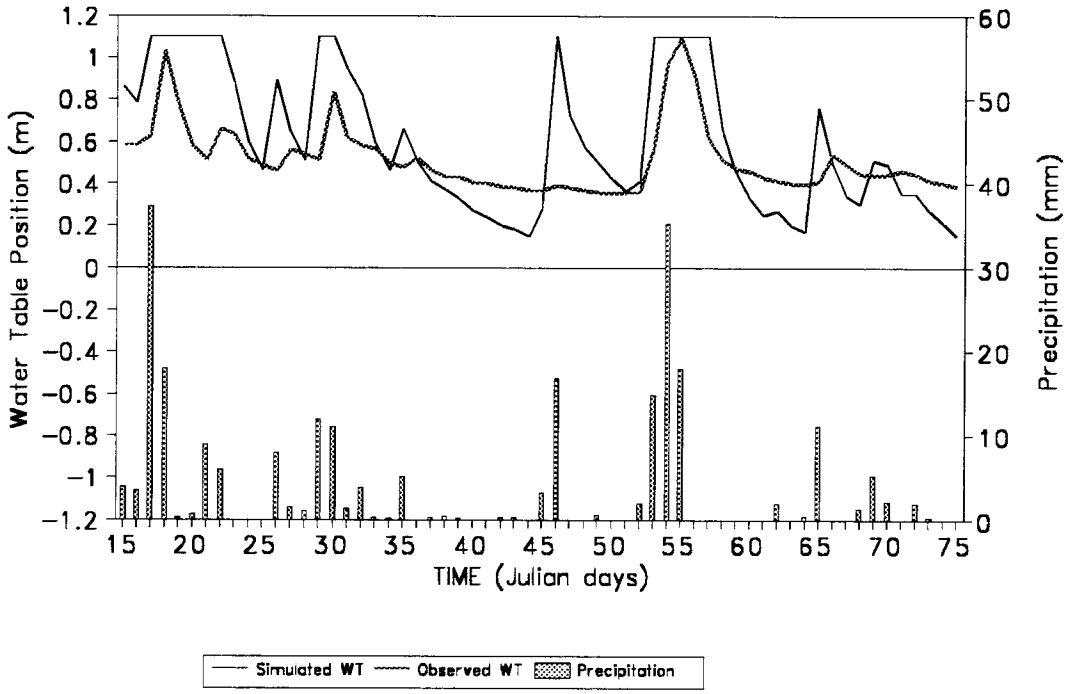

Figure 4.23 Simulated and observed water table fluctuation for regime A (1986).

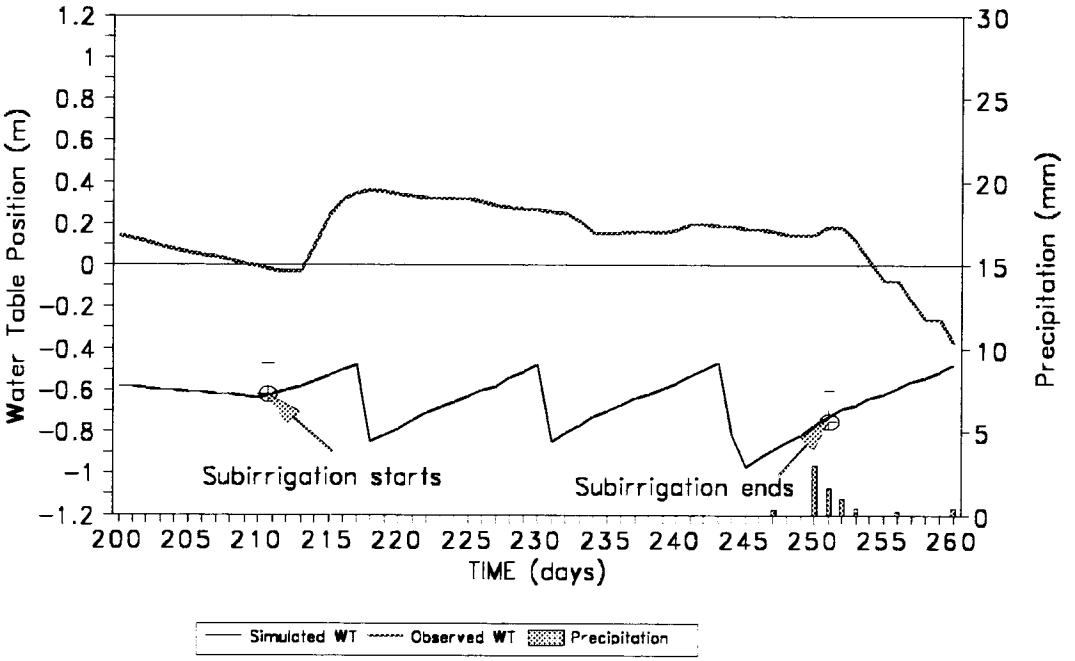

Figure 4.24 Simulated and observed water table fluctuation during subirrigation for regime B (1986).

The sharp rise in water table due to rainfall is of particular interest in the design of subsurface drainage and subirrigation systems. The quick rising and falling of the water table is an indicator of lower drainable porosity values, which are considered in DRAINMOD indirectly (i.e., through the volume drained versus water table depth relationship).

The calculated PET and simulated evapotranspiration for years 1985-1988 are shown in Figures 4.25 - 4.28. The PET were calculated using Penman method and were obtained from Gao (1990). The calculated PET and simulated ET for only regime C is shown as the PET for other regimes (A and B) are very similar to that of regime C.

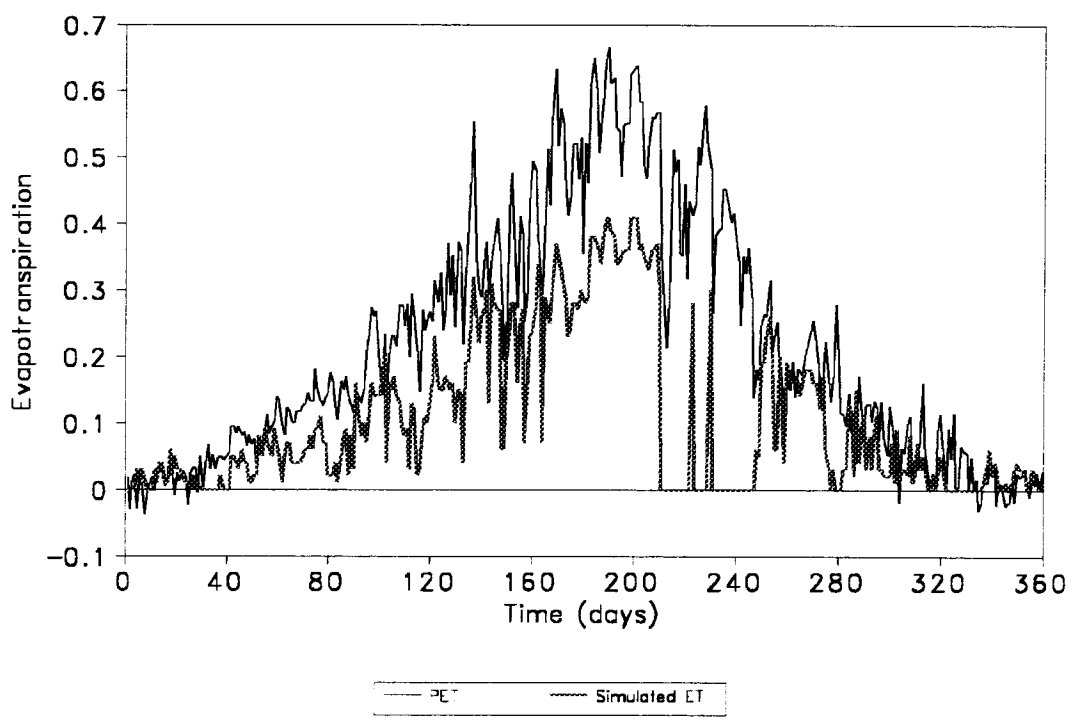

Figure 4.25 Simulated ET for regime C and calculated PET (1985).

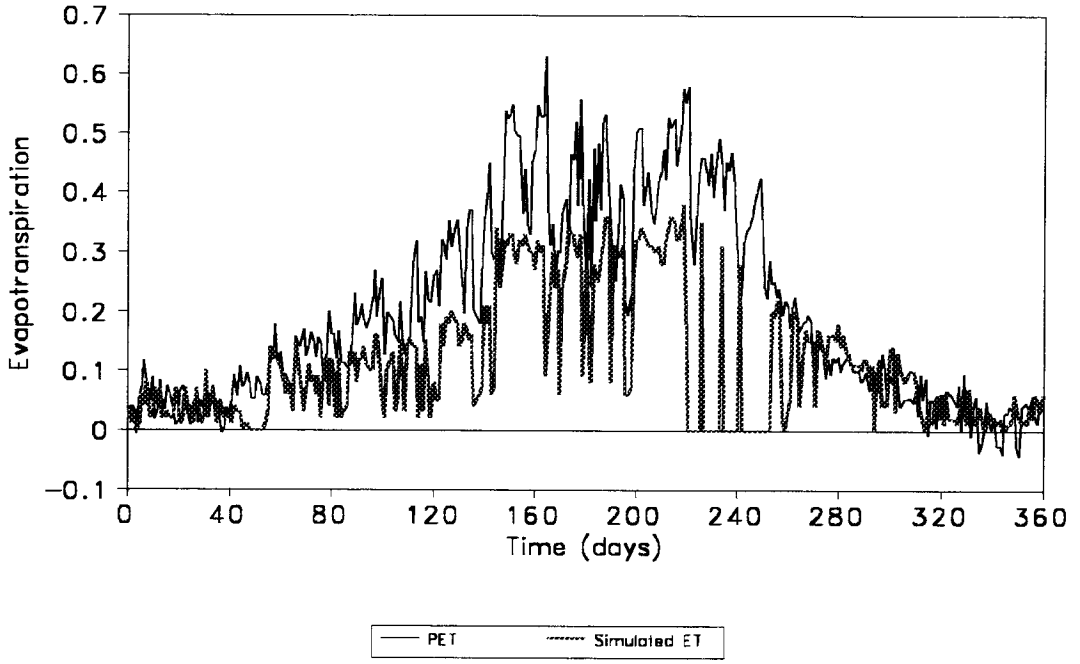

Figure 4.26 Simulated ET for regime C and calculated PET (1986).

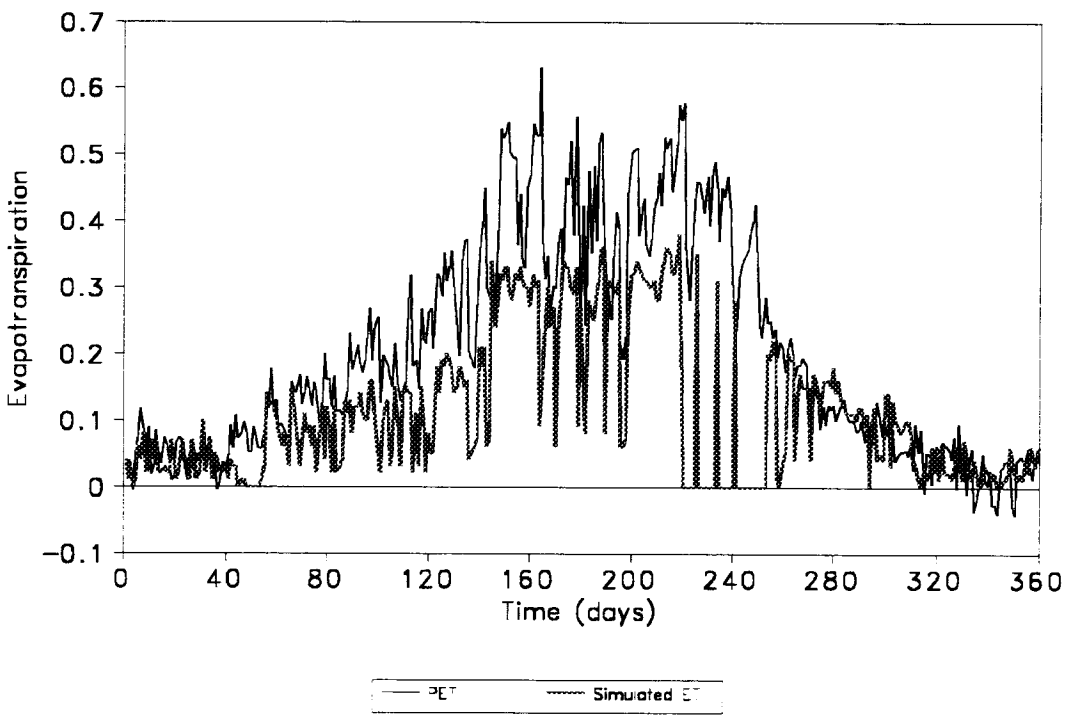

Figure 4.27 Simulated ET for regime C and calculated PET (1987).

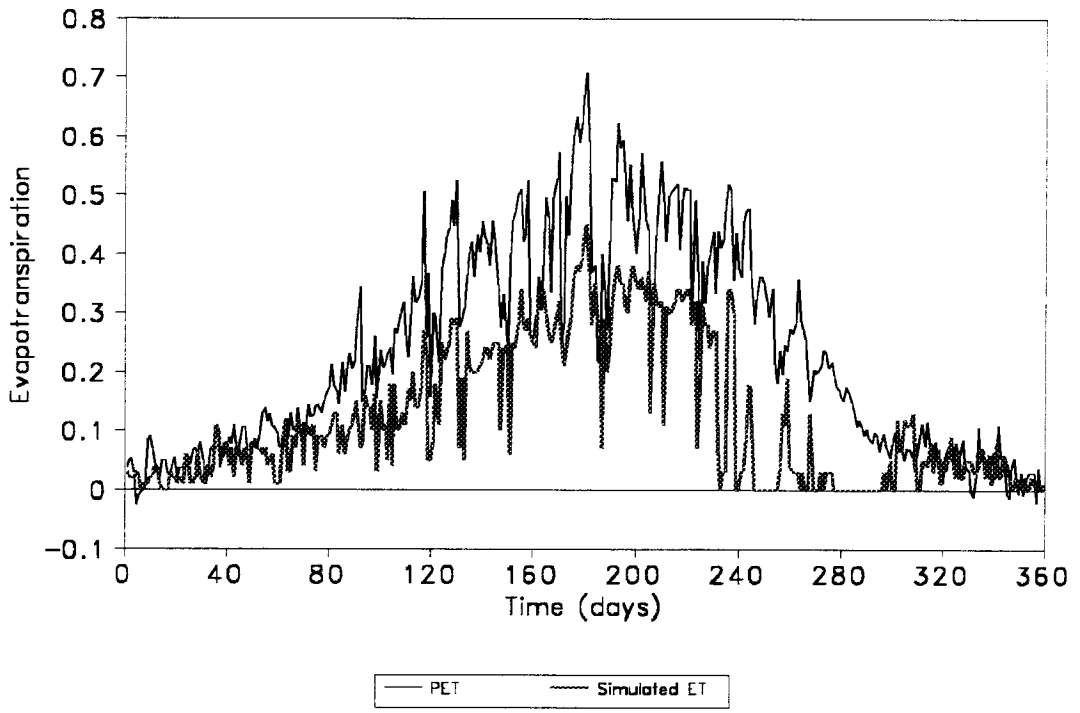

Figure 4.28 Simulated ET for regime C and calculated PET (1988).

The actual ET, however, is generally a function of PET but is also affected by soil water availability, plant canopy coverage of the surface, etc., therefore DRAINMOD simulated different ET values for each regime. As shown in Table 4.4, the standard error of estimate ranged from 0.150 mm/day to 0.189 mm/day. Thus for humid conditions as in the LFV, instead of simulating PET from DRAINMOD, PET should be computed from Penman method. PET input data should be used, instead of temperature input data for better estimation of ET. If data for Penman method is unavailable, FAO Blaney-Criddle method should be used.

Jensen et al., (1990) showed that Thornthwaite method had a weighted standard error of 0.86 mm/day and a standard error of estimate of 0.79 mm/day whereas Penman method had a weighted standard error of 0.32 mm/day and a standard error of estimate of 0.31 mm/day for humid conditions. FAO Blaney-Criddle method has a weighted standard error of 0.79 and standard error of estimate of 0.71 mm/day.

Table 4.4 Standard error and average deviation for the comparison of model simulated evapotranspiration and calculated PET.

DRAINAGE REGIME	1985 S	1985 α	1986 S	1986 α	1987 S	1987 α	1988 S	1988 α
REGIME A	0.187	0.128	0.171	0.117	0.189	0.134	0.181	0.125
REGIME B	0.172	0.117	0.155	0.189	0.165	0.122	0.158	0.112
REGIME C	0.165	0.116	0.152	0.104	0.151	0.114	0.150	0.107

The requirements for Thornthwaite equation are that the albedo of the evaporating surface must be standard (i.e., uniform throughout the year). The rate of evaporation must not be influenced by advection of moist or dry air and the ratio of energy utilized in evaporation to that of the heating of the air must remain essentially constant.

Albedo is of the order of 10 to 30 % for vegetation and 15 to 40 % for bare soil (being lower for wet dark clays and higher for light colored sands) (Hillel, 1990). Therefore in the LFV, where the cropping season is only 5-6 months, the albedo varies in the range of 10 to 30 % for the cropping season and 15 to 40 % for the non cropping period. Therefore the non-uniform albedo results in the large standard error of estimate and higher average deviation.

The Thornthwaite method is based on the exponential relation between mean monthly temperature and mean monthly consumptive use. It makes no allowance for different crops or varying land uses as the formula was originally developed for the purpose of a rational classification of the broad climatic patterns of the world.

DRAINMOD tended to predict a deeper water table than measured for most of the period evaluated. The model predicted a more rapid drainage and subirrigation of the soil profile than observed in the field. This can be seen in Figure 4.13, 4.14 and 4.15 around days 120 and 140. The over predictions could result from the hydraulic conductivity input values being greater than actual field values. Simulations with lower hydraulic conductivities values improved the result of the model. The model is very sensitive to saturated hydraulic conductivity values (Skaggs, 1978)

The peaks and the valleys had a larger magnitude of response which could be attributed to higher storage capacity as a result of the soil preparation programs. Since most of the soil data was not available, the number of assumptions and approximations resulted in higher storage capacity.

Another reason for the errors in the water table depth prediction by DRAINMOD are inaccuracies in predicted evaporation and transpiration. An example of the problem can be seen in Figure 4.21 during the period between days 240 and 250 when the midpoint water table depth was at or below the drains. Since water could not leave the system through the drain, the only remaining pathway was soil evaporation and plant transpiration. The continued recession of the predicted water table depth while the observed water table remained at the drain depth indicates that evapotranspiration must have been overestimated by DRAINMOD.

In every case the agreement between the simulated and observed results could be improved by changing one or more of the model inputs. However, changing the inputs to improve agreements with the observed data would not provide a meaningful result of model reliability. The results could be improved by making more field measurements of the soil properties, thereby eliminating most of the approximations used in soil data preparation.

4.4 Capillary Rise

Soil capillary action and diffusion draw water upward from the water table to provide suitable soil moisture for root growth. Since the zone of aeration begins at the top of the capillary fringe, the top of the capillary is more significant for crop growth than the water table. The capillary fringe forms the boundary between the saturated hydraulic conductivity and the unsaturated hydraulic conductivity. The top of the capillary fringe therefore forms the upper boundary of the drainage flow or subirrigation system.

A capillary rise of approximately 24 cm above the water table was observed during the laboratory experiment in the sand tank as shown in Figure 4.7 where the difference between the water table profile and wetting front profile is the capillary rise or the unsaturated flow. Silin-Bekchurin (1958) had suggested a capillary rise of 35-70 cm in fine sand. A more accurate result was obtained from the capillary rise test column as shown in Figure 4.27. The water was drawn upward due to the flux created by the dry sand conditions. As shown in the figure, the actual range of capillary rise for experimental sand is 27.5 to 33.5 cm for hydraulic heads of 10 to 50 cm. An average capillary rise of 29 cm for an average hydraulic head of 30 cm was observed.

The relation of capillary rise and water table elevation are shown in Figure 4.29. The height of capillary rise had a linear relation to the height of the water table as expressed by as Equation 4.3:

$$h_c = 0.18h + 25.5 \tag{4.3}$$

where,

h_c = height of capillary rise in cm and

h = hydraulic head in cm.

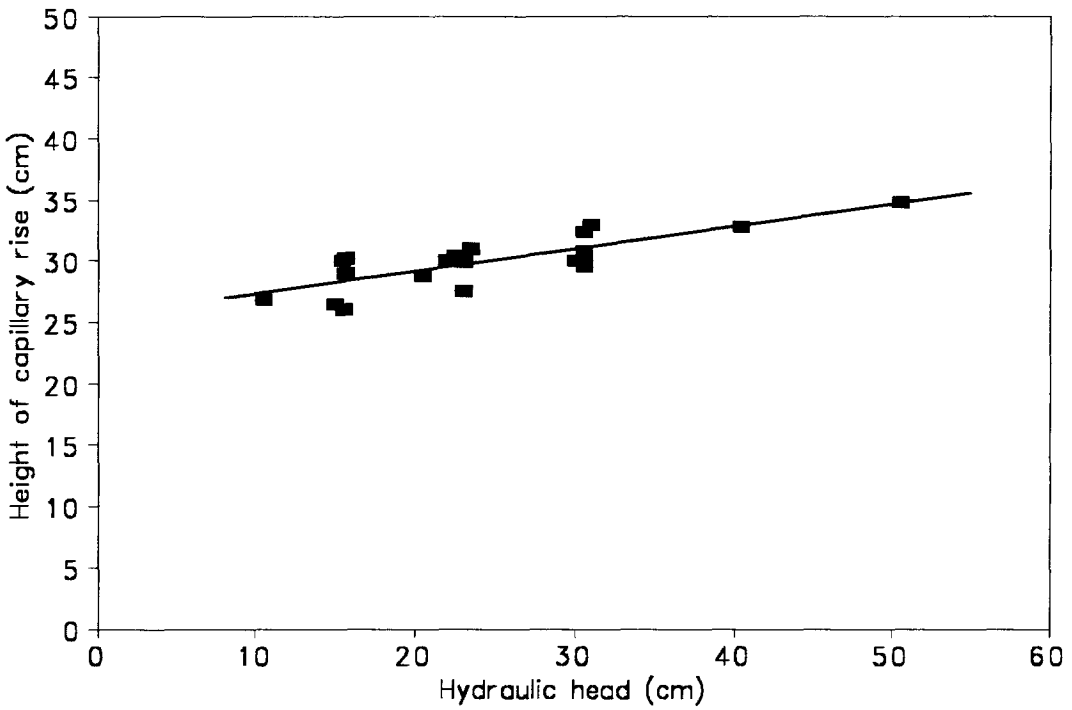

Figure 4.29 Relationship between water table elevation and capillary rise.

The standard error of estimate for height of capillary rise is 1.6 cm. As per the Polubarinova-Kochina equation (Equation 2.5) the height of capillary rise for fine sand used in this study would be 73.56 cm (with d_{10} = 0.13 mm and n = 0.32). This value is about 2.6 times higher than the average observed value.

The actual height of capillary rise from the water table can vary widely depending on the textural and humus content differences in the soil profile and on the depth of the water table (Bloeman, 1980).

The terminal capillary response time could not be determined but it was observed that the capillary rise stabilizes after 72 hours in most cases. For all practical purposes 72 hours could be treated as terminal capillary response time.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

A physical model was used to evaluate the shape of the water table profile and the capillary rise in a subirrigation system. From the experiments, the following conclusions can be made:

1. A slow transition from semi elliptical water table profile at the initiation of irrigation to nearly flat water table profile at stable state is observed. The hydraulic head does not result in the change in the shape of the water table but causes a initial change only in the position of the water table.

2. A linear relationship between capillary rise and water table elevation was obtained as given in Equation 4.3. A average capillary rise of 29 cm was observed for an average hydraulic head of 30 cm, with a terminal capillary response time of about 72 hours.

Subsurface drainage and subirrigation was simulated in the LFV using DRAINMOD. The following conclusions can be made from the simulation results.

3. DRAINMOD could be used to simulate the performance of subsurface drainage and subirrigation in the Lower Fraser Valley with some modifications. The water table elevations simulated by DRAINMOD agreed reasonably well with observed water table elevations for the 4 year period (1985-1988) in the LFV.

4. In general the model preditions followed the trend of the observed values. The model predicted a more rapid drainage and subirrigation of the soil profile than actually observed in the field. The model also showed a higher water storage capacity for the soil profile.

5. The model overestimated the evapotranspiration as well as the water table depth when the water table drawdown exceeded 110 cm (i.e., the drain depth).

6. The standard error of estimate of daily water table depth ranged from 0.41 m to 0.759 m. The average absolute deviation between predicted and observed water table depths for 4 year of data (approximately 4300 pairs of predicted and measured values) was 0.519 m and 0.447 m and 0.448 m and 0.383 for the whole year and wet season,respectively. It is concluded that DRAINMOD simulated conventional subsurface drainage and subirrigation better for the wet season during the year.

5.2 Recommendations

As a result of this study, the following recommendations are made for further investigation:

1. Numerical methods should be used to solve Richards or Boussinesq equation and the solutions should be compared with the results from the physical model.

2. For evaluating the reliability of the model, actual field measurement of soil properties is recommended.

3. To use DRAINMOD in the LFV, the Thornthwaite method for estimation of ET used in the model should be replaced by Penman or Blaney-Criddle method depending upon the data availability.

4. DRAINMOD should be modified to simulate for undrained conditions as well to get a better comparative idea of the advantages of a water management system.

5. DRAINMOD could be evaluated using the laboratory experimental setup (the one used for water table profile evaluation) with soil from the field experimental plot to minimize spatial variability of soil properties..

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APPENDIX A

SOIL PHYSICAL CHARACTERISTICS AND SOIL WATER RETENTION CHARACTERISTICS

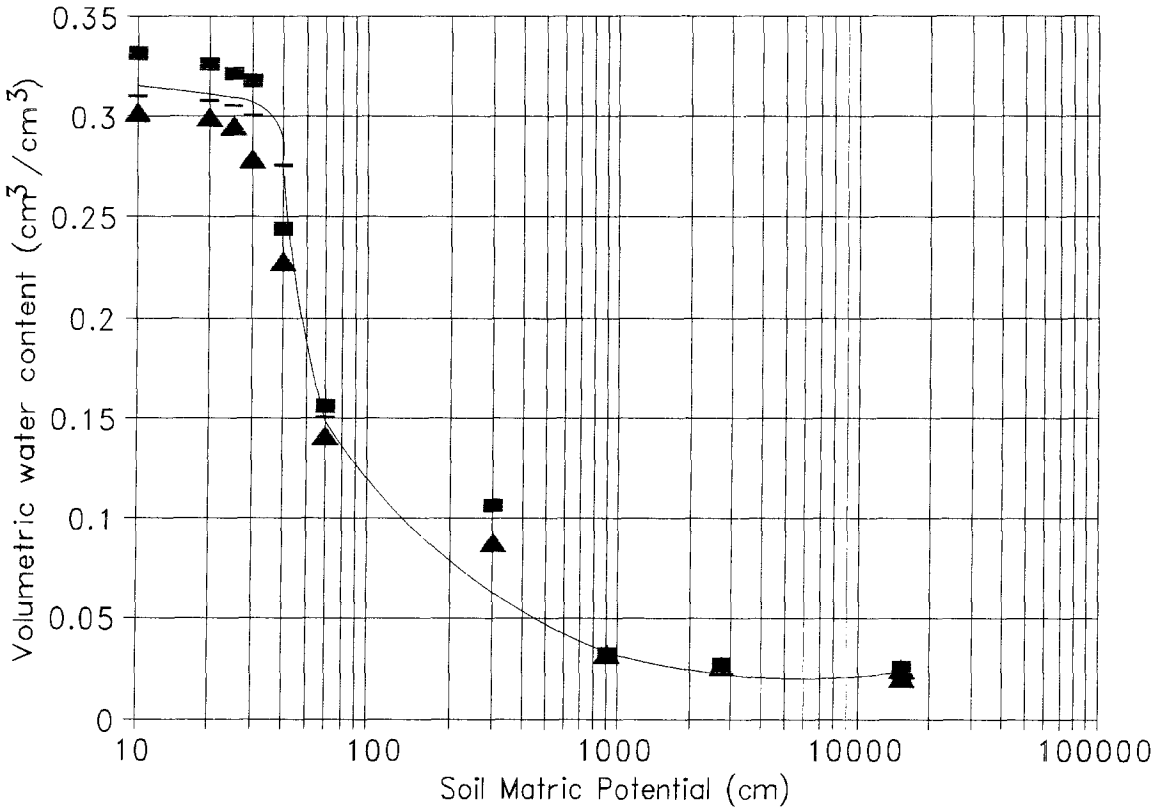

Figure A.1 Soil water retention characteristic curve for sand.

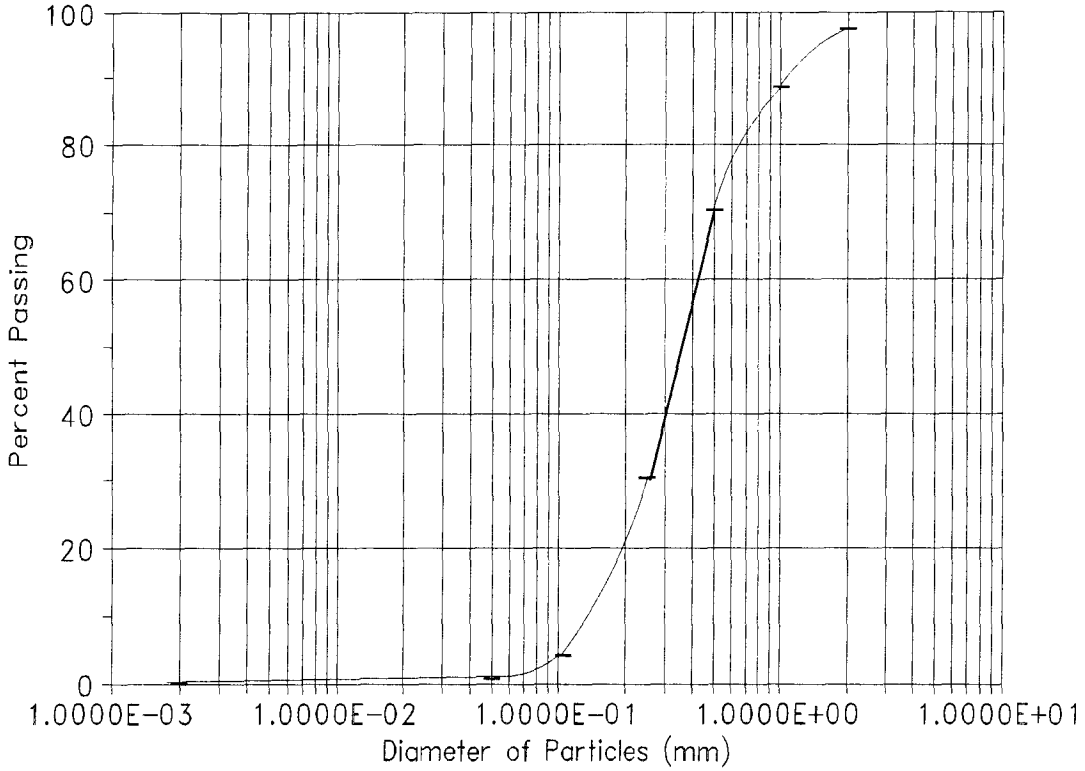

Figure A.2 Particle size distribution curve for sand.

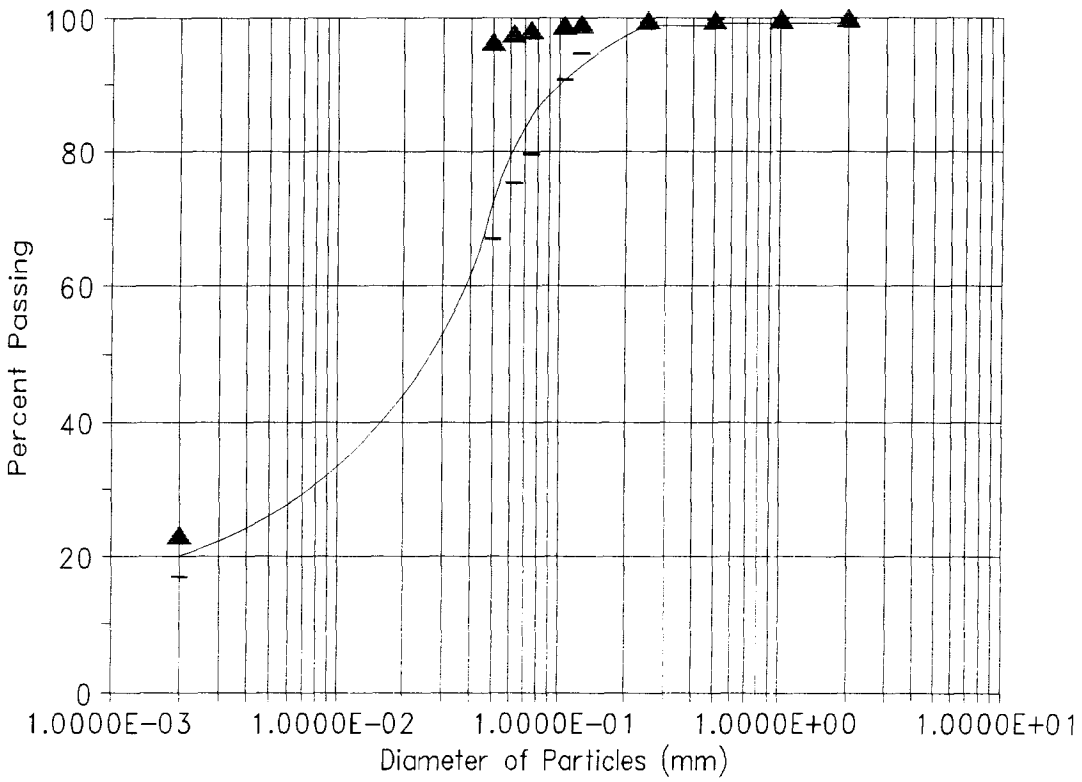

Figure A.3 Particle size distribution curve for Boundary Bay soil.

APPENDIX B

WETTING FRONT PROFILES FOR DIFFERENT DRAIN SPACINGS

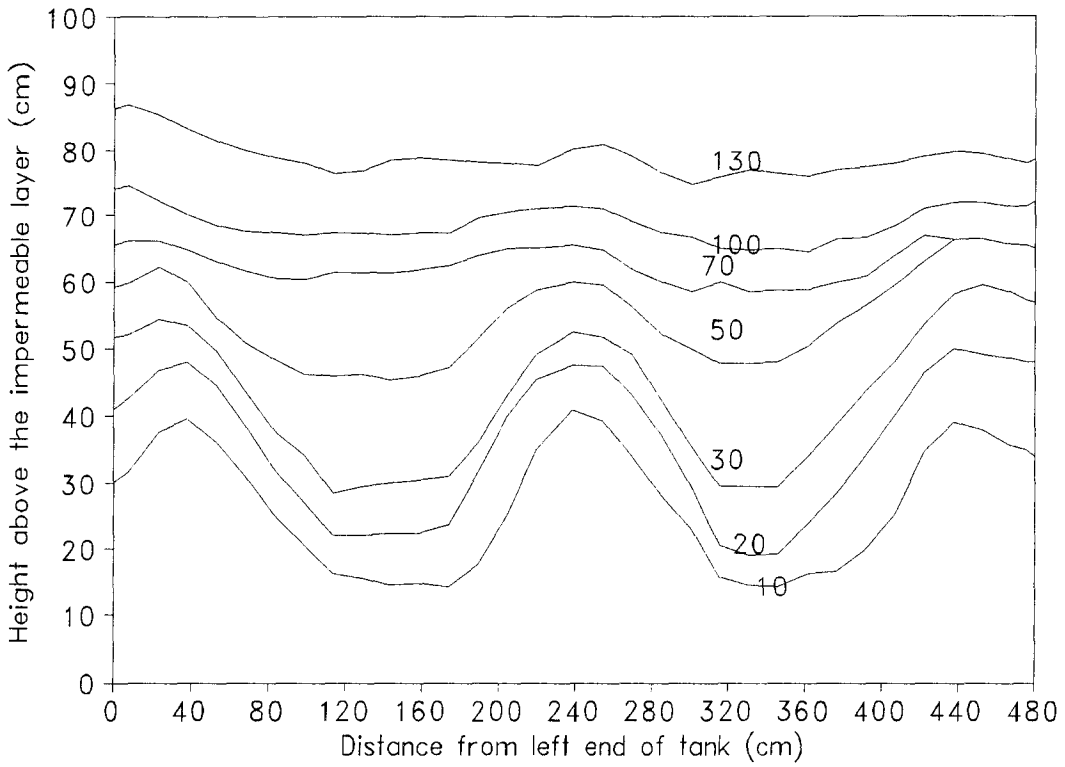

Figure B.1 Wetting front profile for a 2 m drain spacing for a hydraulic head of 95 cm.

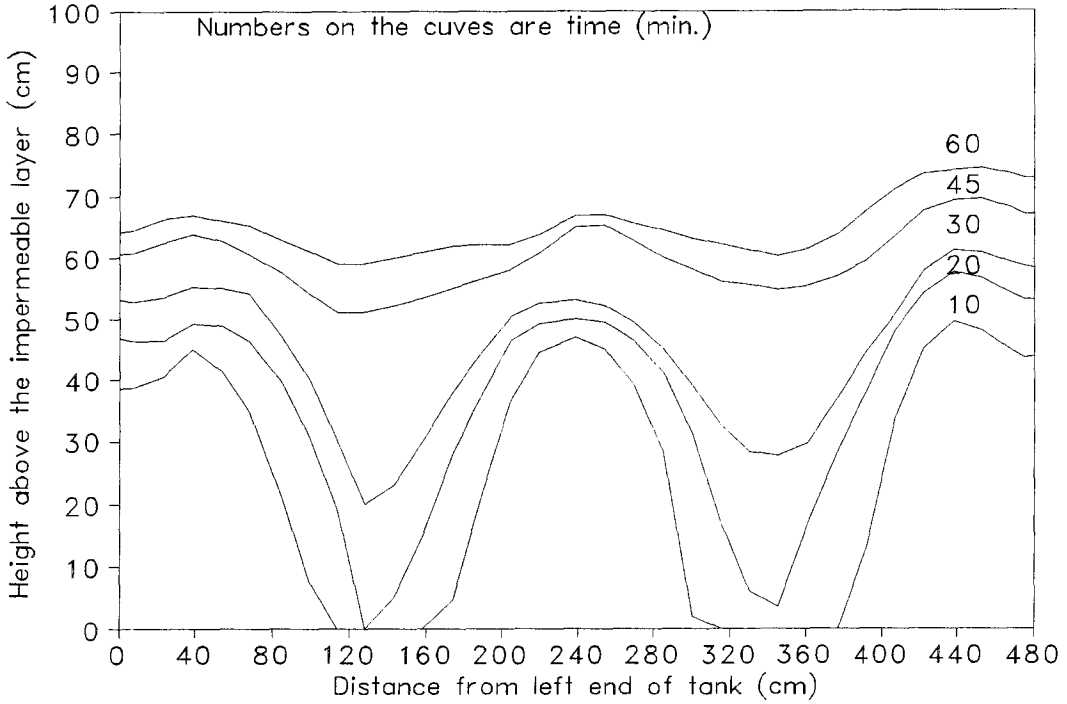

Figure B.2 Wetting front profile for a 2 m drain spacing for a hydraulic head of 70 cm.

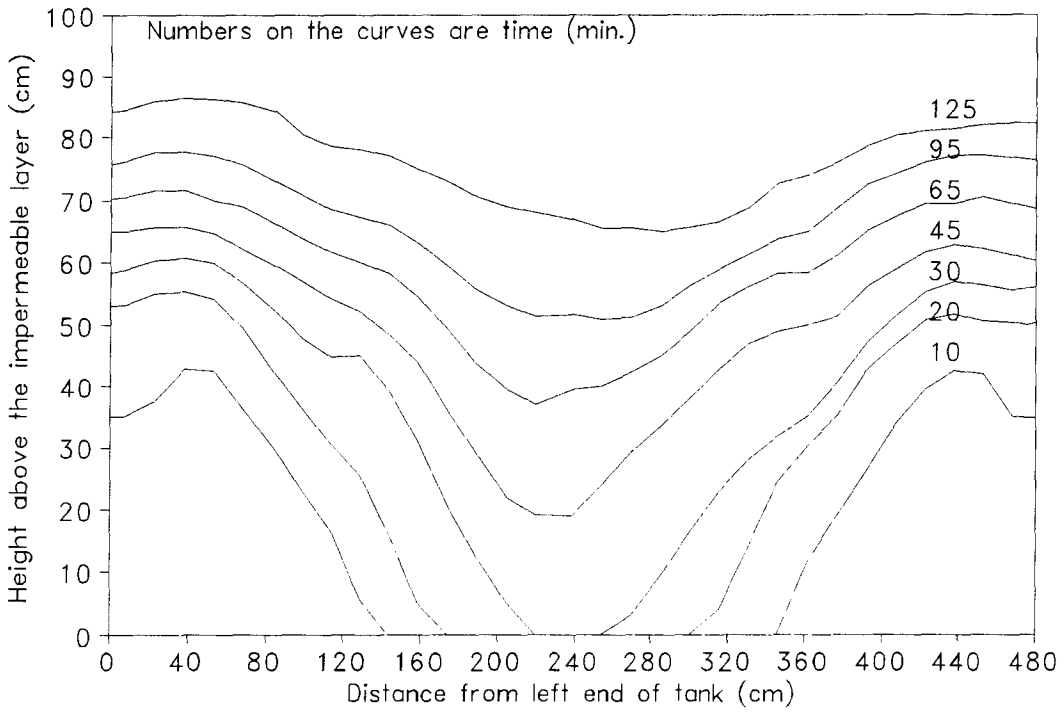

Figure B.3 Wetting front profile for a 4 m drain spacing for a hydraulic head of 95 cm.

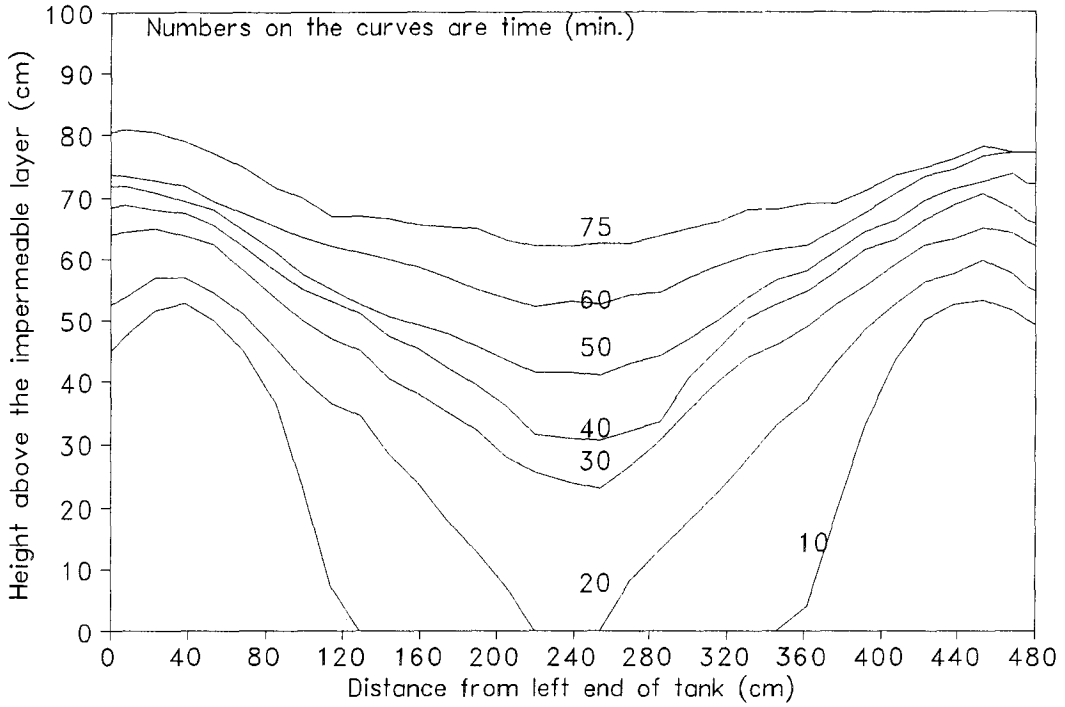

Figure B.4 Wetting front profile for a 4 m drain spacing for a hydraulic head of 85 cm.

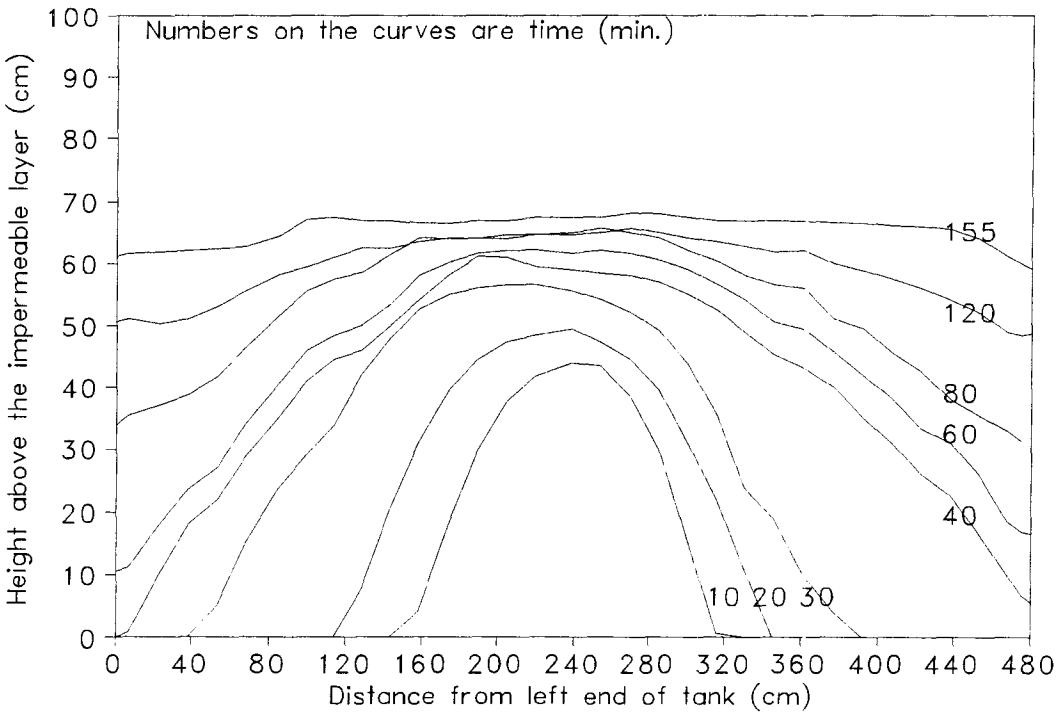

Figure B.5 Wetting front profile for a 4.88 m drain spacing for a hydraulic head of 75 cm.

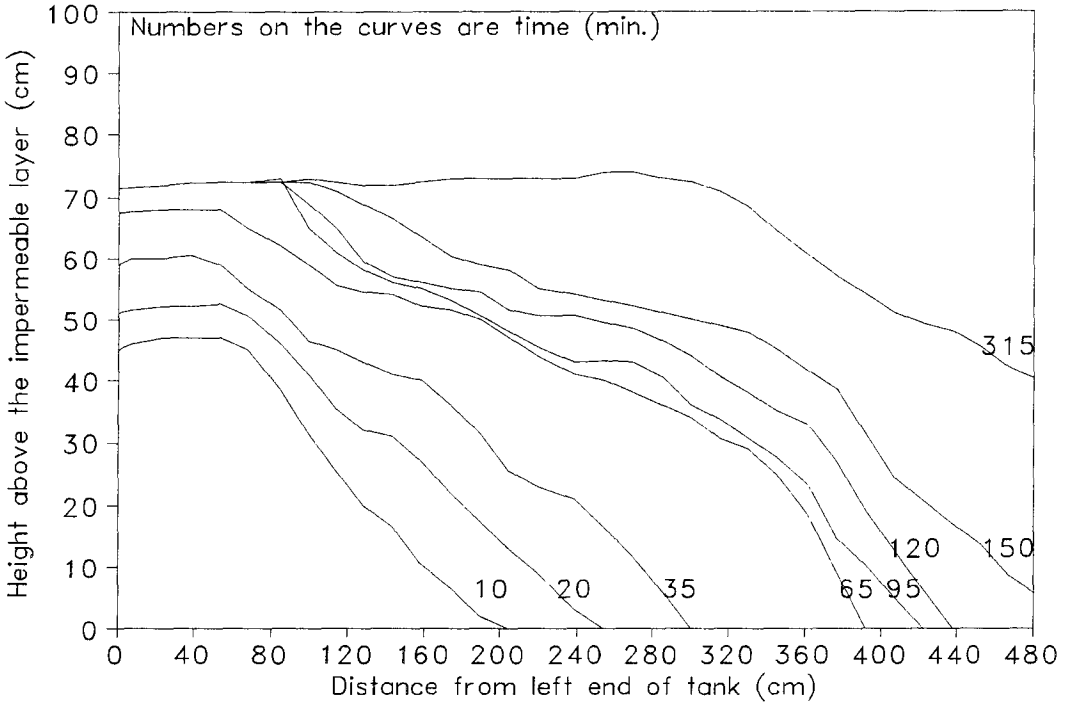

Figure B.6 Wetting front profile for a 8.88 m drain spacing for a hydraulic head of 80 cm.

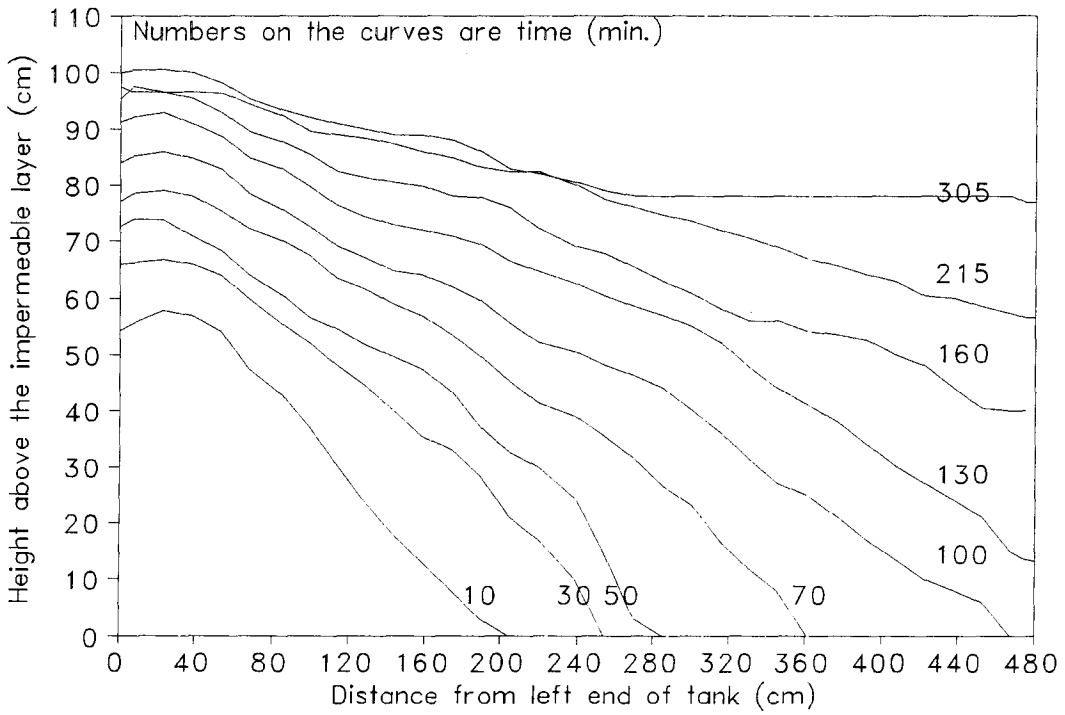

Figure B.7 Wetting front profile for a 8.88 m drain spacing for a hydraulic head of 105 cm.