LINKFLOW,

A LINKED SATURATED - UNSATURATED WATER FLOW COMPUTER MODEL FOR DRAINAGE AND SUBIRRIGATION

by

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LINKFLOW, A COMPUTER MODEL FOR DRAINAGE AND SUBIRRIGATION

Abstract

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LINKFLOW, A LINKED SATURATED - UNSATURATED WATER FLOW MODEL FOR DRAINAGE AND SUBIRRIGATION

A computer simulation model, LINKFLOW, has been developed to simulate the movement of water during various water table management practices, such as subsurface drainage, controlled drainage and subirrigation. Water movement is simulated to, or from, a buried tile drainage system through a heterogeneous and anisotropic soil to a zone of water extraction by plant roots and the atmosphere. The computer package links a newly-developed one-dimensional unsaturated ground water flow model to a three-dimensional saturated water flow model that was modified for the linkage and for simulating water flow under different water table management systems and varying climatic conditions. The movement of water is determined for a region of the field and the model can show the effectiveness of a water table management scheme to meet moisture conditions for crop growth for a wide range of soil, topographical, drain layout and weather conditions. LINKFLOW was validated and verified with measurements on subsurface drainage, controlled drainage and subirrigation systems in a corn field in southwestern Quebec. The model provides a powerful tool for the design and evaluation of water table management systems, and it can assist in developing control strategies for efficient management of water resources. LINKFLOW is unique among soil water models for the following features: 1) it can be used to simulate with varying topography; 2) it determines 3-D flows from drains in a heterogeneous, anisotropic soil; 3) it presents results in tabular format, contour map format, or

3-D surface format; and 4) it contains software routines for automated control in subirrigation. The formation of the conceptual model, numerical relations, methods of solution, validation, field verification and examples are presented.

Resume

Ph.D. Peter Havard Génie Rural

LINKFLOW - Un modèle de simulation des écoulements de l'eau en milieux saturés et non saturés, pour l'irrigation souterraine et le drainage.

LINKFLOW, un modèle informatique, a été développé afin de simuler le mouvement de l'eau selon le mode de gestion de la nappe phréatique: drainage souterrain, drainage contrôlé ou irrigation souterraine. Le modèle simule les écoulements hydriques entre le réseau de drains souterrains et une zone du sol où les plantes extraient l'eau. Le modèle peut être utilisé dans des sols hétérogènes et anisotropes. Le logiciel développé lie un nouveau modèle de simulation des écoulements hydriques dans une dimension et dans un milieu non saturé, à un modèle existant qui simule les mouvements de l'eau dans les trois dimensions en milieu saturé. Ce dernier modèle a été modifié pour simuler les écoulements de l'eau dans différents modes de gestion de la nappe et pour des conditions climatiques variables. Le logiciel simule les écoulements hydriques dans des sections de champs pour une grande variété de sols, de topographie et de climat, et permet de déterminer l'efficacité du système de gestion de nappe adopté. LINKFLOW a été validé et vérifié avec observation sur drainage souterrain, drainage contrôlé et irrigation souterraine dans un champ de maïs du secteur sud-ouest de la province de Québec. Le modèle développé est un outil puissant pour la conception et l'évaluation de systèmes de gestion de la nappe et permet d'élaborer une stratégie efficace de gestion des ressources hydriques. LINKFLOW est un modèle unique qui se distingue pour les raisons suivantes:

1) les simulations peuvent être faites pour des conditions de topographie variable; 2) le mouvement de l'eau en 3 dimensions à partir des drains dans les sols hétérogènes anisotropes peut être simulé; 3) les résultats peuvent être présentés sous forme de tableaux, de cartes avec courbes de niveau ou de graphiques en 3 dimensions 4) le modèle comprend des sous-programmes qui permettent de simuler des systèmes d'irrigation souterraine contrôlés automatiquement. Les étapes de conception du modèle, les relations numériques utilisées, les méthodes de solution aux problèmes, de validation et de vérifications aux champs ainsi que des exemples sont présentés.

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A_j,B_j,C_j	coefficients of Equation 21 ((m-day)$^{-1}$)
AWC	available water in root zone for plants (m)
B_1,B_2,B_3	coefficients of Equation 38
C_1,C_2,C_3	coefficients of Equation 39
$C(\psi),C^m_j$	moisture capacity (m^{-1})
CR,CC,CV	conductance values between nodes (m^2-day^{-1})
c_p	specific heat (J-kg^{-1})
d	distance from drain to impermeable layer (m)
d_e	adjusted distance from drain to impermeable layer (m)
dz,Δz	spacing between nodes (m)
D	drain flow (m)
D_j	coefficient of Equation 21 (day^{-1})
DAP	time from planting crop (days)
DEPTHF	weighting factor for root activity with depth
DS	deep seepage flow (m)
DTM	time to plant maturity (days)
e	rate of evapotranspiration (m-day^{-1})
e_a	saturated air vapour pressure (mbar)
e_d	actual air vapour pressure (mbar)
E	outflow due to evaporation (m)
E_i	evaporation of intercepted water (cm-day^{-1})
E_j,F_j	coefficients of Equation 28
E_{wet}	wet crop evapotransiration (cm-day^{-1})
ET	evapotranspiration (m)

ET_p	potential evapotranspiration (cm-day^{-1})
f	effective drainable porosity
h_o	distance from impermeable layer to WT. (m)
h'_o	adjusted distance from impermeable layer to WT. (m)
h_1	distance from impermeable layer to WT. (m)
h'_1	adjusted distance from impermeable layer to WT. (m)
i,j,k	space index coordinates
I	infiltration (m)
K	equivalent conductivity (m-day^{-1})
K_s	saturated hydraulic conductivity (m-day^{-1})
K_{drain}	drain conductivity (m^2-day^{-1} per m of pipe)
$K(\psi)$	unsaturated hydraulic conductivity function (m-day^{-1})
k_h	horizontal saturated conductivity (m-day^{-1})
k_v	vertical saturated conductivity (m-day^{-1})
L	drain spacing (m)
m	space index in time
M	difference in head between drain and mid spacing (m)
MC,$\theta(\psi)$	moisture content (volumetric)
n,α	coefficients in Equation 40
N	number of observations
NNODE	node number at soil surface
O_i	observed value
P	precipitation (m)
P_i	predicted value
$P_{i,j,k}$	sink term dependent on head (m^2-day^{-1})
PET	potential evapotranspiration (m-day^{-1})

q	flow rate betweem cells (m-day^{-1})
q_{wt}	flow across water table for time step (m)
Q	flow from WT. (m)
Q_{drain}	flow per length (m^3-day^{-1} -m^{-1})
$Q_{i,j,k}$	sink term independent of head (m^3-day^{-1})
Q_{sr}	rate of water flow from soil to roots (m^3-s^{-1})
r_e	effective drain radius (m)
r_a	diffusive resistance to water vapour for air (s-m^{-1})
r_s	diffusive resistance to water vapour for crop, soil (s-m^{-1})
R	coefficient of regression
R'	degree of anisotropy
R_p	water flow resistance of plant (s-m^{-2})
R_s	water flow resistance of soil (s-m^{-2})
R_n	net radiation flux (W-m^{-2})
RD	root depth (m)
RD_{max}	maximum root depth of crop at maturity (m)
RNODE	node number at bottom of root zone
RO	runoff (m)
S	sink term (m^3-m^{-3}-day^{-1})
S_e	effective saturation
$S(z),S(j)$	root water extraction term (m^3 -m^{-3}-day^{-1})
S_{max}	potential root water extraction (m^3-m^{-3}-day^{-1})
Ss	specific storage (m^{-1})
t	time (days)
T	outflow due to transpiration (m)
TD	time of day (days)

T_p	potential transpiration rate (m-day^{-1})
T_{s1}	morning hour (day)
T_{s2}	night hour (day)
WET	measure of water stress of the crop due to soil water
WT.	water table
x	distance in the horizontal direction (m)
Y_o	distance from drain to WT. at drain (m)
Y_1	distance from drain to WT. at mid drain spacing (m)
Z,z	distance in vertical direction (m)
Z_r	depth to bottom of root zone (m)
$\Delta c_i,\Delta r_j,\Delta v_k$	width,height,thickness of cells in saturated model (m)
ΔS	surface storage (m)
ΔV_A	change in drained air space (m)
ΔW	change in water storage (m)
β,Γ	terms in Equation 57
γ	psychrometric constant (mbar-K^{-1})
$\gamma(\psi)$	sink factor
θ	moisture content (mm^3-mm^{-3})
θ_s	moisture content at saturation (mm^3-mm^{-3})
θ_r	residual moisture content (mm^3-mm^{-3})
ψ	pressure head (m)
ψ_{50}	pressure head at 50% available water content (m)
ψ_{pwp}	pressure head at permanent wilting point (m)
ψ_{air}	pressure head at air entry point (m)
Ψ	total water potential (m)
$\Psi_{i,j,k}$	total water potential for cell (i,j,k) (m)

Ψ_{drain}	total water potential in drain (m)
Ψ_s	total water potential in soil next to roots (m)
Ψ_p	total water potential in plant (m)
σ_a	density of moist air (kg-m^{-3})
Ω	slope of saturated vapour pressure curve (mbar-K^{-1})

Contributions to Knowledge

The use of existing subsurface drainage systems as water table management systems in coarse and medium textured soils has been actively experimented with over the past ten years in eastern Canada and United States. Approximate methods have been used by designers to specify the drain layout criteria. However, much is unknown about how well these systems could work in other soils and in variable soil and topographic conditions. In this study, a model has been developed to simulate water flow for a wide range of conditions such as: heterogeneous and anisotropic soil, variable topography, subirrigation, drainage, infiltration and root water extraction. This is the first model to link a one-dimensional unsaturated flow model to a three-dimensional saturated flow model for calculation of water flows in subsurface drained farmlands at a field scale. This work contributes to the existing knowledge as follows:

1) A new computer model, LINKFLOW, that simulates 3-D saturated and 1-D unsaturated transient ground water flow has been developed for drainage, controlled drainage, subirrigation, and a combination of these systems. A 1-D unsaturated flow model was linked with a specially modified 3-D saturated flow model to achieve a detailed physical model with reduced computational requirements compared to a 3-D saturated-unsaturated flow model.

2) The model can simulate the operation of a subirrigation system using automated control that will change the water head supplied to the drains

according to current field water table levels or moisture levels in the root zone. This is a new feature for water table management models and when combined with the output information determined for water conditions over the entire area, provides a unique means to learn how to manage a system more effectively to provide crops water over a growing season.

3) The model can include soil heterogeneity and anisotropy in determining the movement of the water table for a given system. Most current design procedures assume homogeneous and isotropic conditions. Some do consider layered soil properties but each layer is considered homogeneous and isotropic. The model presented here provides new capabilities for considering these soil properties.

4) The model can simulate the effect of clay lenses on the performance of a water table management system. The location, size, and number of lenses may be varied to investigate the impact on water table movement.

5) The model can be used to simulate water movement on regions with sloping or varying topography. This, combined with the feature of contour maps of output variables or 3-dimensional surface representation, allows for new approaches to water table management research and development.

6) The inclusion of a collector and/or non parallel laterals can be simulated to define their effect on the uniformity of water removal or

delivery.

7) A new parameter called "WET" has been proposed to describe soil moisture conditions in respect to the crop, so that the uniformity of favorable moisture conditions in the field can be readily examined and evaluated.

In addition to the above contributions, the thesis presents examples of how to use LINKFLOW while evaluating different types of water table management systems. As a result the model can be used to design and evaluate various water table management options.

Chapter 1: Introduction

1.0 Introduction

The high costs associated with growing crops in North America has forced producers to search for any means of producing consistently high yields. Globally, consistent crop yields may be needed to avoid wide spread starvation, so any alternative strategies that ensure reliable crop performance are vital. Water table management can play an important role in stabilizing crop performance by reducing moisture stress in the root environment. Water table management applies to regions where a shallow ground water table exists or could be artificially created. Management involves lowering of the water table during wet periods, raising the water table to supply water to the crop during dry periods and maintaining it in periods neither wet or dry.

In humid regions, such as Eastern Canada, the benefits of artificial drainage to ensure good trafficability and root environments, especially during seedbed preparation, seeding and harvest have been established. Many shallow sandy soils in Eastern Canada would benefit from subsurface drainage, but due to an inherent unstable soil structure, sediment build up can occur in the drains reducing performance of the system. However, the advent of effective drain filter materials has resulted in more sandy soils being drained with subsurface drainage. The effect of over-drainage on sandy soils has been examined by Rashid-Noah (1981), who illustrated the need for careful water table management of these soils. A problem with sandy soils is that they have a low water holding capacity that results in a shortage of water for the crops during extended dry periods. In addition, as the water table is lowered, the amount of water held in a fixed depth of soil decreases due to higher matric potential (Criddle and Kalisvaart, 1967). Other soil types are affected to a varying extent depending on their water holding properties.

There are approximately 200,000 hectares of sandy soils in Quebec alone (Von Hoyningen Huene et al., 1986), and a climate pattern in southern Quebec such that 4 out of 5 years are dry enough to cause crop losses (Lake and Broughton, 1969). Water table management could improve crop yields most years on these soils. The interest in water table management is growing rapidly with producers who recognize the potential returns from a small investment in modifying existing drainage systems. The benefits of drainage on soil types in the region are well understood, however, the use of water table management techniques, such as subirrigation and controlled drainage, is new and not as well understood.

Tools to quantify the effect of different water table management systems allow designers to make knowledgeable decisions in system development. Computer simulation models are approximations of reality and aid in our understanding of how a system will react for a given set of conditions. The computer model developed in this dissertation furnishes a method to simulate water table management systems. The method works in a broad range of soil, topographic, and climatic conditions, and can be used to study the impact on the crop root environment due to modifications of a water table management system.

1.1 Statement and nature of problem

Subsurface drainage systems have been accepted in Eastern Canada for their benefits to crop environment, length of growing season and trafficability. New techniques for water table management can further increase the benefits of subsurface drainage systems. Water table management systems in humid areas control the height of the water table with consideration of the crop, its stage of development, and cultural practices. Water table management systems can be characterized into conventional drainage, controlled drainage and subirrigation. The purpose of conventional drainage is to lower the water table below the crop root zone within a certain period of time and it will continue to allow drainage to the drain depth or outlet elevation. Controlled drainage allows drainage to a user set water table level in order to conserve water and to benefit crop performance. Subirrigation maintains a water table level by supplying water through the drains to meet crop water demand.

Existing drainage systems can be modified to act as a water table management system. This has been shown to be technically and economically effective for subirrigation in the Eastern region of Canada (Gallichand, 1983; Von Hoyningen Huene, 1984; Memon, 1985; Plante and Prasher, 1991) and in other humid regions of the world (Skaggs,1980; Criddle and Kalisvaart,1967; Haman et al.,1986). The optimal height to maintain the water table during subirrigation depends upon the soil type, topography, crop and climatic factors present. Water flow in the soil during subirrigation uses the same mechanisms of water flow as during drainage. Therefore a model to describe subirrigation should be able to describe several types of water management systems. The model would need to include these mechanisms and be able to alter its boundary conditions to suit each water table management system. The focus in this thesis is primarily on the modelling of subirrigation, and secondly to test the model for application to other water table management systems. Designers and researchers developing subirrigation systems can use such a model to predict how well a system will work for a given set of conditions. Factors such as topography, soil heterogeneity, soil anisotropy, the transient nature of water movement and the uniformity of irrigation are not included in current models. The acceptance and success of water table management methods depends on our ability to understand how these systems work for a wide variety of conditions. Microcomputers are becoming a universal tool in design and information handling, thus an adaptive and compatible computer model is required to ensure that it can be readily used anywhere in the world.

1.2 Objectives

The overall objective of this thesis is to develop a field-scale soil water flow model which can simulate moisture conditions that occur in the soil profile during various water table management practices. More specific objectives are:

1. To develop a microcomputer-driven simulation model which can describe the transient movement of water during drainage, controlled drainage or subirrigation using a subsurface drainage system as the method of water removal/supply. The model should analyze the flow for varying topography in heterogeneous and anisotropic soils.

2. To validate the computer simulation model for various water table management options by comparing model results with field observations on water table management research plots and with other published studies.

3. To analyze the performance of a drainage/subirrigation system in non-uniform soils, with anisotropic conditions and presence of clay lenses.

4. To demonstrate the model's ability to simulate automated controllers and their effect on the performance of a subirrigation system.

This thesis has been organized in the following manner. Chapter 2 contains the Literature Review, where literature used to develop the computer model is discussed. This chapter also contains a review of basic theory concerning water movement in and to plants, and methods of quantifying water movement to and from drains. Chapter 3 describes the components of the model. Comparison of field measurements and simulation results of LINKFLOW is made in Chapter 4. The comparison includes verifying the developed unsaturated flow model with data from published reports and the comparison of field measurements from research plots to simulation values. The sensitivity of the model to various input parameter error is tested. This sensitivity will assist users of the model to know which input parameters cause the most impact on results. Chapter 5 examines a case example, using the model LINKFLOW, for an investigation of a water table management system. The use of the input program LINKINP and the simulation program's output are also discussed. Chapter 6 investigates the use of LINKFLOW to simulate water movement in soils with (1) anisotropic conditions, (2) the presence of lenses and

(3) an automated controller for system water levels. Chapter 7 contains a summary and the conclusions drawn from this thesis. Chapter 8 suggests areas for further research upon this topic. The thesis concludes with the references cited and appendices.

1.3 Scope of Project

A model has been developed to simulate flows to and/or from a subsurface drainage system that could provide subirrigation, conventional drainage and controlled drainage operation. The model does not account for overland or surface storage flows such as that occurring, for example, during surface drainage.

Water flow is assumed to occur due to differences in matric and gravitational gradients only; therefore, flows due to chemical, osmotic and thermal gradients are not considered.

The pumping facilities, water supply, or drainage outlets are assumed to be of sufficient capacity to maintain levels of water in the system.

Chapter 2: Review of Literature

2.0 Review of Literature

Water table management systems control primarily the shallow ground water table at levels beneficial for the crop, field trafficability and water conservation. In this chapter, the role of crop root water extraction as an objective of water table management and how it may be modeled are discussed. Following this, subirrigation will be described. This method of water supply to the roots is a newly developed approach to enhancing crop production in Eastern Canada. Few simulation models exist to model subirrigation, and none have been developed to consider three-dimensional water flow between drains and evaluate the uniformity of irrigation or drainage on the root environment. One reason for this, is the difficulty in modelling unsaturated water flow with its high calculation requirements, and the need for detailed soils information. Typically, drainage models do not treat for unsaturated flow since they need to lower water tables in short time frames so they can neglect the evaporation component and during drainage the greatest distances for flow are in the saturated zone. However, unsaturated flow is the primary mechanism of supplying water to the crop roots and should be included. The last part of this chapter examines the predominant design methods and how the developed model compares to them.

2.1 Crop Water Uptake

Crop growth will be reduced when there is a shortage of water in the root zone. A resulting reduction in crop yield will depend on a variety of factors such as agronomic and climatic history. Water deficit for a crop is defined as the difference of water a healthy plant can use compared to the amount of water the plant can remove from the soil. Water deficit in the crop develops due to the loss of moisture vapour from the plant's stomata being greater than the plant is able to replenish from the soil. The stomata are located on the leaves and open to allow uptake of CO_2 from the atmosphere for photosynthesis. Water loss through leaves and plant metabolization is replaced by water drawn from the soil through the roots, stems and leaves. Water moves in the plants due to the difference in total water potential between the atmosphere and the soil. The rate of flow in the plant is determined by this potential difference and the resistances to flow in the plant. The water loss in the leaves creates a low water potential, and if there is a difference in potential between the immediate soil environment and the plant, flow begins. The flow rate can be described by the following relation (Gardner, 1960):

$$Q_{rs} = \frac{\Psi_s - \Psi_p}{R_s + R_p} \tag{1}$$

Where Q_{rs} is the rate of water flow along a path from the soil to the roots to the leaves(m^3-s^{-1}); 'Ψ_s' and 'Ψ_p' are the total water potentials (m) of the soil and the plant, respectively; 'R_s' and 'R_p' are the resistances to water movement (s-m^{-2}) in the soil and plant. The resistance terms are inversely related to the conductivities for flow. The flow rate at any point along a path will be equal, so this equation may be applied at different locations of the plant or at the soil interface to find out intermediate pressure heads. There is some question as to the validity of this approach since the resistance in plants will change at low flow rates (Turner, 1986). However, it does illustrate the direct effect soil water potential has on the crop's ability to supply itself enough water for growth. Yields have been directly related to evapotranspiration of the crop (Hanks and Rasmussen, 1982). With respect to the availabilty of water, maximum crop yield can be achieved by maintaining the root zone in an optimal moisture level. The soil water status in the root zone is often described by the pressure head of the soil since it relates directly to accessibility of water to the crop.

Despite the complicated root geometry and the processes involved, some crop models have been developed to simulate water uptake on a microscopic level (Gardner, 1960; Tollner and Molz, 1983), where flow is radial around a single root. These models require abundant detailed input information to operate and have limited applications. An approximate approach has been to view the process from a macroscopic level, ie. the root system extracts water from a volume of soil in the root zone (Bellmans et al., 1983). The macroscopic approach simplifies the process and input information involved. Most ground water models incorporating root water extraction have a root-water extraction term (sink term) which is included in the governing equation for unsaturated flow. The objective of the sink term is to distribute the atmospheric demand over the root zone and to be sensitive to the water status of the soil (Alaerts et al., 1985). Feddes et al. (1978) and Hoogland et al. (1981) used the approach that the root water extraction term S(z) was estimated from the product of the potential root water extraction ($S_{max}(z)$, m^3-m^{-3}-day^{-1}) times a factor '$\gamma(\psi)$' (dimensionless sink factor) accounting for the pressure head effect in the profile (Equation 2). $\gamma(\psi)$ will have a value of 1 for good moisture conditions and decreasing values as the soil becomes excessively dry or wet.

$$S(z) = S_{max}(z)\gamma(\psi) \tag{2}$$

Hoogland et al. (1981) and Prasad (1988) also included the effect of depth, so that the potential root water extraction will vary with depth to reflect the increased work involved in bringing water from deeper depths in the soil. The maximum root extraction '$S_{max}(z)$' can be described as:

$$S_{max}(z) = \frac{2T_p}{Z_r}[1 - \frac{Z}{Z_r}] \tag{3}$$

where 'T_p' is the potential transpiration rate (m-day^{-1}) (the transpiration rate when the crop is not lacking moisture), 'Z_r' is the depth to bottom of root zone (m), and Z is the depth (m) from soil surface.

The root distribution will depend on the crop, the soil characteristics, and the water history in the soil profile. Surface irrigated crops tend to have shallow root zones since this is where the water usually concentrates. During subirrigation the roots can be limited to shallow depths by an overly high water table. This illustrates the need of proper water table elevation management. An empirical method of describing the depth of the root zone during a growing season is given by Borg and Grims (1986). The depth of the root zone, RD (m), given by Equation 4 is represented as a sinusoidal function of: the maximum root depth of a particular crop, 'RD_{max}'(m), the time from planting, 'DAP'(days), and the time to plant maturity, 'DTM'(days).

$$RD = RD_{max}[0.5 + 0.5\sin(3.03\frac{DAP}{DTM} - 1.47)] \tag{4}$$

They found that their model can be successfully applied to a wide variety crops and growing conditions. The simplicity of their model makes it well suited for incorporation into other models.

The effect of water deficit on crop yields will depend on such agronomic factors as, stage of growth, fertilizer use, health of the crop, its resistance to pathogens, weed competition and water logging (French and Scholtz,1984). Water deficit in Eastern Canada is often limiting only on a short-term seasonal basis, and on a diurnal basis when the potential water demand may exceed the water supply capacity of the soil for periods of the day (Stanhill, 1986).

The relations presented to describe root water extraction with consideration of diurnal effect, depth in soil and status of water in the root zone are important and should be incorporated into a physically-based model for crop water use. The model used in this thesis uses the relations described. The next section discusses subirrigation and how it may be used to meet the water requirements of the roots.

2.2 Subirrigation

Subirrigation has been practised in several parts of the world especially United States and Europe (Criddle and Kalisvaart, 1967; Skaggs et al., 1972; Haman et al., 1986). It can be used efficiently in humid areas where it has been combined with drainage systems. In Eastern Canada, the requirement for artificial drainage is often necessitated due to the presence of an impervious soil layer at a shallow depth that restricts deep drainage. This impervious layer can be beneficial in the operation of subirrigation systems by reducing deep seepage losses that could occur while maintaining a high water table. The following discussion will look at subirrigation systems using buried perforated pipes, typically installed in a grid pattern to distribute water to the field (Figure 1).

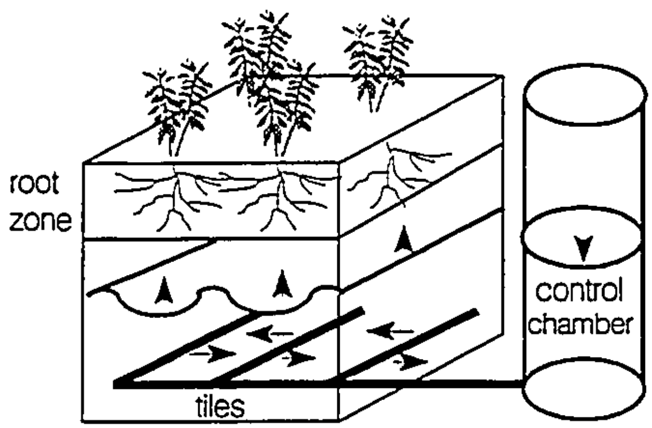

Figure 1. Schematic of a subirrigation system.

The control chamber maintains a water level high enough to supply water through the drain lines (tiles) to maintain a high enough water table to supply water to the root zone. The control chamber(s) will be located at one or more points in the subirrigation system depending on the topography and lateral extent of the system. A water table high enough in the soil so that capillary rise will meet the water requirements of the crop without limiting aeration in the root zone will vary in elevation depending on soil, crop and climate conditions.

Figure 2 illustrates the major flow processes occurring during the supply of water to the crop. Water flows out of the drains due to a higher water level in the control chamber. This creates a region of high water table near the drain lines resulting in largely saturated flows to the regions between drain lines in the field. Water flow in the unsaturated zone above the water table will be mainly vertical. The direction of flow to the plant roots and soil surface, during irrigation periods, will be upwards. These flows will fluctuate diurnally and could be reversed during periods of high precipitation.

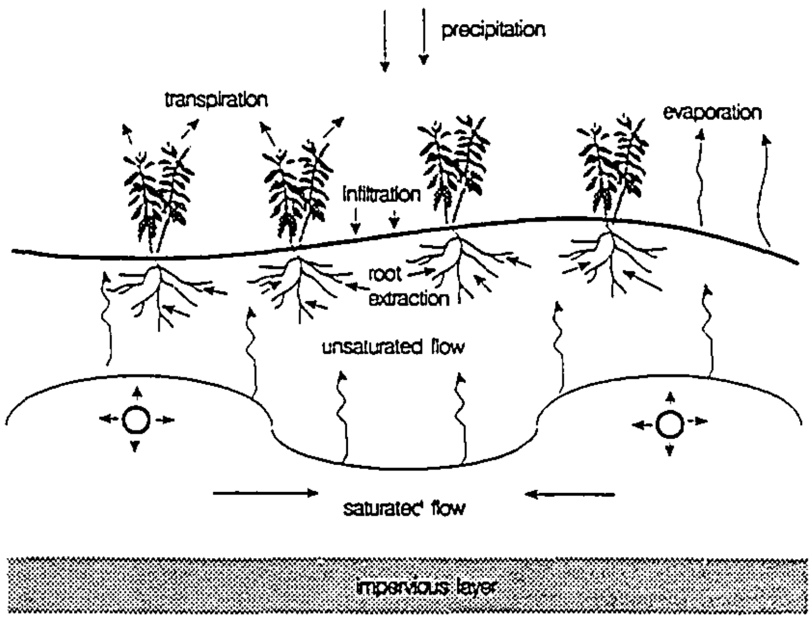

Figure 2. Conceptual model of processes involved in subirrigation.

Currently, most water table management systems use manual control for their operation. Manual control normally entails changing the head level in the control chamber based on experience, observations of water table depth in the field or crop conditions. A large rainfall would require the subirrigation system to be switched back to operate as a drainage system to avoid crop damage from excess water. This type of management may not be timely or consistent from year to year. Automated controls range in sophistication, but essentially they reduce or eliminate the need for manual adjustments by adding or removing water automatically from the control chamber in response to water levels in the field.

Fouss (1985) discussed the use of automated controls for water table management systems to optimize their ability to minimize periods of excess or deficit soil water conditions in the root zone. In addition, use of an automatic head controller promotes more efficient use of natural water resources and may decrease the use of pumped irrigation water. He discussed a modified version of DRAINMOD to simulate conditions while using automated control systems. Fouss et al. (1987) reported fair success in the use of DRAINMOD simulations when compared to actual control systems, but recommended that the model would simulate better if the soil conditions could be better characterised.

MacKenzie (1992) reported on two types of automated controls for water table management systems including a single and a double chamber type of system. The single chamber system responded to water levels in the control chamber to determine whether to operate in drainage or subirrigation mode, and the double chamber system responded to the water levels at drain lateral mid-spacing. While both control systems appeared to work satisfactorily, the double chamber type was the most responsive to field conditions. However, adequate simulation tools to describe how well they would work under different field conditions are not currently available.

Johnson et al. (1993) discussed the use of microcomputer controlled systems and field tested one using soil water pressure head measurements in the root zone as a control parameter. The use of a microcomputer allows greater flexibility in setting control strategies to optimize root zone conditions. In addition, the use of sensors to measure root zone water conditions is more directly related to crop performance than water table depth. Another advantage of microcomputer controlled systems compared to other systems is that additional parameters such as solar radiation, wind speed and rainfall can be included. Future control systems will be more sensitive and set water levels according to the crop type, stage of growth, current and future weather predictions, cultural practices, and the cost of available water. These control systems will greatly enhance the operation of water table management systems but adequate models to test their operation will need to be formulated both for their development and to aid in their operation.

Some advantages and disadvantages of subirrigation systems are listed in the following sections.

2.2.1 Advantages

1. It is often more cost-effective to convert an existing drainage system to operate as a dual irrigation-drainage system than to invest in separate drainage and irrigation schemes.

2. They are most effective on soils with low water holding capacity and high intake rates where other methods of irrigation would have higher labour, energy, equipment and water requirements.

3. Water is continuously supplied to the crop, while most other systems supply water periodically. This can ensure a higher quality crop due to consistency of soil moisture conditions.

4. Labour required for operation is low since the system is permanently set and little or no movement of equipment is necessary.

5. Much less land preparation is required compared to surface flood irrigation systems.

6. Evaporation losses are lower than surface irrigation systems.

7. Nutrient and chemical losses due to leaching are reduced since water movement is predominantly upwards through the root zone rather than falling through it, as is the case with other irrigation systems.

8. Less energy is required for pumping since operating heads in these systems are much lower than those used in sprinkler systems.

9. Farming operations are not hindered due to above ground obstructions such as ditches or piping.

11. Very little maintenance is required.

2.2.2 Disadvantages

1. Subirrigation works best with a specific combination of physical conditions not found in every field (i.e., high water table, medium or coarse textured soil, impermeable layer just below drain pipe level and flat land). The natural conditions where subirrigation will not work are

not well defined. Adequate evaluation methods do not exist.

2. It is desirable that adjoining lands use the same practice to avoid excessive lateral seepage losses or possible flooding of adjacent land.

3. Water low in salts may be necessary in some areas to avoid salinity problems. Soultani (1989) analyzed this possible problem in a loamy sand in Quebec and found no build up of salts. His conclusion seems a reasonable one to make when assessing the effects of a humid climate, where an excess annual precipitation could leach out any temporary build up of salts. Subirrigation cannot be used in arid regions unless a means of surface leaching is possible during some portion of the year in order to maintain a long term salt balance in the root zone.

4. The effect of subirrigation may be detrimental to the drainage characteristics of certain soils in that they maintain their permeability by the effect of wetting and drying cycles.

5. The water source must be a low iron and sediment content to avoid clogging of drains.

6. Topography variation can result in uneven distribution of water to the crop. No design tool exists to describe how well a system might work with varying topography.

2.3 Current Design Methods

Drain spacing and depth of installation are critical design determinations for subirrigation. Design methods for these parameters should calculate three operational situations for the subirrigation system (Skaggs, 1981):

1. Steady state operation over an extended dry period tests the system's ability to supply water. This requires the irrigation system to directly supply the peak water use to the crop on a continuous basis.

2. Transient state operation examines the system's ability to bring the water table up to the required height for plant use within an acceptable length of time. This may be critical at the beginning of the irrigation period or after a breakdown of the system.

3. Subirrigation under changing weather conditions includes the system's ability to handle excess water after periods of rain. Excessively high water table conditions should be drained from the root zone within a specified amount of time.

2.3.1 Steady State Operational Mode

The rate of crop water demand varies with the crop type, stage of growth and with weather conditions. The depth of the water table at which the water flux is sufficient to supply crop water requirements must be determined. This rate of water flow through the unsaturated zone will require a knowledge of the hydraulic conductivity function, the pressure head in the root zone and depth of the water table. Skaggs (1981) discussed the use of Richard's equation for one dimensional, steady state flow to solve for upward flux from the water table (Equation 5).

$$\frac{d}{dz}[K(\psi)\frac{d\psi}{dz}-k(\psi)]=0 \qquad (5)$$

Where 'K(ψ)' is the hydraulic conductivity function(m-day^{-1}), 'z' is the vertical distance(m) measured downward from the soil surface, and 'ψ' is the pressure head(m). This relation can be solved with numerical methods when the necessary soils' information is available and boundary conditions are known. Once the required water table depth has been determined, the following steady state subirrigation situation can be assumed for the determination of drain depth and spacing. The approach shown here is subject to the following assumptions:

1. The soil and water are homogeneous in chemical and physical properties.

2. The drains are evenly spaced at a distance (L) apart.

3. The hydraulic gradient $\delta\Psi/\delta x$ at any point is equai to the slope of the water table and the flow is horizontal (Dupuit-Forchheimers(DF) assumptions). Where Ψ is the total head (ψ+z) with pressure head and gravitational components.

4. Darcy's law is valid for flow through soils.

5. The origin of coordinates is taken at the impervious layer below the center of a drain.

6. Water is depleting from the root zone at a constant rate 'e' (evapotranspiration, ET).

Fox et al. (1956) developed a steady state relation (Equation 6) for subirrigation with open ditches to find the required spacing 'L'(m) (Figure 3) and to maintain a water table at 'h_1'(m) for an upward water flux equal to 'e' (m-day^{-1}), the constant evapotranspiration rate.

$$L = \left(4K_s\, M\frac{(2h_o - M)}{e}\right)^{\frac{1}{2}} \qquad (6)$$

Where $M = h_o - h_1$ (m) is the difference of water table elevation above the drain and that at mid spacing, and 'K_s' (m-day^{-1}) is the saturated hydraulic conductivity (considered constant in a homogeneous, isotropic soil profile). This equation applies where the ditches are at or near the impermeable layer. However, for deeper soils or for subsurface drains, radial flow must be accounted for. For the drainage case Hooghoudt's equation (Hooghoudt ,1940) accounted for radial flow by using a factor termed equivalent depth 'd_e'(m). The idea of equivalent depth greatly increased the usefulness of D-F theory for a wide range of water flow applications. Moody (1966) improved the methods for solving equivalent depth to Equations 7 and 8, and by adjusting water table elevation h_o' (m) for h_o (m) according to Equation 9, then a corrected spacing equation can be written (Equation 10).

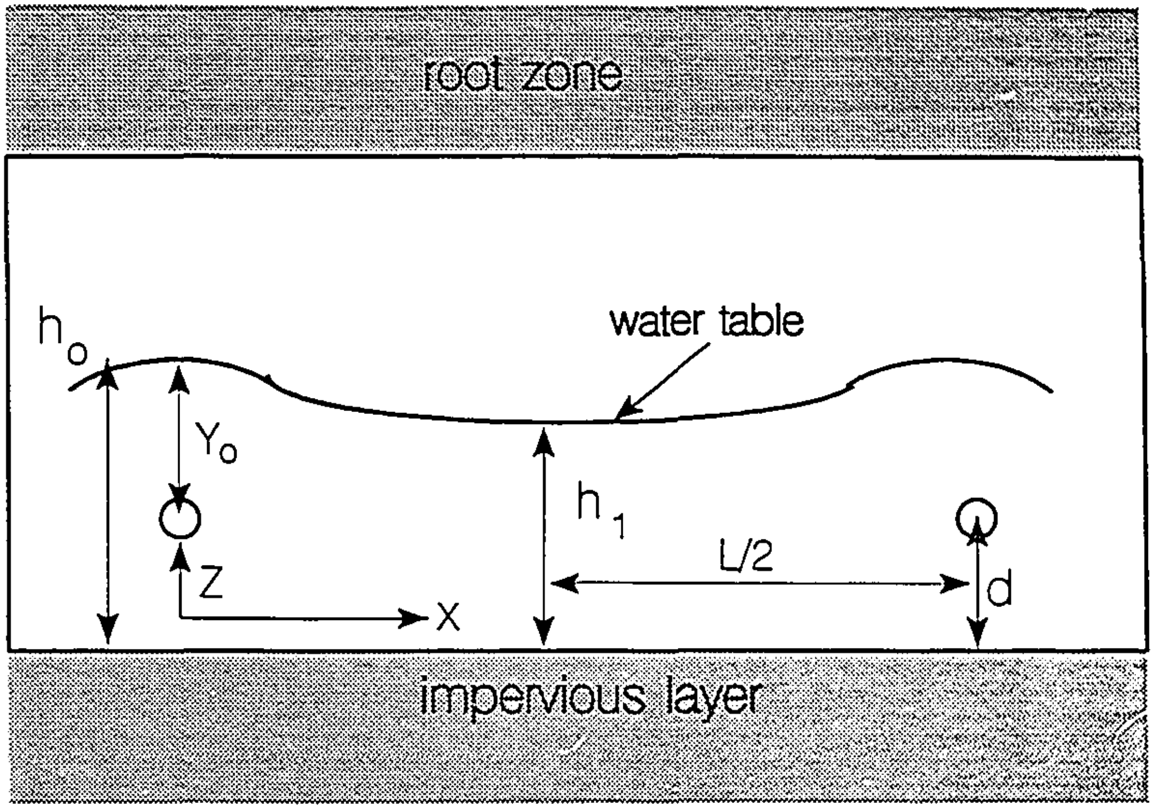

Figure 3. Variables used in a steady state analysis.

'Y_o'(m) and 'Y_1'(m) are the water head from above the drain center and at mid spacing. The equivalent depth of the impermeable layer below the drains 'd_e '(m) is determined by:

$$d_e = \frac{d}{\left(1+\frac{d}{L}\left(\frac{8}{\pi}\ \ln\left(\frac{d}{r_e}\right)-3.4\right)\right)} \qquad (7)$$

Where d/L is less than 0.3 (Equation 8) and when d/L is greater than 0.3 then 'd_e 'is determined by:

$$d_e = \frac{\pi L}{8\left[\ln\frac{L}{r_e}-1.15\right]} \qquad (8)$$

The effective radius 'r_e' (m) is included to represent the radius of a tube that is completely permeable with the same surface area as the total openings in perforated drain tubing (Skaggs, 1978).

$$\acute{h}_o = Y_o + d_e \ , \ \acute{h}_1 = Y_1 + d_e \tag{9}$$

For deep soils Ernst (1975), using equivalent depth, improved Equation 6 to find drain spacing L (m) during subirrigation:

$$L = (4K_s \ M \frac{(2\acute{h}_o - \frac{\acute{h}_o}{h_o}M)}{e})^{\frac{1}{2}} \tag{10}$$

To solve for spacing, an iterating approach is required. One would select appropriate 'h_o', 'h_1', 'e', input measure 'K', and 'd' values, then arbitrarily select a drain spacing 'L' to solve 'd_e'. The value of 'L' is then recalculated with the most recent value of 'd_e'. When estimated drain spacing and calculated spacing are approximately the same, the spacing is solved and iterations end.

Ernst's and Hooghoudt's equations are popular for finding drain spacing for drainage and subirrigation. The factor 'e' for evapotranspiration is used for the subirrigation case and a constant downward flux factor, called the drainage coefficient, is used for the drainage case.

In reality a steady state situation does not occur, as water consumption by plants depends on climatic conditions. The presence of soil anisotropy or heterogeneity will also affect the validity of the Dupuit - Forchheimer assumptions. Approximate relations are widely used due to their practicality. They form the basis for the saturated soil flow calculations in popular water table management models, namely DRAINMOD (Skaggs, 1978) and SWATRE (Feddes et al.,1978).

The next section discusses briefly the methods used to approximate transient water movement during subirrigation.

2.3.2 Transient State Operational Mode

When subirrigation is first started or after a breakdown in the system, a certain amount of time is required to raise the water table to a desired level. The Boussinesq equation has been used to describe transient change in water table height for cases such as this.

$$f\frac{\delta\Psi}{\delta t} = K_s \frac{\delta}{\delta x}(\Psi\frac{\delta\Psi}{\delta x}) - e \tag{11}$$

Where 'f' is the effective drainable porosity of the soil, "Ψ" is the head (m), 't' is time (days), 'K_s' saturated hydraulic conductivity (m-day^{-1}) and 'x' is the horizontal distance from the drain (m) and 'e' is the evapotranspiration rate (m day^{-1}) used in subirrigation or recharge rate (drainage coefficient) in drainage. This equation has been linearized using Fourier Series for the drainage case by Glover (Dumm, 1964). Others have linearized Boussinesq's equation or used a water potential theory (Kirkham ,1964) to develop approximate relations for a falling water table. Skaggs (1981), using numerical methods, solved the Boussinesq's equation for the rising water table from subirrigation. Graphical solutions were produced from that study to aid in determination of the mid spacing water table levels with time for different rates of evapotranspiration loss. This approach does not find water movement in the unsaturated zone (simplifies it to the constant 'e'), uses the D-F assumptions, and assumes a constant effective drainable porosity. Heterogeneous soils or anisotropic condition can only be approximated using this approach and the results are limited in accuracy by the D-F assumptions.

The following section introduces models in common use for simulating how a water table management system might react to changing weather conditions.

2.3.3 Under Changing Weather Conditions

A water management system will react to changes in climatic conditions. How it will react and how such reactions may affect crop and timeliness factors are questions that can be estimated by computer simulation models. Two widely used computer simulation models for this purpose are SWATRE and DRAINMOD. Each of these models finds moisture conditions in the root zone at mid spacing between drainage lines. They both simulate water table levels and drain outflows for a given set of soil and weather data, from which estimates of the number of dry days, wet days, and potential work days for the field can be found. These are one-dimensional models in the unsaturated soil zone that are linked to the approximate solutions of Hooghoudt or Ernst for water table movement due to drains/ditches. The methods used in SWATRE and DRAINMOD to find this information are different, so the fundamentals of each of these models will be examined in the next two sections.

2.3.4 SWATRE

SWATR (soil water actual transpiration rate) was developed by Feddes et al. (1978) to describe transient water flow in a heterogeneous soil-root system. SWATR was upgraded (SWATRE) by Bellmans et al. (1983) to include an improved numerical solution scheme to Richard's equation and additional boundary conditions. SWATRE was upgraded to SWATREN by Dierckx et al. (1986).

SWATR and subsequent versions are based on a single column in the soil profile that has the water balanced as follows for the incoming and outgoing fluxes:

$$\Delta W = I + Q - (E + T) \qquad (12)$$

Where 'ΔW' is the change in water storage (m), 'I' is the infiltration (m), 'Q' is the upward flow (m) from the bottom boundary, minus the outflow due to evaporation 'E'(m) and transpiration 'T'(m). The pressure head 'ψ'(m) within the soil column is calculated by solving a one dimensional representation of Richard's equation, Equation 13, with an additional sink term 'S' (day^{-1}) for water extracted by roots.

$$\frac{\delta\psi}{\delta t} = \frac{1}{C(\psi)}\frac{\delta}{\delta z}[K(\psi)(\frac{\delta\psi}{\delta z}+1)] - \frac{S}{C(\psi)} \qquad (13)$$

Where 'C(ψ)' is the moisture capacity (m^{-1}), 'z'(m) is the vertical direction positive downward, 'K(ψ)' is the unsaturated conductivity function (m-day^{-1}) and 't' is time in days. The volumetric flow rate 'q' (m-day^{-1}) between cells or at a boundary can be determined using Darcy's law written for the one dimensional case, as:

$$q = -K(\psi)(\frac{d\psi}{dz}+1) \qquad (14)$$

SWATRE solves Equation 13 using a finite difference solution and incorporates a term for root water extraction. The root water extraction term 'S', in the form described by Equations 3 and 4, is included in Equation 13 for nodes in the root zone. The finite difference solution distributes the root water extraction throughout the root zone. Equation 14 is used to determine flows between layers or at boundaries. Equation 12 summates the flows and determines the change in water storage in a soil layer over time.

Top boundary conditions include constant flux for a time step (rainfall, potential soil evaporation and potential transpiration). The sum of potential evaporation and potential transpiration is the potential evapotranspiration ET_p (m) which is calculated using a modified Penman's equation (Feddes et al., 1978):

$$ET_p = \frac{\Omega + \gamma}{\Omega + \gamma(1+\frac{r_s}{r_a})}(E_{WET} - E_i) + E_i \tag{15}$$

Where 'Ω' is the slope of the saturation vapour pressure curve (mbar-K^{-1}),'γ' is a psychrometric constant (mbar-K^{-1}), 'r_s' is diffusive resistance to water vapour for both crop and soil surface (s-m^{-1}), 'r_a' is the diffusive resistance to water vapour of the air layer surrounding the leaves (s-m^{-1}), 'E_i' is the evaporation flux of intercepted water (cm-day^{-1})(estimated from curves) and 'E_{WET}' is the wet crop evaporation (cm-day^{-1}) calculated below:

$$E_{WET} = \frac{\Omega R_n + c_p \rho_a \frac{(e_a - e_d)}{r_a}}{\Omega + \gamma} \tag{16}$$

Where 'R_n' is net radiation flux (W-m^{-2}), 'c_p' is the specific heat (J-.kg^{-1}),'ρ_a' is the density of moist air (kg-m^{-3}), and 'e_a', 'e_d' are the saturated and actual air vapour pressures (mbar), respectively.

The bottom boundary conditions may consist of, a constant flux to or from the saturated zone, a constant water table level, a moving boundary due to ditch or drain influence, a situation of deep seepage or a zero flow boundary. Heterogeneity in the soil profile can be described by dividing the soil profile into layers each with its own soil properties (Note the saturated flow relations are for homogeneous soil conditions or an arithmetic average to represent heterogeneity). Flow to drains in the saturated zone is calculated using the steady state equation of Ernst.

SWATRE has been linked to FLOWEX to predict trafficability, germination and emergence, and to CROPR to predict crop growth and production (Van Wijk and Feddes, 1986). Brandyk et al. (1992) compared SWATRE linked to a simple flow resistance model for saturated flow and found excellent agreement with observations for a ditch supply system for drainage and subirrigation in a polder area. Feddes et al. (1978) showed good field comparison for SWATR and CROPR to simulation results for two different crops in terms of temporal soil moisture contents, daily evapotranspiration rates and dry matter yield.

SWATRE is a detailed root-water unsaturated flow model, it does need some modifications to deal with water tables rising to the surface. It is limited in its capability to describe saturated flow for water table management systems due to the use of Ernst's equation, which cannot account for field heterogeneity.

2.3.5 DRAINMOD

DRAINMOD (Skaggs, 1978) was developed for humid conditions along the eastern sea board of the United States, but it has proven effective in various parts of the United States and Canada (Skaggs, 1982; Fouss et al., 1987; Sanoja et al., 1988; Gupta et al., 1992). The program simulates water table conditions at a single point in the field, normally at mid spacing between ditches or tile drains. DRAINMOD can simulate drainage or subirrigation conditions in the field. The model is based on a water balance of the soil that is solved for each time increment:

$$\Delta V_A = D + ET + DS - I \tag{17}$$

Where 'ΔV_A' (m) is the change in drained air space, 'ET' (m) is the amount of evapotranspiration, 'D' (m) is the drainage, 'DS' (m) is the deep seepage, and 'I' (m) is the amount of infiltration.

Another water balance is computed at the soil surface to include surface storage effects:

$$P = I + \Delta S + RO \tag{18}$$

Where 'P' (m) is the precipitation, 'F' (m) is the infiltration, 'S' (m) is the surface storage, and 'RO' (m) is the runoff.

Drainage and subirrigation contributions are calculated using the methods of Hooghoudt and Ernst's equations, respectively. Input data includes hourly rainfall, daily potential evapotranspiration data, soil moisture retention curve data, saturated hydraulic conductivity, Green-Ampt equation coefficients for infiltration, rooting depth and effective radius of drains.

DRAINMOD and SWATRE are similar in that they describe water conditions at a point in the field. DRAINMOD's treatment of the flow in the unsaturated zone is a simpler approach. While SWATRE is based on the numerical solution of the governing flow equation, DRAINMOD uses empirical relations to describe unsaturated flow. What DRAINMOD may sacrifice in accuracy by using approximations it gains in reduced data input requirement and computation time. DRAINMOD has the ability to rapidly simulate water tables for years of weather data. The two models assume level land and uniform soil. Program output can include the number of dry days, wet days and work days to provide useful indicators of how well a water table management system will work.

The next section will discuss some of the other ground water flow models that have been developed. Most were not designed for agricultural applications but they have the capabilities to be configured for such use.

2.3.6 Other Ground Water Flow Models

The analytical solutions to the governing differential equations for describing the ground water flow process have not been used in this study for three-dimensional flow due to their inherent analytical complexity and their narrow range of applications. The high accuracy in computation is usually unwarranted due to the variability of soil physical parameters. This is one reason for the popularity of approximate methods (such as Houghoudt's equation) which depend on the use of Dupuit-Forchheimer's (DF) assumptions to simplify relations. Governing differential equations can be solved using numerical methods with the aid of computers. More comprehensive models often lead to a better understanding of the processes and provide a means to test the applicability of approximate relations. The increasing computational capability of microcomputers is making the use of these models more feasible in design work on a day to day basis. Tang and Skaggs (1980) showed the use of Amerman's (1969) model for drainage conditions to test the accuracy of approximate methods.

A large amount of the work on unsaturated ground water flow models has been done by soil physicists who were mainly concerned with water movement in soil layers near the root zone. Engineers and ground water hydrologists, on the other hand, have been concerned with water movement at greater depths, where saturated water flow is the dominant feature. Rubin (1968) demonstrated a numerical solution to a two dimensional, transient ground water movement combining saturated and unsaturated flow components. Several researchers (Table 1) have developed composite models using the finite difference technique. The early studies were largely limited to homogeneous, incompressible and unconfined aquifers, since Laplace's equation was used to solve flow in the saturated zone. Freeze (1971) presented a more general equation for solving the composite model that could include heterogeneity, anisotropy, compressibility and confined aquifer. A problem associated with the more comprehensive models is their high memory and computational requirements, particularly when solving the nonlinear relations due to the functional variables for unsaturated flow. The size of the region being studied may be limited, such as in Watson (1974), where his region of simulation was 279 cm by 360 cm. Most studies use a nodal spacing in the unsaturated zone in the order of 5 cm increments or less, and a spacing in the saturated zone magnitudes greater, depending on the hydraulic gradients and time increment size.

Table 1 presents some of the characteristics that combined unsaturated-saturated flow models have used. It would be desirable for water table management studies to have all these features, however, only main frame computers can handle the computational requirements.

Cichowicz (1979) reduced the computational requirements by combining a 2-dimensional saturated flow model with 1-dimensional unsaturated flow model. This allowed whole watersheds to be simulated. None of the models in Table 2 incorporated root water extraction in the soil profile and most operate only on a mainframe computer.

Some studies (Narasimhan and Witherspoon, 1978; Fipps and Skaggs, 1989) use the finite element technique which has a greater flexibility for studying complex geometries, and provides computational stable results (calculations do not accumulate error). The layout of the grid for a finite element model is more complicated than the finite difference approach. Finite differences are conceptually simpler to set up and more efficient in treating time derivatives; however, their slow convergence on solutions can offset these advantages.

Name	1	2	3	4	5	6	7	8	9	10	11
<u>Dimension</u>											
1d up		x	x					x			
down	x	x	x			x		x			
2d			x	x	x	x	x		x	x	x
3d			x			x		x		x	
Hydraulic Gradient	x	x	x	x	x	x	x	x	x	x	x
Soil Homogeneous	x	x	x	x	x	x	x	x	x	x	x
Heterogeneous			x					x	x	x	x
Hysteresis		x	x		x						
Same wetting & drying relation	x			x		x	x	x	x	x	x
<u>Problem Type</u>											
Gravity drainage				x	x		x	x	x	x	x
Evaporation		x	x			x		x	x		
Redistribution	x	x	x		x		x				
<u>Initial Conditions</u>											
Constant Head	x			x					x		
Specified MC		x	x		x	x	x	x			
Steady State		x	x						x	x	x
<u>Form of Solution</u>											
MC profile	x	x	x								
Pressure Heads	x	x	x			x					x
Total Head		x	x	x	x	x		x		x	x
Flux Calculations		x	x		x						

1 Rubin, 1966
2 Freeze, 1969
3 Freeze, 1971
4 Todsen, 1973
5 Watson, 1974
6 Pikul et al., 1974
7 Tang and Skaggs,1980
8 Cichowicz, 1979
9 Amerman, 1969
10 Fipps and Skaggs, 1989
11 Rogers and Selim, 1989

Table 1. Review of some composite finite difference ground water models.
*Note that MC refers to the volumetric moisture content

A computer simulation model that operates on a microcomputer, that numerically solves the governing flow relations for 3-dimensional flow in saturated and unsaturated soils, and adequately accounts for topography, root water extraction and non-uniformity of soil properties, does not currently exist. It is proposed in this thesis to develop a simulation model to do this by upgrading an existing proven model to meet part of these goals and add to it the additional required features. A saturated flow model that would be a platform on which to build this model is MODFLOW. It is a commonly used ground water flow model that provides a high level of analysis and versatility far beyond what most current water management models provide. A brief description of MODFLOW follows.

2.3.7 MODFLOW

MODFLOW is a computer model that can simulate the movement of ground water in three dimensions. The program was written by M.G. McDonald and A.W. Harbaugh (1984) for the U.S. Department of the Interior, Geological Survey, Reston, Va.. It was developed to find the effect of hydrologic stress or events upon a ground water system (such as rainfall, wells, drains, rivers, evaporation). MODFLOW is written in Fortran 77 language and is structured so that subroutines are grouped by hydrologic process (a module). The modules are compiled separately and linked together to produce the final, executable file. Only modules and related data sets that are required for a particular simulation need to be used, allowing more efficient use of computing resources. The grouping of the modules also simplifies making additions to the program, since only one module is affected and not the whole program. The program can accept a wide range of boundary conditions, soil and system parameters (anisotropic, nonuniform, transient saturated water flow parameters). It has been used by ground water hydrologists and upgraded over the years to suit demand and to operate on microcomputers.

The modular structure, versatility in boundary conditions and proven nature of this computer program make it a logical choice for modification to create a linked unsaturated-saturated ground water flow program. More detail concerning the finite difference relations and defining the grid arrangement in MODFLOW will be given in Chapter 3 where the relations used in LINKFLOW are discussed.

Chapter 3: Model Development

3.0 Model Development

This chapter describes the development of the computer simulation model LINKFLOW. Each component of the model, its mathematical representation, the methods of solution and the structure of computer program, is described.

3.1 Ground Water Flow Components

Water flow in the soil can be considered to occur in two zones. Saturated flow occurs when all soil pores are filled with water. Unsaturated flow occurs when water moves through soil pores that are only partially filled with water. In this thesis an unsaturated model is developed instead of using an existing one. The reason for this is to include the features needed for modelling subirrigation processes and to be able to integrate it into the saturated flow model. The following section examines the flow components and the conditions assumed to occur during water table management.

3.1.1 Unsaturated Flow in the Water Table Management Model

Water flow in the unsaturated zone during water table management will occur in the region between the soil surface and the water table. The water flow is assumed to follow Darcy's law. Therefore, water is assumed to be incompressible, to be contained in a rigid soil matrix, not to be influenced by air dynamics, and to move due to gradients caused by gravitational and water pressure differences. Soil properties in the profile for unsaturated flow are treated as homogeneous, and single relationships for hydraulic conductivity and moisture contents versus pressure head are valid in both wetting and drying. Water is extracted from the soil profile by plant roots. Evaporation from the soil surface is combined with transpiration from plants for calculations. This applies best to fields with complete crop coverage. The rate at which water is removed by roots will depend on the time of day, moisture conditions in the soil profile and the potential evapotranspiration. Water infiltrates at the top of the profile during rain events. Its rate of entry will depend on soil moisture conditions and rainfall intensity. At the bottom of the unsaturated soil profile, water can either drain out or rise from the water table depending on the total potentials present.

The mathematical model describes the unsaturated flow as one-dimensional between the ground surface and the water table. The water table elevation is defined by the saturated flow model. The height of the unsaturated flow columns may vary from zero for fully saturated conditions to the distance between the soil surface and the bottom elevation of the saturated flow model grid.

The pressure head (ψ) is used to describe moisture conditions in the soil profile. The pressure head is a measure of how tightly the water is held by the soil. The pressure head is quantified as a height of water (m). The pressure head is zero at the water table and has a negative value in the unsaturated zone. Below the water table, it increases positively with depth due to the weight of water above.

Richard's equation is derived from a combination of Darcy's law for water flow in a porous media and the equation of continuity. Equation 18 states that the change in water storage in the profile will equal the sum of the flows in and out of the profile. The expression '$C(\psi)\delta\psi/\delta t$' describes the change in storage of the soil with time, where '$C(\psi)$' is the moisture capacity (m^{-1}) defined as the change in moisture content 'θ' per unit change in pressure head ($\delta\theta/\delta\psi$).

$$C(\psi)\frac{\delta\psi}{\delta t} = \frac{\delta}{\delta z}[K(\psi)(\frac{\delta\psi}{\delta z}+1)] - S \tag{18}$$

This relation is the one-dimensional case of Richard's equation. This relation calculates the temporal and spatial pressure head values, and quantifies water flows to the saturated zone, water extracted by plant roots, and infiltration.

Richard's equation is highly nonlinear, due to the functional nature of soil properties to pressure head, and can be solved using an implicit numerical solution. The finite difference solution used here requires two equations, the predictor (Equation 19) and the corrector (Equation 20), each advancing the solution one-half of a time step (Douglas and Jones, 1963). Figure 4 shows how the nodes in the model are arranged. The predictor written for time steps m to m+1/2 is:

$$\frac{1}{\Delta z}[K^m_{j+\frac{1}{2}}(1+\frac{\psi_{j+1}^{m+\frac{1}{2}}-\psi_j^{m+\frac{1}{2}}}{\Delta z}) - K^m_{j-\frac{1}{2}}(1+\frac{\psi_j^{m+\frac{1}{2}}-\psi_{j-1}^{m+\frac{1}{2}}}{\Delta z})] - S_j = C^m_j(\frac{\psi_j^{m+\frac{1}{2}}-\psi^m_j}{\frac{\Delta t}{2}}) \tag{19}$$

where j is the space index, Δz is the spacing between nodes (m), and $K_{j+1/2} = (K_j*K_{j+1})^{1/2}$ and $K_{j-1/2} = (K_j*K_{j-1})^{1/2}$. (These are the geometric means of the conductivities between nodes ($m\text{-}day^{-1}$)). The corrector is written to advance from time step m to m+1.

$$\frac{1}{2\Delta z}[K_{j+\frac{1}{2}}^{m+\frac{1}{2}}(\frac{\psi_{j+1}^{m+1}-\psi_j^{m+1}}{\Delta z}+1) - K_{j-\frac{1}{2}}^{m+\frac{1}{2}}(\frac{\psi_j^{m+1}-\psi_{j-1}^{m+1}}{\Delta z}+1)$$
$$+K_{j+\frac{1}{2}}^{m}(\frac{\psi_{j+1}^{m}-\psi_j^{m}}{\Delta z}+1)-K_{j-\frac{1}{2}}^{m}(\frac{\psi_j^{m}-\psi_{j-1}^{m}}{\Delta z}+1)]-S_j=C_j^{m+\frac{1}{2}}(\frac{\psi_j^{m+1}-\psi_j^{m}}{\Delta t}) \quad (20)$$

The advantage of the predictor-corrector technique is its stability in converging on a solution.

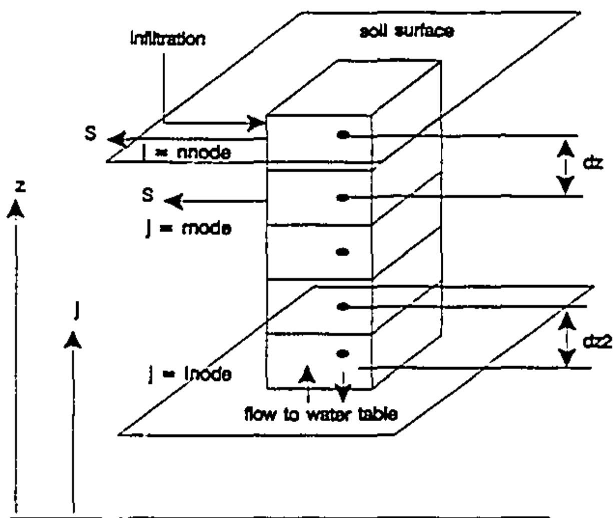

Figure 4. Nodal arrangement for unsaturated flow soil column. 'j' is the node number with a value of 'nnode' at the soil surface, 'rnode' at the bottom of root zone and 'inode' at the water table.

If a small enough time step is used, it may not be necessary to iterate (Pikul et al.,1974, used 0.1 to 4 minutes as suitable time steps).

The finite difference predictor equation (Equation 19) is rearranged into the order shown in Equation 21 for solution using the Thomas algorithm (Gerald and Wheatley, 1984). This algorithm solves tridiagonal matrices of simultaneous equations.

$$-A_j\Psi_{j+1}^m + B_j\Psi_j^m - C_j\Psi_{j-1}^m = D_j \tag{21}$$

A, B, C and D coefficients are solved for the boundaries and the main flow region (Equations 22-25) for the predictor relation. The coefficients for the predictor relation are calculated for the first half time step.

$$A_j = -\frac{K_{j+\frac{1}{2}}^m}{\Delta z^2} \tag{22}$$

$$B_j = -((\frac{K_{j+\frac{1}{2}}^m}{\Delta z^2} + \frac{K_{j-\frac{1}{2}}^m}{\Delta z^2}) + \frac{2C_j^m}{\Delta t})) \tag{23}$$

$$C_j = -\frac{K_{j-1}^m}{\Delta z^2} \tag{24}$$

$$D_j = -(2C_j^m\frac{\Psi_j^m}{\Delta t} + \frac{K_{j+1}^m}{\Delta z} - \frac{K_{j-1}^m}{\Delta z}) + \frac{S_j}{\Delta z} \tag{25}$$

The Thomas algorithm is used to solve for pressure head in the soil profile at the half time step as follows.

$$E_j = \frac{A_j}{(B_j - C_jE_{j-1})} \tag{26}$$

$$F_j = \frac{D_j + C_jF_{j-1}}{B_j - C_jE_{j-1}} \tag{27}$$

$$\Psi_j^m = E_j\Psi_{j+1}^m + F_j \tag{28}$$

The pressure head at the water table is zero. Using Equation 28 with coefficients A to F (Equations 22-27), one can find new pressure head values for each node in the profile. The values of pressure head are then used to solve new values for the functional soil properties to use in the corrector equation (Equation 20). Then, a new set of coefficients are calculated (Equations 29-32), and used to solve for the pressure heads using the Thomas algorithm for the full time step.

$$A = -\frac{K_{j+\frac{1}{2}}^{m+\frac{1}{2}}}{2\Delta z^2} \tag{29}$$

$$B = -\left(\left(\frac{K_{j+\frac{1}{2}}^{m+\frac{1}{2}}}{2\Delta z^2} + \frac{K_{j-\frac{1}{2}}^{m+\frac{1}{2}}}{2\Delta z^2}\right) + \frac{C_j^{m+\frac{1}{2}}}{\Delta t}\right) \tag{30}$$

$$C = \frac{K_{j-1}^{m+\frac{1}{2}}}{2\Delta z^2} \tag{31}$$

$$D_j = -C_j^{m+\frac{1}{2}} \frac{\psi_j^m}{\Delta t} - \frac{K_{j+\frac{1}{2}}^{m+\frac{1}{2}}}{2\Delta z} + \frac{K_{j-\frac{1}{2}}^{m+\frac{1}{2}}}{2\Delta z} - \frac{K_{j+\frac{1}{2}}^{m}}{2\Delta z}\left(\frac{\psi_{j+1}^m - \psi_j^m}{\Delta z} + 1\right) + \frac{K_{j-\frac{1}{2}}^{m}}{2\Delta z}\left(\frac{\psi_j^m - \psi_{j-1}^m}{\Delta z} + 1\right) + \frac{S_j}{\Delta z} \tag{32}$$

The zone of active nodal points is bound by the soil surface at the top and the water table at the bottom as shown in Figure 4. Since the water table can move, the model varies the number of active nodal points to fit the current water table depth. The water table level is assumed not to move during a time step, but does so instantaneously between time steps. All the nodes have the same spacing (dz) except for node (dz2) which is calculated as halfway from the water table elevation to the first regularly spaced node (Figure 4). Therefore, the Δz in Equations 19 and 21 will change near the bottom node. These two values for Δz are used in Equation 29. One represents the span of the cell, and the other represents the distance between nodes. Only at the bottom boundary will these values be different from the nodal spacing. The flux between the unsaturated model and the saturated model across the bottom boundary is found by the water budget on the unsaturated flow column (Equation 33) for each time step.

$$q_{wt} = \Delta W - S + I \tag{33}$$

Where 'q_{wt}' is the amount of flow across the water table (m), 'ΔW' is the change in water storage (m), 'S' is the amount of water removed by the plant roots (m), and 'I' is the amount of rainfall (m) that infiltrated during the time step. A plant canopy interception value of 5 mm per day is assumed for each rainfall event. The rate of infiltration has a maximum value equal to the assigned K_s value. If the rainfall rate exceeds the maximum allowable infiltration, then excess water is considered ponded on the surface until it can infiltrate. No run off feature was included in the model at this time. The upper boundary condition is treated as a no-flow boundary (Neumann condition). This means all flows that cross this boundary due to rain and evapotranspiration are included in the sink/source term of the finite difference relation instead of being a boundary condition.

3.1.1.1 Root Water Extraction

The root water extraction value 'S' is determined in a means similar to that used by Feddes (1978) in SWATR, except for the addition of terms to account for the time of day and method of defining evapotranspiration. The daily potential evapotranspiration rate is modified to a root water extraction rate by multiplying factors which represent the effects of soil moisture status, time of day and depth in the soil (Equation 37). Figure 5 shows the relation between '$\gamma(\psi)$' and the pressure head. This is further defined in Equation 34 to account for the ease with which water can be extracted by roots from the soil due to existing soil pressure head.

$$\begin{aligned} \gamma(z) &= 1 \ \mathit{if}\ \psi > \psi_{50}\ ,\ \psi < 0 \\ &= 0 \ \mathit{if}\ \psi < \psi_{pwp} \\ &= \frac{\psi - \psi_{pwp}}{\psi_{50} - \psi_{pwp}}\ ,\mathit{if}\ \psi_{pwp} \le \psi \le \psi_{50} \end{aligned} \tag{34}$$

The equation requires: a defined pressure head 'ψ' at each node within the root zone, a permanent wilting point pressure head 'ψ_{pwp}'(m), and a pressure head at 50% available moisture content for each soil being examined. The 50% available water content is suggested as a level where irrigation is needed for a number of crops. The program user can select other values to represent more accurately the crop response he or she wishes to simulate. The model currently does not reduce the root water extraction for very high moisture contents where, due to lack of aeration, root growth would be limited. To account for aeration problems, evaporation and transpiration would need to be treated separately. However only evapotranspiration was used in the model with the assumption that the soil surface is covered by a crop. This coverage would ensure most of the water loss from the soil can, therefore, be represented as evapotranspiration through the root extraction model.

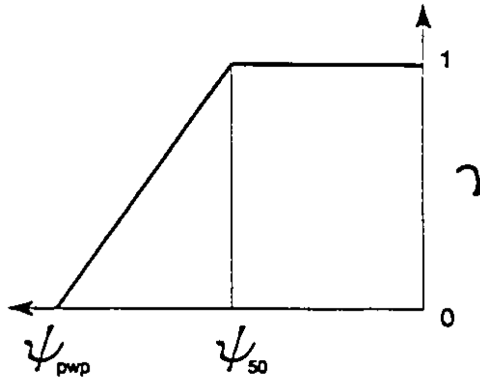

Figure 5. Relationship between soil factor for root water extraction and soil water pressure head.

A linear distribution of root activity with depth is assumed, and a relation (Equation 35) was developed to find the amount of water that can be extracted at each nodal point in the profile. The nodal nomenclature shown in Figure 4 and equation 35 is a linear relation. At RNODE-1 there will be zero root extraction, and the sum of the DEPTHF factors over the nodes in the root zone will be one. The relation for factor 'DEPTHF' is:

$$DEPTHF = 2 \frac{(j - RNODE + 1)}{(NNODE - RNODE + 1)^2} \tag{35}$$

where 'DEPTHF' is the weighting factor for roots with depth, 'j' is the node number in root zone, 'RNODE' is the node number at bottom of root zone, and 'NNODE' is the node number at soil surface. In situations where the water table rises into the root zone, 'RNODE' will become the first node above the water table.

To account for diurnal variation of evapotranspiration, Equation 36 was developed. Factor 'TIMEF' is calculated using the morning hour 'T_{S1}', the night hour 'T_{S2}' and time of day 'TD' (all times in days). The coefficient TIMEF when multiplied by the daily potential evapotranspiration gives the rate of evapotranspiration at the specified time. This relation was found by integrating a sinusoidal relation equal to the amount of potential evapotranspiration for that day.

$$TIMEF = \frac{\pi}{2(T_{S2}-T_{S1})}\sin(\pi * \frac{TD-T_{S1}}{T_{S2}-T_{S1}}) \tag{36}$$

The root water extraction 'S(j)' for each node within the root zone is the product of these factors multiplied by the peak evapotranspiration rate 'S_{max}' (Equation 37).

$$S(j) = DEPTHF * TIMEF * \gamma(j) * S_{max} \tag{37}$$

These procedures allow the simulation to account for depth, time of day and water potential. Each relation can be updated as others more suitable for different crops are found. The S(j) value for each node is used in the sink term during solution of the finite difference equations (Equations 25 and 32).

The number of nodes active in the root zone depends on the depth of root zone used in the simulation. The user can select between a fixed root depth that would be suitable for perennial crops, or a changing root depth with time, which is more suitable for annual crops. If the user selects a varying root depth, then the relation developed by Borg and Grimes (1986) is utilized (Equation 4).

The method of describing root water extraction from the soil has been discussed, next the method of depicting the unsaturated soil properties is presented.

3.1.1.2 Soil Properties

The relationships to describe the moisture characteristic and hydraulic conductivity versus pressure head (Figure 6) are those discussed in Hoover and Grant (1983) or those from van Genuchten (1978a). To find B_1, B_2, B_3, C_1, C_2 and C_3 for Hoover's relations, pressure heads, associated moisture contents and hydraulic conductivities are required. A least squares method is used to find the best fit to solve for the coefficients. Hoover and Grant (1983) provide a table of coefficients for many soils in the United States, and a listing of their computer program used to find coefficients from soil's data.

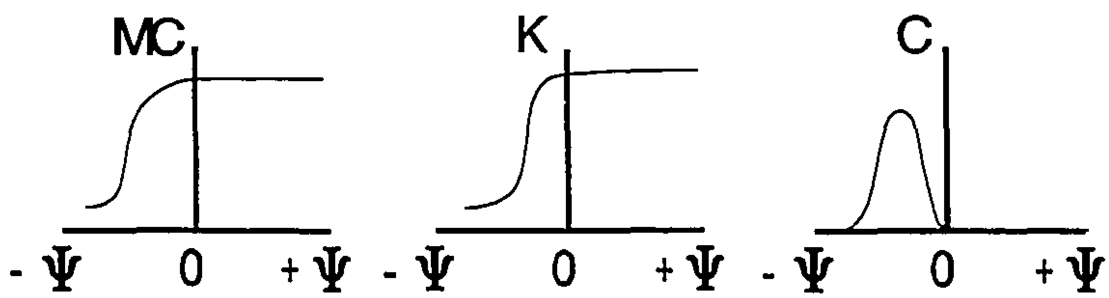

Figure 6. Functional relationships for moisture content MC, hydraulic conductivity K, and moisture capacity C to pressure head (redrawn from Freeze, 1971).

Equations 38 and 39 show the empirical relations used by Hoover and Grant (1983):

$$\theta(\psi) = \frac{B_1}{[(\psi - \psi_{air})^{B_3} + B_2]} \qquad (38)$$

$$K(\psi) = \frac{C_1}{[(\psi - \psi_{air})^{C_3} + C_2]} \qquad (39)$$

where '$\theta(\psi)$' is the volumetric moisture content, 'B_1','B_2','B_3' are coefficients found by curve fitting, 'ψ_{air}' (m) is the air entry pressure head, '$K(\psi)$' (m day^{-1}) is the conductivity function, and 'C_1','C_2','C_3' are coefficients for conductivity relation. Equation 38 was first described by Taylor and Luthin (1969). While Equation 39 is a modified form of what was described by Gardner (1958).

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{[1+(\alpha|\psi|)^n]^m} \tag{40}$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{41}$$

$$m = (1 - \frac{1}{n}) \tag{42}$$

$$K(\psi) = K_s S_e^{\frac{1}{2}} [1 - (1 - S_e^{\frac{1}{m}})^m]^2 \tag{43}$$

The other set of empirical relations used to describe the soil properties is that developed by Van Genuchten (1978a). Van Genuchten's relationships (Equations 40,41,42,43) require data to describe the moisture retention curve and the saturated hydraulic conductivity 'K_s'. These data are entered into a computer program (SOIL (El-Kadi, 1984)) to derive 'n','α' coefficients and the residual moisture content 'θ_r' from a statistical fitting of data. The unsaturated hydraulic conductivity function is based on the series parallel model of Childs and Collis-George (1950). Pressure heads used for calculations must be in centimetres for coefficients calculated by SOIL program. Other units remain the same.

Both approaches describing the unsaturated soil information are included in the model so the user may select the one that best describes the soils data or use coefficients reported in the literature for different soils.

3.1.1.3 Field Wetness

A universal method is proposed here to depict the level of moisture stress on the crop as a function of moisture conditions in the soil. Equation 44 defines the quantity called WET by using an average pressure head in the root zone and the pressure heads defining a crops range of performance.

$$WET = 1-\frac{\psi}{\psi_{air}}, \quad for\ \psi>\psi_{air}$$

$$WET = 0, \quad for\ \psi<\psi_{air},\ \psi>\psi_{50} \tag{44}$$

$$WET = \frac{\psi-\psi_{pwp}}{\psi_{50}-\psi_{pwp}} - 1, \quad \psi<\psi_{50}$$

WET can be used to spatially describe the moisture to plant stress status with a single variable. WET has a value of plus one in saturated soils which reduces to zero at the air entry value 'ψ_{air}'. WET equals zero for decreasing pressure

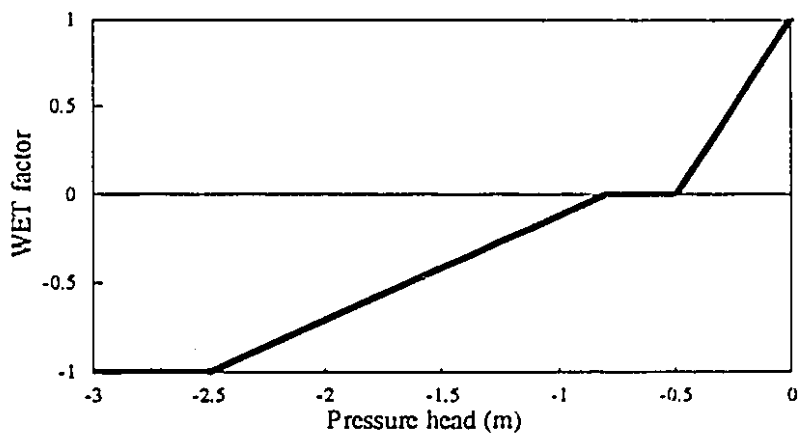

Figure 7. The WET factor versus pressure head for an example soil and crop situation.

heads between the air entry value and 50% available water point (the range most suitable root soil-water conditions). If pressure head decreases below the 50% available water towards the permanent wilting point 'ψ_{pwp}', WET changes from 0 to -1. The WET value is used to identify the regions of moisture stress with values greater than zero indicating dry and below zero indicating wet. Since its value is based on water available to the crop, it gives a better indication of plant stress than moisture content or pressure head alone or other indicators such as the SEW_{30} (the number of days the water table is within 30cm of the soil surface) and number of dry days (Skaggs, 1978). Figure 7 graphs the change in WET value versus pressure head using a soil and crop with limiting aeration at -0.5 m, a permanent wilting point at -2.5m and a 50% available water content at -0.8m.

The following section presents the saturated flow model components as the last part of the water table management model.

3.1.2 Water Flow in Saturated Soil

Saturated flow is said to occur when water is assumed to fill all soil pores. This is the condition which is assumed to occur below the water table. Saturated flow is mainly lateral between locations in the field and the drain system. During subirrigation, water moves into the soil radially away from a drain. Then the water may flow upward to the unsaturated zone, horizontally to adjacent areas, downward as deep seepage or in a fashion combining any of these three directions.

The governing partial differential equation for transient saturated flow is derived by combining the continuity equation and Darcy's law; resulting in Equation 45:

$$\frac{\delta}{\delta x}(K_x \frac{\delta \Psi}{\delta x}) + \frac{\delta}{\delta y}(K_y \frac{\delta \Psi}{\delta y}) + \frac{\delta}{\delta z}(K_z \frac{\delta \Psi}{\delta z}) - S = S_s \frac{\delta \Psi}{\delta t} \quad (45)$$

where x,y,z are distances along the major coordinate axis (m), 'K_x','K_y','K_z' are hydraulic conductivities along the major axes (m-day^{-1}), 'Ψ' is the total hydraulic head (ψ + z) (m), 'S' is the volumetric flux per unit volume which represents sources and/or sinks of water (m-m^{-1}-day^{-1}), 'S_s' is the specific storage (the change in moisture stored per unit volume caused by a change in head) (m^{-1}), and 't' is time (days).

3.1.2.1 MODFLOW

A description of the program MODFLOW is now presented as the means used in the model developed to describe water flow in saturated soil. MODFLOW is a program that simulates in three dimensions the movement of ground water in aquifers. It finds the effect of hydrologic stress or events on the ground water system (such as rainfall, wells, drains, rivers, and evaporation). MODFLOW is written in Fortran 77 language and is structured to group all subroutines for each hydrologic process (a module). The modules are compiled separately and linked together in the finished, executable file. Since only the modules and related data sets that are required for a particular simulation need to be used, allowing more efficient use of computing resources. The grouping of the modules also simplifies making changes to the program, since only one module may be affected and not the whole program.

The modular structure, versatility in data input and proven nature of this computer program make it a logical choice to be modified to a linked unsaturated-saturated ground water flow program.

The method of solution for the saturated flow zone is given in the MODFLOW manual (MacDonald and Harbaugh, 1984). However, some explanation will be given here in order for the reader to understand how the unsaturated model is linked and how the processes occurring during water table management are incorporated.

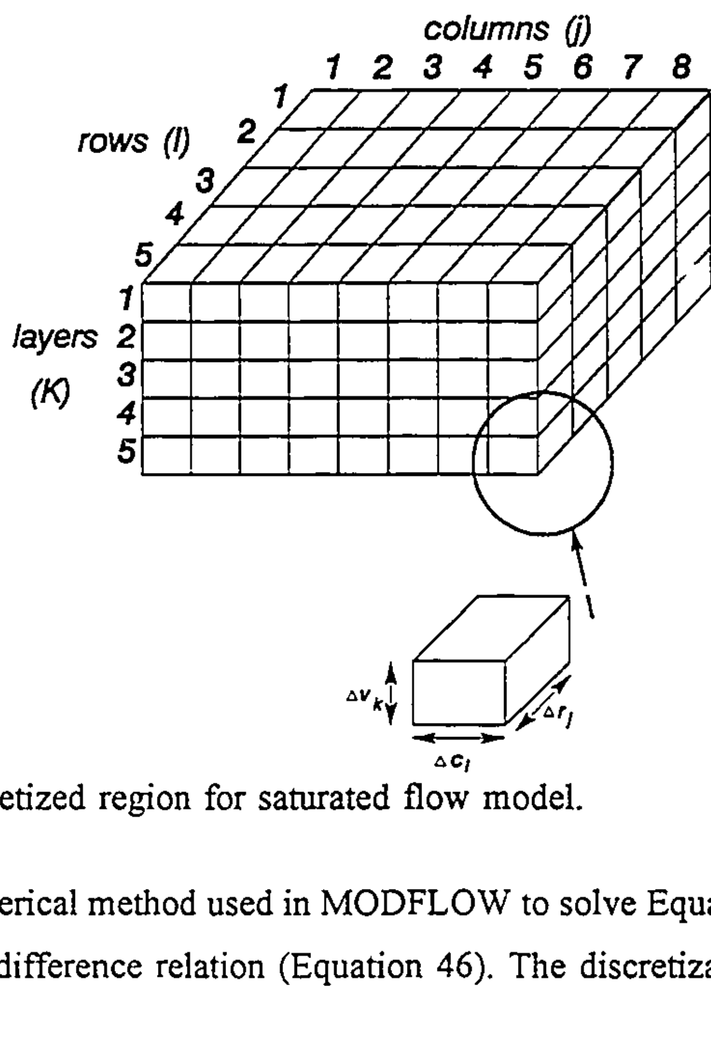

Figure 8. Discretized region for saturated flow model.

The numerical method used in MODFLOW to solve Equation 45 rewrites it into a finite difference relation (Equation 46). The discretization convention for the saturated flow reduces the region into a mesh of points, termed nodes, forming rows, columns, and layers. The i,j,k coordinate system is used to define the mesh (Figure 8). The origin of the system is the upper left corner of the top layer. "Cells" are blocks of soil represented by each node. The width of the cells along rows is Δr_j for the j'th column. Similarly, Δc_i is width of the column along row i and Δv_k is height of the k'th layer. The sizes of cells are adjustable but will affect all other cells along that column and row. The cell height Δv_k can be set individually.

The finite difference equation is arranged into three groups of terms. The first group is the sum of six flow components into or out of the faces of a cell based on Darcy's law. The second group consists of the source (or sink) term for water flow dependent on hydraulic head, a source (or sink) term independent of hydraulic head. The third group on the right-hand side of Equation 46 is a term representing the change in storage of water in the cell.

$$\begin{aligned}
&CR_{i,j-\frac{1}{2},k}(\Psi^m_{i,j-1,k}-\Psi^m_{i,j,k})+CR_{i,j+\frac{1}{2},k}(\Psi^m_{i,j+1,k}-\Psi^m_{i,j,k})\ + \\
&CC_{i-\frac{1}{2},j,k}(\Psi^m_{i-1,j,k}-\Psi^m_{i,j,k})+CC_{i+\frac{1}{2},j,k}(\Psi^m_{i+1,j,k}-\Psi^m_{i,j,k})\ + \\
&CV_{i,j,k-\frac{1}{2}}(\Psi^m_{i,j,k-1}-\Psi^m_{i,j,k})+CV_{i,j,k+\frac{1}{2}}(\Psi^m_{i,j,k+1}-\Psi^m_{i,j,k})\ + \\
&P_{i,j,k}\Psi^m_{i,j,k} + Q_{i,j,k} = Ss_{i,j,k}(\Delta r_j \Delta c_i \Delta v_k)\frac{(\Psi^m_{i,j,k}-\Psi^{m-1}_{i,j,k})}{(t^m-t^{m-1})}
\end{aligned} \tag{46}$$

In Equation 46 'm' designates the time step, and 'CR', 'CC', 'CV' are the conductance values ($m^2\ day^{-1}$) between nodes for rows, columns and layers respectively. The conductance is equal to the hydraulic conductivity times the area between cells divided by the distance between nodes in the center of the cells.

The storage coefficient 'Ss' (m^{-1}) can be present in two forms: 1) the specific yield that is used in the unconfined conditions; and 2) the specific storage for confined conditions. During water table management situations the water flow will be in an unconfined condition. The unsaturated flow model calculates specific yield during the simulation using the method described in Pikul et al. (1974). The specific yield is the difference between the saturated moisture content and the minimum moisture content between the water table and the root zone. The specific yield will decrease as the moisture content in the soil increases and will result in the model simulating a faster rising water table.

The method used to solve the finite difference equation (Equation 46) uses the backward difference technique that gives a numerically stable solution. The term "numerically stable" implies that as heads are calculated at successive times, errors will not accumulate and dominate the results. The iterative method used starts the calculations with an initial trial solution. Then a procedure of calculations is employed to find an interim solution. The interim solution is compared to the trial solution. If they are nearly equal, calculations end for that time step. If they are not, the interim becomes the new trial solution and calculations continue.

MODFLOW was developed to calculate water flow in the saturated zone; however, several modifications were necessary to meet conditions during water table management. One change was to enable the model to simulate a rising water table through soil layers. The original MODFLOW would turn off a cell if the water table dropped below the bottom elevation of that cell. This would leave that cell out of any future calculations. The revised MODFLOW component will recognize a fluctuating water table and include that cell in relevant calculations. MODFLOW's flow budget needed extensive changes to incorporate subirrigation, and the relationships for the unsaturated flow.

A module was developed to simulate drain activity by creating drain cells that can operate in several modes (subirrigation, drainage, control drainage, in combination, and automated control).

$$Q_{drain} = K_{drain}(\Psi^{m}_{i,j,k} - \Psi^{m}_{drain}) \qquad (47)$$

Each cell that contains a drain is identified (Equation 47) and its contribution to flow per unit drain length 'Q_{drain}' (m^3-day^{-1}-m^{-1}) is calculated by multiplying a conductivity constant 'K_{drain}' (m^2-day^{-1}-m^{-1}) times the difference in head inside the cell '$\Psi_{i,j,k}$' (m) with that of the tile 'Ψ_{drain}' (m). The sink terms '$P_{i,j,k}$' and '$Q_{i,j,k}$' in Equation 46 indicate where the two terms in Equation 47 are included in the finite difference relation for each cell containing a drain. When the subsurface drains are operating in the drainage case, no flow is assumed from the tile if the water level in the field drops below the drain. For controlled drainage, there will be no flow to the drain if the water level in the drain cell is at the head level set for the drain. During subirrigation, water is supplied from the drain when the water table over the drain cell becomes less than the head in the drain. If the water table level rises too high (currently set at 10cm above drain head), then drainage can occur until the water level drops to that level.

The combination mode of operation for the drains refers to the case where during a simulation the drain operation is switched, such as is the case between drainage and subirrigation.

Automated control mode lets the program adjust the water level in the drain according to the water level at some designated point in the field or due to moisture stress (WET variable). The change of head in the drain is limited to steps of 5 cm once every 24 hours in the range between the ground surface and drain elevation. The step size was selected as a reasonable value but could be changed if needed. This type of simulation provides insight on how a managed system will act for a given layout and weather conditions.

Since large errors can occur in regularly spaced grids (Fipps and Skaggs, 1986), care must be taken to reduce spacing in the regions near a drain. Smaller spacings near the drain will better represent the high gradients occurring in this area. The conductivity constant 'K_{drain}' was estimated from data reported by Bournival et al. (1986), whose studies were performed on the same subirrigation system used for the field verification in this thesis (Chapter 5). Their report included flow rates, observed head loss and the length of drain distributing this flow. From this data, the conductivity constant for the drain was calculated as 0.33 m^2-day^{-1}-m at a total flow rate in the lateral of 0.11 m^3-day^{-1}, and a drain conductivity of 0.727 m^2-day-m for a total lateral flow rate of 0.33 m^3/day. During operation of a subirrigation system the flow rates are low, so a value of 0.4 m^3-day-m was used in the calculations for verification in this thesis.

The finite difference equation is written for each cell in the saturated region and solved simultaneously. The boundary conditions for the saturated model can be varied, but for the applications used in this thesis the upper boundary is the water table with its flux being included in the top cells. The sides and bottom boundaries are considered no-flow.

3.1.3 Linking the Saturated and Unsaturated Models

The unsaturated flow model requires considerable computation due to the nature of the governing equations of flow. Linking of the one dimensional unsaturated flow model to the three dimensional saturated model can therefore be done to different degrees by selecting an acceptable computational requirement and accuracy needed for the analysis. The user of the linked model selects the area which the unsaturated model is to be used (see Figure 9), and by doing this, controls the amount of computation required. The saturated model's grid consists of cells that are solved for total head below the water table. Columns representing the unsaturated model are solved for one value of total head above the water table.

Figure 9 presents the different cases of linkage that can be selected between the flow models. Each case has a grid of cells representing the saturated flow model that can have different heights for the water table. Cylinders represent the unsaturated flow model that are located on top of cells in the saturated model.

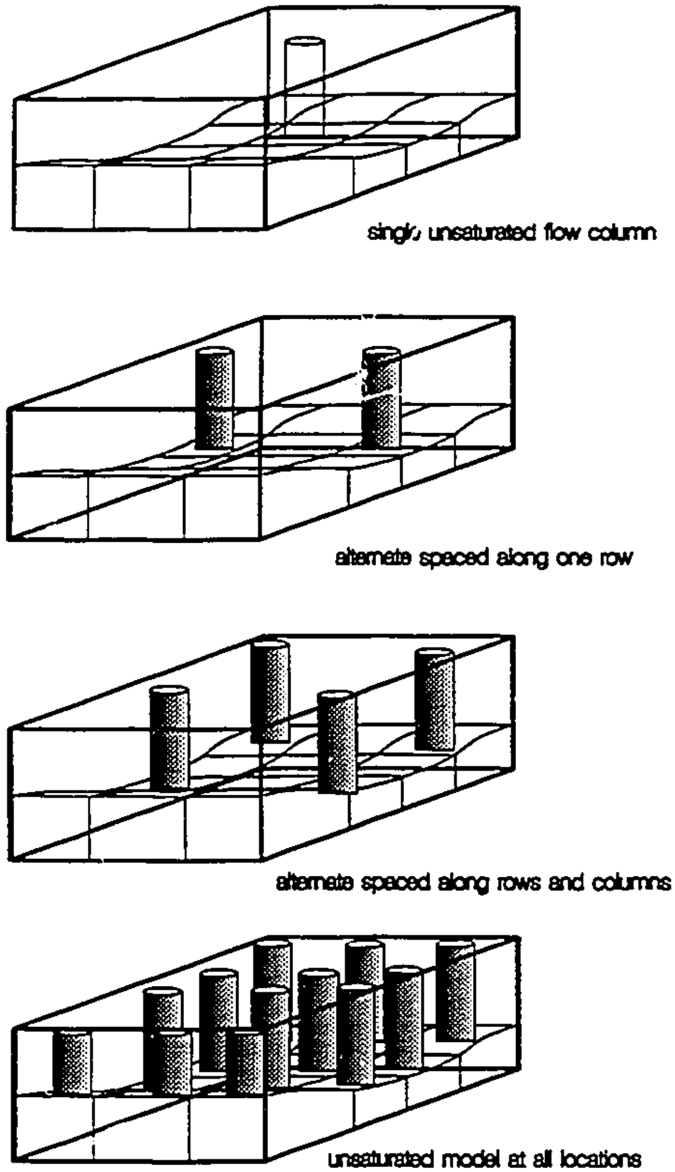

Figure 9. The linkage options between the unsaturated model (cylinders) and the saturated model grid.

Four combinations of unsaturated columns and the saturated cells are used in the computer model: 1)The use of one unsaturated column at a single location in the saturated model grid assume the same conditions for all other locations in the unsaturated zone; 2)The use of an unsaturated column above alternate columns in the saturated model grid, solves values of the unsaturated zone along a single row; 3)The unsaturated column above alternate rows and alternate columns in the saturated model grid is solved and results are interpolated for unsolved locations; and 4)The unsaturated columns are located above each top cell of the saturated model grid. Since the user can simplify the model to different degrees, fast results can be used to test the effect of different soil or system parameters. The user may then select for the most comprehensive study at the expense of much more computational time for a final simulation.

When the saturated and unsaturated models are linked, the following procedure is used during the simulation:

1) The unsaturated model is solved at time t_m for pressure heads with the water table levels set at the initial conditions for the saturated model. The lower boundary of the unsaturated zone is the surface of the water table. Flows to/from the unsaturated zone and the specific yield are calculated for this same time step. This is repeated for each active unsaturated column selected for the simulation.

2) The saturated flow model is then solved for hydraulic heads over the same time step for each active cell in the finite difference grid. The new levels for the water table are determined as well as all flows into and out of the saturated flow region including drains, infiltration and upward flux.

3) A mass balance of water flow to and from the saturated flow model is

made for the current time step. The difference between the flows, in and out of the saturated flow region are compared to the change in water stored. A small overall difference is a check for the calculations. Results are determined as a percentage error on the accumulated flow in the simulation and on the rate of flow in the current time step.

4) Steps 1 and 2 are repeated for advancing time steps to the end of a designated time period (such as a stress period). A printout is made of all hydraulic heads in both the unsaturated and saturated zones and a water budget if initially requested by the user. Then the steps are repeated for the next stress period.

3.1.4 Assumptions and Limitations to the Mathematical Model

1. Finite difference relations for saturated and unsaturated ground water flow represent the governing equations.

2. Unsaturated flow is treated as vertical and at this stage of model development, the unsaturated soil properties are homogeneous in the soil profile. The model user must select unsaturated soil properties that are representative of the unsaturated soil profile in the region being simulated. This limitation should be removed in future upgrading of the model to be consistent with the heterogeneous capability of the saturated model, but at this stage a workable linkage with a less complicated unsaturated model was aimed for.

3. Flow rates and specific yield to and from the saturated to unsaturated zones are treated as constant for any one time step.

4. The water table is at a constant level during the calculation of unsaturated flow for any one time step.

5. The unsaturated flow component currently does not consider the hysteretic nature of the functional relations of soil properties in the profile.

6. Preferential flow paths and the effect of air dynamics are not considered in the relations used.

7. The computer program LINKFLOW was designed to solve moisture conditions for a transient case. Steady state situations can be approximated by simulating a long time period under constant hydrologic stress.

8. Head levels set in the drains are assumed not to change with different flow rates. This is reasonable under the low flow conditions that occur a few days after startup.

3.2 Computer Programs

Two main programs are used when working on a water table management simulation. The simulation program LINKFLOW is written in Fortran 77 and consists of a specially developed unsaturated flow model which provides a linkage to the revised saturated ground water flow model. A program

LINKINP, written in Visual Basic, was developed to provide an interactive interface for preparation of the data sets for LINKFLOW. In addition to these, several other application programs are used. SURFER (Golden Software) is a contour and surface mapping package used by LINKINP to prepare graphical output. SOIL (El-Kadi, 1984) is an interactive program used to determine coefficients for the unsaturated soil properties.

3.2.1 LINKFLOW

LINKFLOW is the linked unsaturated-saturated ground water flow computer program that was developed in this thesis. The program is written in Fortran 77 and has been compiled by the Lahey77 32 bit compiler. The Lahey compiled program runs in a DOS environment and requires a 386 or 486 PC computer to operate.

The main program that directs the flow of events occurring was rewritten from MODFLOW to include the unsaturated model. The structure is presented in the flow chart in Figure 10. Each block in the chart represents a function being performed in the main program. Each function contains several subroutines. **Data preparation** uses the program LINKINP to prepare the required data sets. **Starting** LINKFLOW begins with reading initial data such as the names of data sets, size of the grid and modes of operation to **initialize** variables and **allocate** memory by dimensioning arrays. It is necessary to **Read**

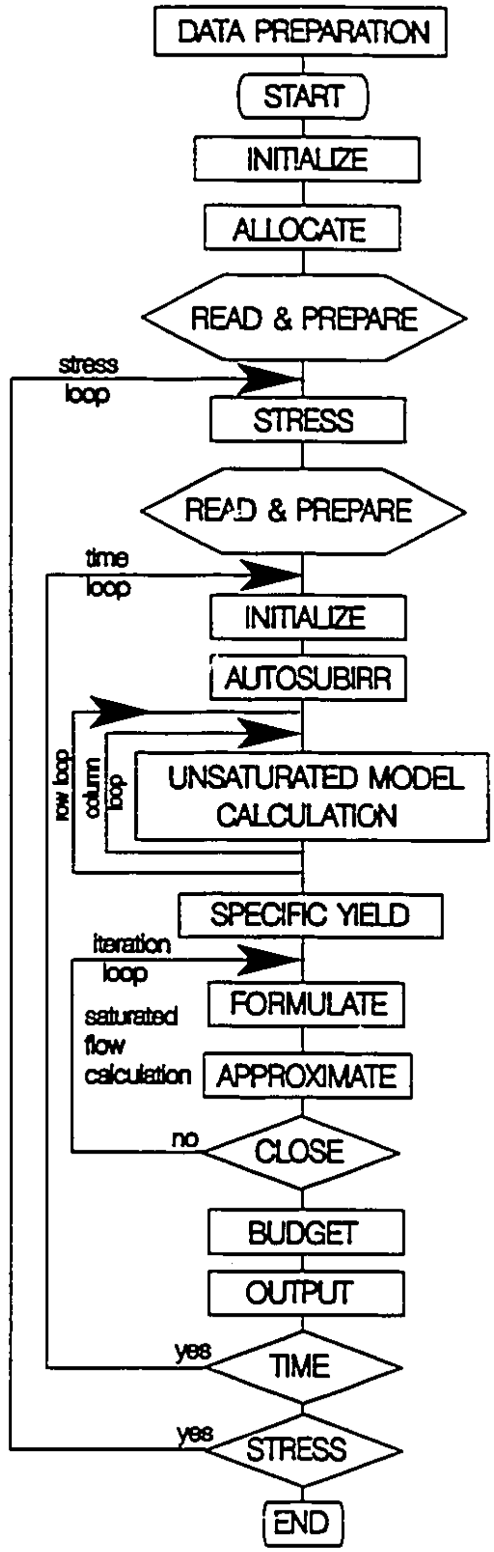

Figure 10. Structure of the main program in LINKFLOW.

and prepare data such as soil properties, dimensions of grid and layout of drains for the entire simulation. The program enters the first loop, called the **Stress** loop, which designates a time period (stress period) where constant hydrologic stress (such as rainfall, evapotranspiration rates and head in the subirrigation control chamber) will be imposed on the system.This stress includes rainfall events, potential evapotranspiration rates, heads in drains and can designate the output interval. Data are **read and prepared** for all data that are constant during a given stress period. The **time** loop reduces the time intervals in the stress period to manageable lengths for the calculations. The number of time steps required will depend on the flow gradients occurring in the simulation. The higher the gradients are, the shorter the time intervals for calculations. Calculations may cease due to intermediate solutions not converging to a final solution. Several parameters are **initialized** at the beginning of a time step, such as water budget quantities and constants used to test the head change in the saturated flow model. The **autosubirrigate** represents the option for allowing the program to automatically adjust the head in the drains according to field moisture conditions. These routines, if selected, will check the time of day, the field conditions and make adjustments accordingly. The next two loops, **row** and **column,** take the unsaturated model to all locations of the saturated model grid where linking was requested. The unsaturated model routine calculates pressure heads for each node in the unsaturated column, also estimating flow and specific yield to and from the saturated zone. After the first time increment, the **specific yield** routine estimates values at points needed in the saturated grid using known values and water table depths(as discussed in section 3.1.2.1)). The **iteration loop** for the saturated model is the point where the coefficients for the finite difference relations are **formulated**. Then an

approximate solution is calculated. The **closure** tests the difference between the present solution and the last approximation. If it is less than the tolerance, iterations cease and the program proceeds, otherwise, a new solution is calculated using the latest hydraulic head estimates. Water **Budget** quantities are accumulated for the time step, and on the last time step of a hydrologic stress period an **output** of hydraulic heads and the water budget are sent to disk. If **time** and **stress** loops are finished then the program ends, otherwise the next time step begins.

The format for each data set required for LINKFLOW is described in Appendix A. LINKINP, the program written to aid the user in preparing the data sets for LINKFLOW, is described in the next section.

Figure 11 pictorially represents the interactions between various programs that can be used with LINKFLOW. The oval symbols represent programs and the rectangles represent different types of data sets. The output from LINKFLOW comes as a text file with an ".OUT" extension, in which there is: a record of the input data, tabular information on the hydraulic heads, water table depths, water budgets, pressure heads, moisture contents and a summary of moisture conditions in the area being examined. A sample output of LINKFLOW is included in Appendix B for a the case example discussed in Chapter 5. A set of output for graphical interpretation may be produced by the program if the user selects this option. The graphical output data sets have a ".DAT" extension and contain field location coordinates with either water table depths, moisture contents, or a WET value (equation 44). Data in this form may be plotted in a contour or surface plot using the program SURFER. The selection of files, printing and graphing is handled by LINKINP.

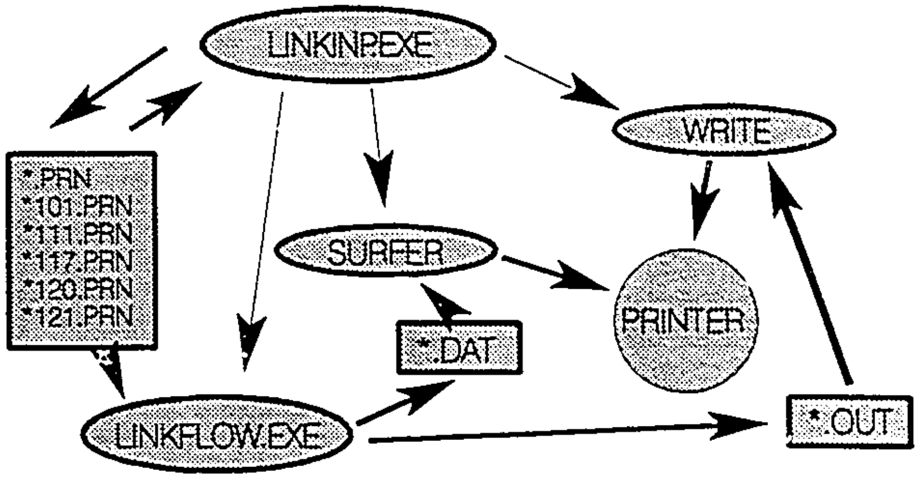

Figure 11. The relationship between programs LINKINP and LINKFLOW with transfer of data sets and of accessory programs.

Performance of LINKFLOW is dependent on the complexity of the situation and the length of time being simulated. The unsaturated flow model component of LINKFLOW requires the most calculation time due to the close nodal spacing. Selecting a linkage that does not require all the unsaturated columns to be active will greatly enhance speed of the simulation. For example, a simulation for a 60 day period using heterogeneous soil properties and topography for full linkage (every saturated model top cell is linked to an unsaturated model column) required 60 hours of computation time on a 33MHz 486 PC computer. However, using alternate rows and alternate columns requires 15 hours. A simple model involving a layered soil and one row of alternate spaced unsaturated columns for 13 days simulation takes 3 minutes on the same computer. This time reduction is due to the reduction in the number of locations having unsaturated flow calculations being performed and interpolating required for unsaturated flow criteria in areas where calculations were not performed. How inaccurate this will be depends on the particular simulation being done. These programs can operate in the background in the Windows or OS2 environment, which allows several simulations to be run at once.

3.2.2 LINKINP

The LINKINP program was developed to assist the user of LINKFLOW in creating new data sets, making modifications to existing data sets, running LINKFLOW, viewing output, creating and viewing contour or surface representations of output data and making printouts.

The program was written in Visual Basic V1.0. This program creates simple forms to ask for input, and the mouse selects actions or data for input from a suggested range of values. The standards for Windows 3.1 are used so that all editing commands, such as copy and paste, are valid. This reduces the time in learning and developing the data sets for LINKFLOW. The input displays are shown in Chapter 5. Most of the selections on those displays will guide the user to other displays that inform and help the user enter the data. Once a data set has been created, it may be reread by LINKINP so that changes can be made for future simulations. LINKINP uses the programs WRITE (WINDOWS 3.1) and SURFER to view the text and graphical representations from the simulations. LINKINP loads these programs, supplies the data sets and returns to LINKINP when the user is finished with these external programs.

Chapter 4 shows how LINKFLOW and the unsaturated flow component of LINKFLOW compare to field observations and published results.

Chapter 4: Validation of LINKFLOW

4.0 Validation of Model

The validation of the linked model initially requires the testing of the specially developed unsaturated flow model. This component was designed specifically to link with the saturated flow model and determine water status in the unsaturated flow profile. Once this component's performance is validated, then the linked flow model can be tested. This next section will use published data to validate the unsaturated flow model. Then in later sections, field measurements from monitoring various types of water table management systems will be used to compare with the linked model's simulation results.

The comparisons between results simulated by the program to either published or measured results will use the following statistical relations (Gupta et al.,1993).

$$AVERAGE\ ERR = \frac{\Sigma(P_i - O_i)}{N} \tag{48}$$

$$RELATIVE\ ERR = \frac{AVERAGE\ ERR}{AVERAGE(O_i)} \tag{49}$$

$$STANDARD\ ERR = \sqrt{\left(\frac{\sum (P_i - O_i)^2}{N}\right)} \tag{50}$$

$$COEFFICIENT\ OF\ VARIATION = \frac{STANDARD\ ERR}{AVERAGE(O_i)} \tag{51}$$

Where "O_i"and "P_i" are the observed and simulated values being compared for "N" number of observations. The regression coefficient "R" is determined as an indicator of how well the observations and simulated results compare. The "R" values can range between zero to one, with one being a perfect correlation.

The next section, through several test cases, validates the performance of the unsaturated flow model.

4.1 Validation of Unsaturated Soil Water Flow

The unsaturated flow component of the LINKFLOW model will be compared with results of some unsaturated flow studies (field measurements or validated model ouputs). The first case involves one-dimensional infiltration into a dry soil as described by Van Genuchten (1978b). The next case involves drainage of a wet profile as described in Dane (1982). The third test concerns a case of evaporation and drainage over a fixed water table first solved by Klutz and Heerman (1978) and described by Dane (1981).

4.1.1 Steady Infiltration into a Sandy Profile

Van Genuchten (1978b) used Equations 52-55 to describe the needed soil properties for their example of steady infiltration of water into a vertical sand column. Comparisons are based on their measured data. Saturated flow conditions were assumed if the pressure head was greater that -14.495 cm.

$$K(\psi) = 19.44x10^{4}|\psi|^{-3.4095} \quad cm\text{-}hr^{-1} \tag{52}$$

$$\theta = 0.6829 - 0.09524\ln|\psi| \qquad -29.484 \le \psi \le -14.495 \; cm \tag{53}$$

$$K(\psi) = 516.8|\psi|^{-.97814} \; cm\text{-}hr^{-1} \tag{54}$$

$$\theta = 0.4531 - 0.02732\ln|\psi| \quad \psi \le -29.484cm \tag{55}$$

The initial conditions for a 125 cm deep soil profile included moisture contents defined by equation 56. Z is the positive distance from the soil surface down into the soil.

$$\theta_o = 0.15 + 0.0008333Z \quad for\ 0 \le Z \le 60\ cm \qquad \theta_o = .2 \quad 60 \le Z \le 125\ cm \tag{56}$$

The infiltration rate is set as a constant flux of 37.8 cm-day^{-1} into the soil surface. The soil property relations given in equations 52-55 were incorporated into the unsaturated flow program for this comparison. This was to ensure that differences in the results was due to computation and not the method used to describe the soil properties. Results of the simulation and those from van Genuchten's paper are compared at two and nine hours after the beginning of infiltration. Figure 12 shows the moisture profiles for these times. A relative error of zero and 1.29% indicated a good comparison between the literature data and the simulation results. The high hydraulic gradients involved in this example required time steps to be reduced to 0.0005 days to ensure stable results. This small a time step was not necessary in the other simulations. The results show that the model can respond to a surface flux such that the moisture content of the profile increases.

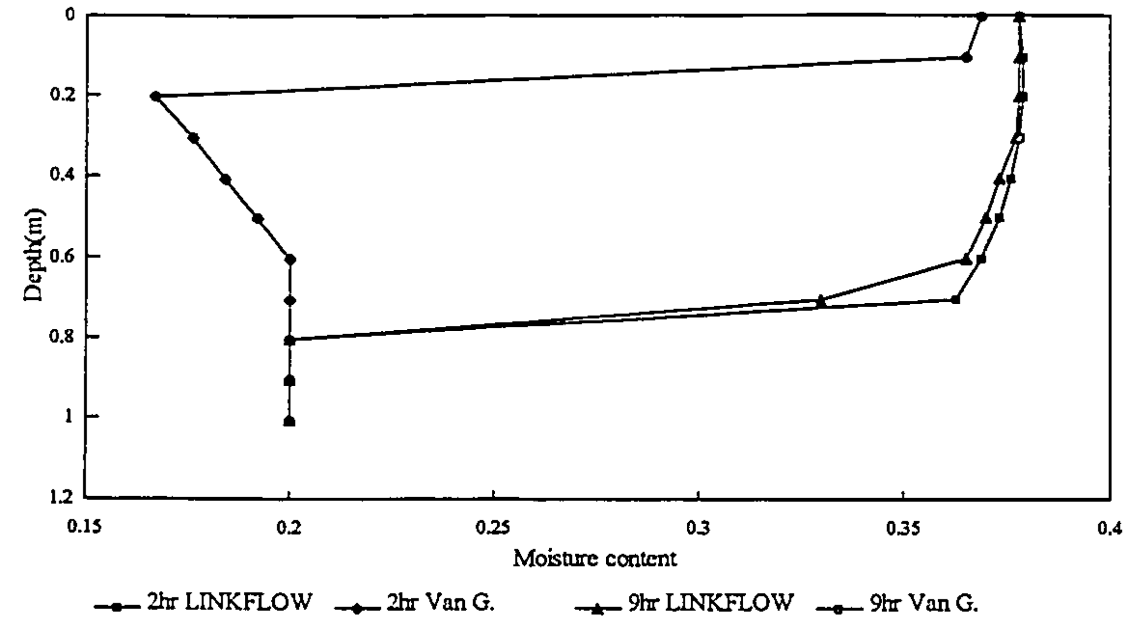

Figure 12. Comparison of unsaturated flow model to Van Genuchten's example for one dimensional infiltration.

4.1.2 Drainage Example

Drainage of a soil profile as described by Dane (1982) on a Troup loamy sand was compared with the unsaturated model's simulation results. This study used the relations in equations 57 to 60 to describe the soil water retention and hydraulic conductivity function.

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1+(\alpha|\psi|)^n]^m} \tag{57}$$

$$\theta_r = Residual\ Water\ Content = 0.069$$

$$m = (1-\frac{1}{n}) \tag{58}$$

$$K = K_s S_e^{\frac{1}{2}}[1 - (1 - S_e^{\frac{1}{m}})^m]^2 \tag{59}$$

$$S_e = \frac{\theta-\theta_r}{\theta_s-\theta_r}$$

$$\theta_s = Sat.\ Water\ Content = 0.365$$

$$n = 3.57168 \tag{60}$$

$$\alpha = 0.02912$$

$$K_s = Sat.\ Hyd.\ Conductivity = 10.95\ cm\text{-}hr^{-1}$$

The boundary conditions are listed below:

- $\psi(Z) = -26.775$ cm at t = 0
- zero flux at the surface at t > 0
- $\delta\psi/\delta z = 0$ at z = -140cm at t > 0

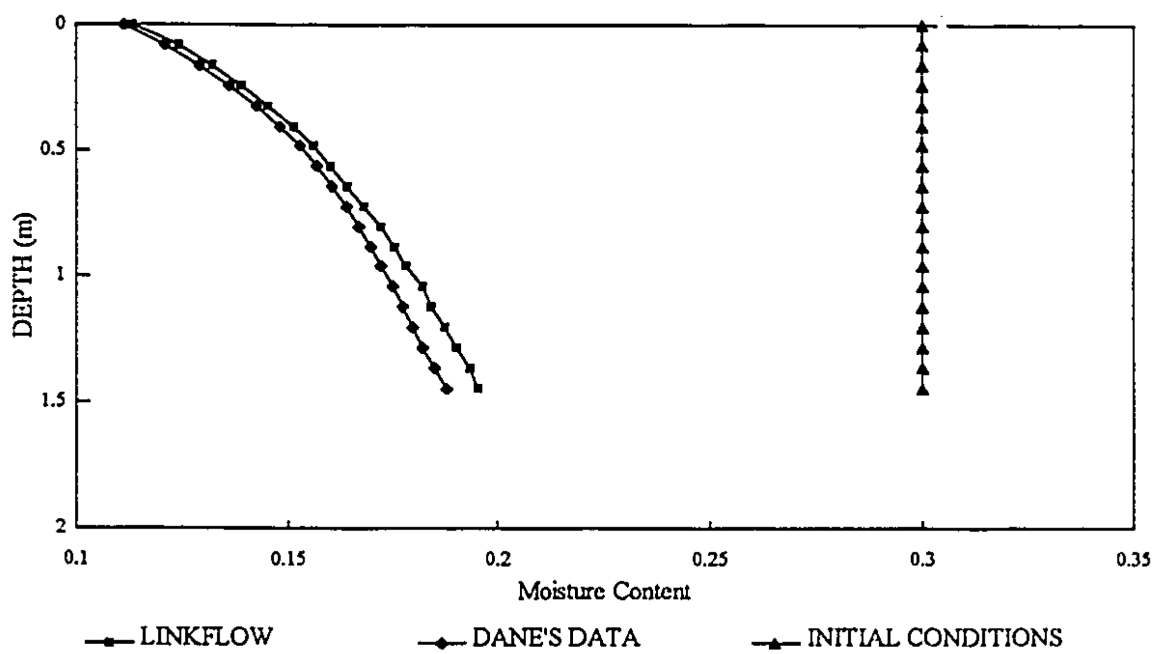

Figure 13. Comparison of unsaturated flow model to Dane's example for one dimensional drainage after 14.4 hours from initial conditions.

After 14.4 hours of drainage, the resulting moisture profiles from the literature and the unsaturated flow model are shown in Figure 13. A relative error of 3.08% occurred. The graph shows slower drainage occurring in the soil profile below the 1 meter depth in the LINKFLOW results than reported by Dane. This difference may be due to the "adaptive technique" of the finite difference solution Dane used in this problem where time and nodal spacing increments are automatically decreased in the areas where there are significant changes in hydraulic head occurring. The unsaturated model simulated with reasonable accuracy the decreasing moisture contents occurring in the soil profile due to drainage.

4.1.3 Evaporation and Drainage Example

Water movement in a uniform soil profile of coarse uranium mill tailings was simulated for a fixed water table at three meters depth. The problem, described by Dane (1982), used the following empirical functions for moisture properties (Equations 61-65).

$$\theta(\psi) = \theta_o \frac{[\cosh\beta - \Gamma]}{[\cosh\beta + \Gamma]} \quad -7320 \leq \psi \leq 0\,cm \tag{61}$$

$$\theta(\psi) = (\frac{\psi}{d}) \quad \psi < -7320\,cm \tag{62}$$

$$K(\theta) = Ae^{B\theta} \tag{63}$$

$$\beta = (\frac{\psi}{\psi_o})^b \quad b<0 \tag{64}$$

$$\Gamma = \frac{\theta_o - \theta_r}{\theta_o + \theta_r} \tag{65}$$

θ_o= 0.43, d= -0.1964cm, θ_r= 0.076, a= -0.1964, ψ_o= -131cm,
A= $0.225*10^{-8}$cm-hr^{-1}, b =-0.46, B=54.29

The boundary conditions used included the following:

$$\psi = -1\text{cm at } t = 0, -300 \leq z \leq 0$$
$$\psi = -15000\text{cm at } t > 0 \text{ and } z = 0$$
$$\psi = 0\text{cm at } t > 0 \text{ and } z = -300\text{cm}$$

Figure 14 shows agreement between LINKFLOW simulated data and those published, at a simulation time of four hours for simultaneous drainage and evaporation. A relative error of 0.31% between the data sets was calculated, thus verifying the excellent agreement for this test.

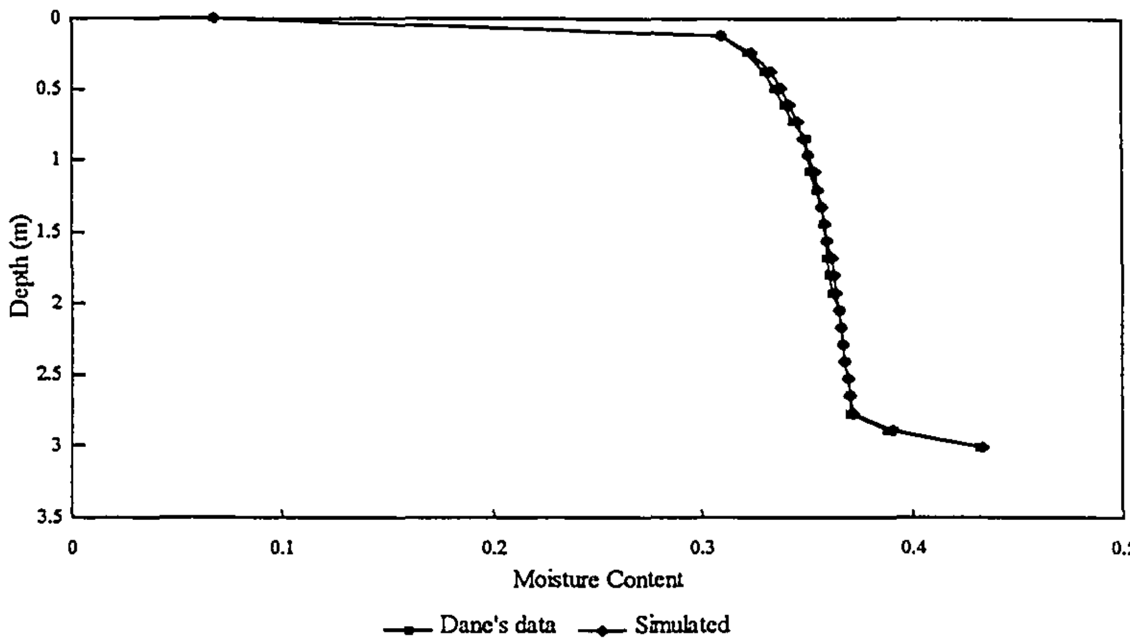

Figure 14. Comparison of unsaturated flow model to Dane's example for simultaneous drainage and evaporation in an unsaturated profile after 4 hours of simulation.

The above three examples show that the unsaturated finite difference model can simulate unsaturated flow processes as reported in selected literature. The next step in this thesis will be to compare literature and field observations to the linked saturated and unsaturated model LINKFLOW.

4.2 Validation of LINKFLOW

The linked flow model will be compared to both published and measured results to establish the accuracy of the simulations that can be done with LINKFLOW. The first case will be to compare published results for drainage to simulated results from LINKFLOW.

4.2.1 Drainage Example

Tang and Skaggs (1980) compared numerical solutions for a two dimensional Richard's equation for the case of open ditch drainage to several approximate methods of solution. The solution to Richard's equation involved solutions using numerical methods developed by Amerman (1969). LINKFLOW will be compared to their results to verify the model for transient drainage conditions.

The soil type is a Panoche soil with soil characteristics reported in Nielsen et al. (1973). The soil profile is treated as homogeneous and isotropic to a depth of 1.6 m where an impermeable layer is present. The water table level is initially at the soil surface. The ditches, spaced 20 m apart, have a water level one meter below the soil surface the instant the simulation begins. Results are given in terms of water table profiles between the drains at two and 50 hours after beginning of drainage. Figure 15 shows the comparison between Tang and Skaggs results to the simulated results by LINKFLOW. Relative errors of 4.5% and 7% occurred for 2 and 50 hours after the beginning of drainage. The flow near the ditch is not well described by LINKFLOW, this may be due to the fact that LINKFLOW was developed to simulate the drains and is not suitably adjusted for ditches. LINKFLOW compares well at the early time steps and further away from the ditch. For example, the relative errors reduce to 3.4% and 2.4% if the data within 4m of the ditch is ignored.

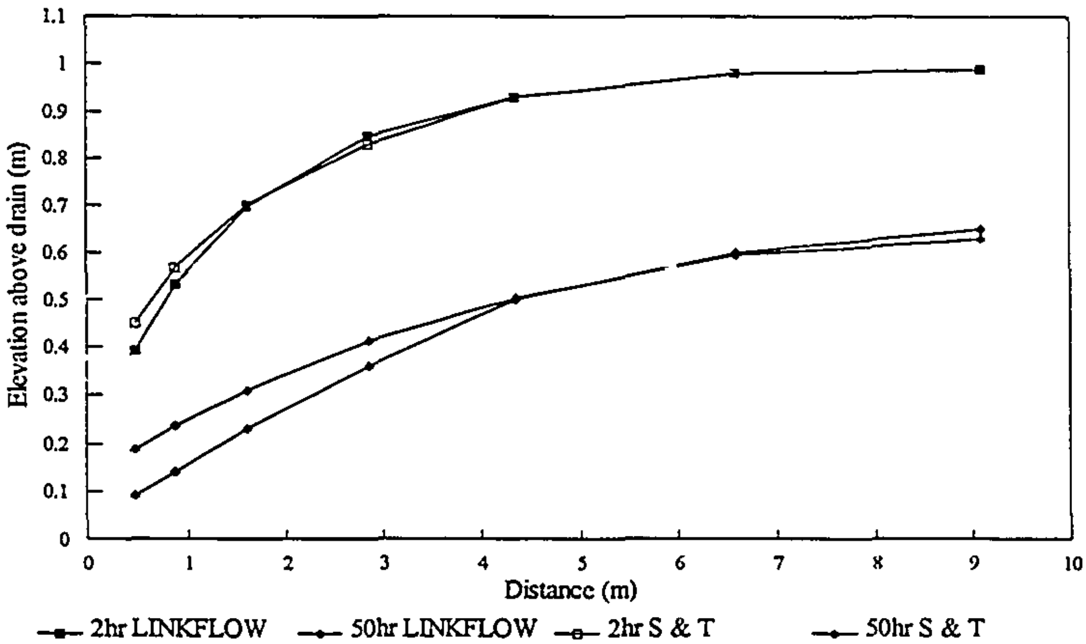

Figure 15. Comparison between LINKFLOW and two dimensional combined saturated and unsaturated soil water flow model described by Tang and Skaggs (1980) for drainage to parallel ditches.

The next section continues the verification by comparing simulation results from LINKFLOW with measured field observations from different water table management systems.

4.2.2 Field Plots

The site used for verification of LINKFLOW was at the experimental plots on the farm of Mr. L. Charbonneau near Saint-Victoire, Richelieu County in Quebec. This has been the site of several research studies (Rashid-Noah, 1981; von Hoyningen Huene, 1984; Gallichand, 1983; Memon, 1985; Soultani, 1989; and Mackenzie, 1992) providing detailed information on the soil and system operation. Values for hydraulic conductivity, soil profile dimensions, weather data and parameters for operation of the system were obtained from earlier and on going studies. A crop of corn was grown on all plots during the period being examined.

The soil profile consists of a dark brown, fine St-Samuel sandy loam layer for the first 20-30 cm. Below this is an olive pale, medium sand to a depth of 1.5 m. Then a marine clay of several meters thickness occurs that can be treated as an impermeable layer (Rashid-Noah, 1981).

A schematic of the field and drain layout is shown in Figure 16. Four treatments of different water table management methods with four replications made up the sixteen plots during the 1987 growing season. The treatments included: saline water subirrigation; fresh water subirrigation; controlled drainage; and conventional drainage. Measurements were taken on all plots two to three times a week between July 2 and August 28..

The system used for subirrigation, supplies water to the drain system from four control chambers. The control chambers could maintain a level of water by using an adjustable float valve to add water, and an adjustable riser pipe to allow drainage under excessive water levels. Details concerning construction and operation are described in earlier studies (von Hoyningen Huene, 1984; Gallichand, 1983; Memon, 1985; and Soultani, 1989).

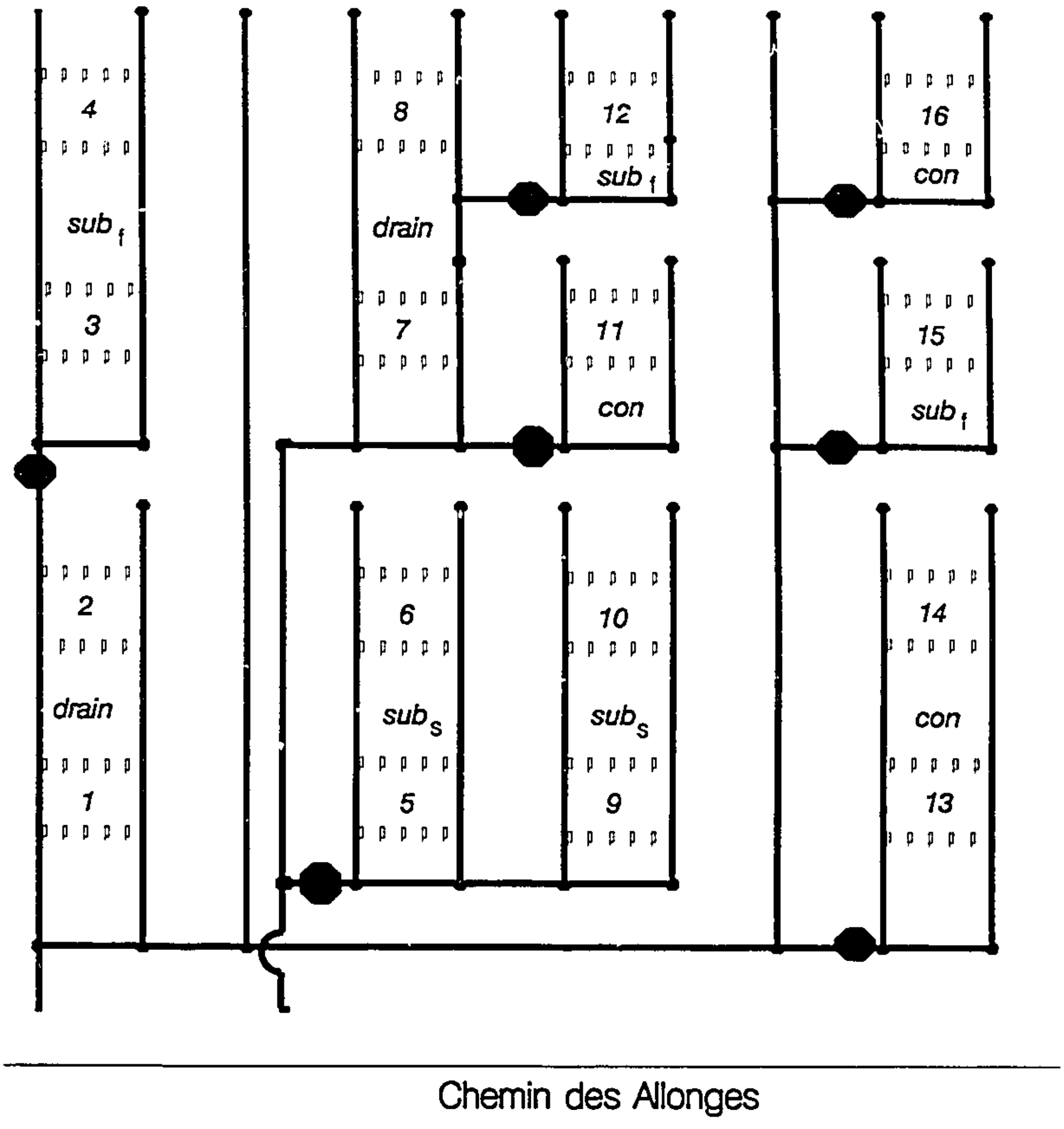

Figure 16. Drain and plot layout, with large dots for control chambers, "drain" for conventional drainage, "sub" for subirrigation ("f" for fresh water, "s" for saline) and "con" for control drainage.

Saline water from a well (plots 5, 6, 9 and 10), and fresh water (plots 3, 4, 15 and 16) from town water supply mixed with drainage water were used to supply water to the field. Experiments were underway on the feasibility of using the saline well water for subirrigation on crop performance and effects to the soil profile (Bonnell and Broughton, 1993; and Bonnell, 1993) since this water is readily available on site. The lateral drains were covered with a knitted polyester sock filter material and spaced approximately 30m in all plots. The length of drains varied from 65 to 130 m depending on the plot. The plots for controlled drainage (plots 11, 13, 14 and 16) used three control chambers to set the allowable drainage height. Conventional drainage plots (plots 1, 2, 13 and 14) allow free drainage to the depth of installed drains. North is at the top of Figure 16 and observation wells are defined using the plot number and direction (for example 4N refers to plot 4 North).

A brief description is given next for the measurements taken in the field plots to be used to verify LINKFLOW.

4.2.3 Field Measurements

Two sets of five observation pipes were installed across each plot at 40 m spacing. The location of each set of pipes, shown by the letter "p" in Figure 16, was 0.15m, 7.5m, 15m, 22.5m, 29.85m, respectively, measured from the drain on the east side of each plot. The two sets of observation pipes within a plot are identified by the plot number, either north or south and the distance from the lateral drain on the west side of plot. The pipes consisted of 19mm I.D., 1.5m long PVC pipes with perforations along the pipe. Each was wrapped in polyester fibre material to prevent blockage by sand. Water levels were observed by lowering a calibrated rod equipped with a sounding device which beeps when in contact with water. Readings were recorded from the top of the observation pipe to the water table. The top of each pipe was surveyed using a surveyors level so that these readings could be converted to water level elevations.

Moisture contents were measured at depths of 15cm, 30cm and 45cm next to each water table pipe using a Neutron probe within installed aluminum observation tubes. Moisture contents at the 7.5m and 22.5m locations from drain were not measured in the drainage and control drainage plots. The Neutron probe was calibrated with gravimetric measurements of soil moisture content.

The field observations for the plots used for verification are given in Appendix C. The following section discusses the input information necessary to begin a simulation of the a field plot.

4.2.4 Input Information for Model

Appendix D contains in the chronological order of the stress periods (the major time increments for printouts and hydrologic events) required by LINKFLOW: time length, weather information and printout status used in the simulation of the field plots. Printouts were requested at intervals corresponding to when observations were taken. Rainfall and potential evapotranspiration values are reported by Soultani (1989).

The saturated soil properties were taken from Rashid-Noah (1981), with values of saturated hydraulic conductivity ranging from 1.5 m-day^{-1} near the surface to 0.1 m-day^{-1} approaching the bottom clay layer.

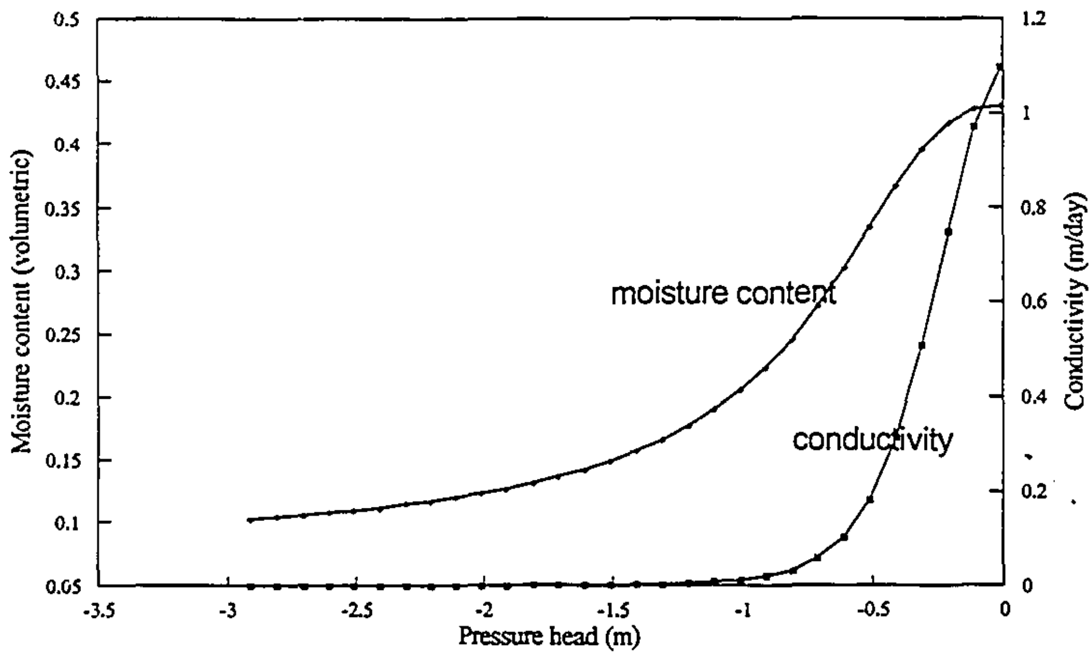

Figure 17. Moisture retention and conductivity relation used for verification of test plots.

The unsaturated soil properties are from Mackenzie (1992) and shown in Figure 17. Since the unsaturated flow component assumes homogeneous soil conditions, the unsaturated soil properties chosen must be representative of the soil properties in the region between the water table and the soil surface. Soil properties used for the saturated water flow are varied over the soil profile and the region. Intermediate topographic elevation points needed for data input for LINKFLOW were determined using the program SURFER. A surface map for each plot is given at the beginning of each section where the simulation and observations results for that plot are compared. The plot numbers indicate where the measurements were taken in the field and under what treatment.

Most of the treatment areas contained two measurement plots with each plot having two sets of observation points, LINKFLOW was then used to simulate water movement over the entire treatment area, so that four sets of observation points could be used for verification.

4.2.3 Subirrigation Plots Comparison

Plots 5 and 6 were subjected to subirrigation with saline water to investigate efficient use of this source of water. Subirrigation began July 13 and readings were taken several times a week until August 28. The two plots (for yield measurements) are contained in the region shown in Figure 18, an area of low elevation occurs at the top of the plot and higher elevations at the bottom or south end of plot. The total difference in elevation was approximately 30cm.

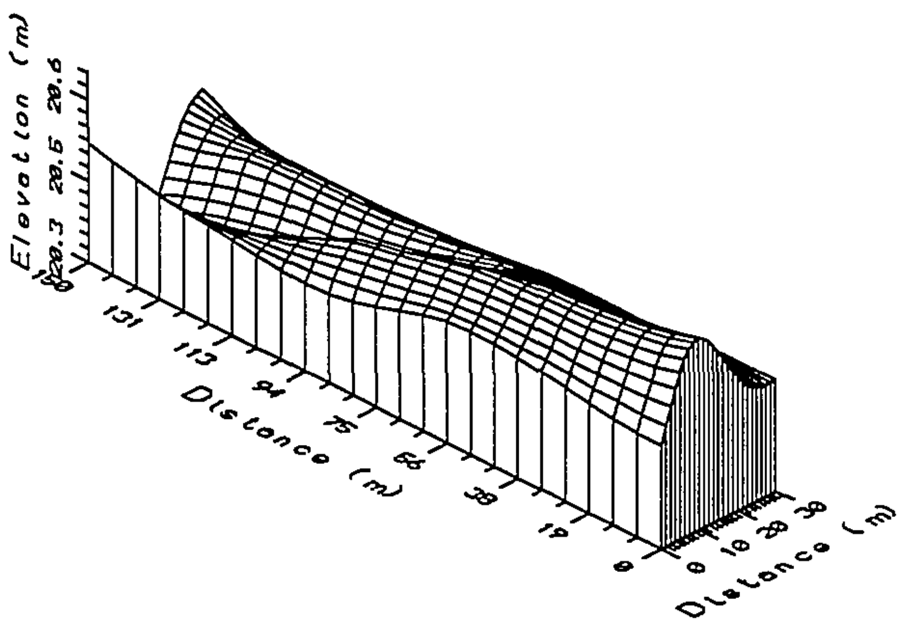

Figure 18. Soil surface representation for subirrigation plots 5 and 6.

The four rows of observation pipes were at distances 15, 55, 90 and 130m respectively from the south end of the plot (bottom right of Figure 18). As described in an earlier section, each row contained five piezometer tubes. The region shown above runs north - south with drains located on the east, west and south boundaries. Results of auger hole tests reported by Soultani (1989) showed hydraulic conductivity values ranging between 0.5 to 0.9 m-day^{-1}. Water levels were maintained on these plots more consistently compared to the other subirrigation plots, due to its being in a low area of the field, and had a good supply of water during that summer.

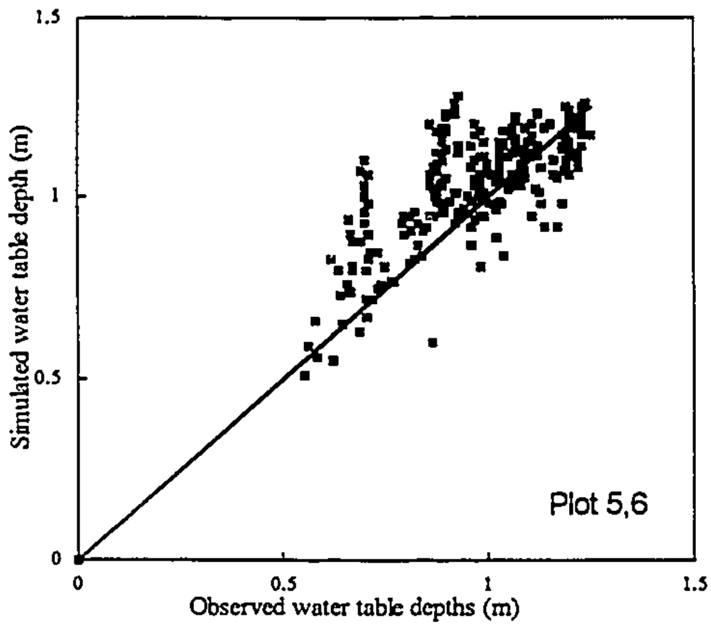

Figure 19. Comparing observed and simulation depth to water table in subirrigation plots 5 and 6. Solid line represents a perfect match.

Figure 19 compares simulated water table depths and those measured in the field. A perfect relation between the observations and simulation values would fall on the solid line in Figure 19. The scatter in the data from the solid line is a measure of how well the data sets agreed for the range of water table depths. The "R" value in Table 2 represents the regression coefficient for this data. The higher the "R" value, the better the simulation data fits the observations with a value of one being a perfect fit.

	7.5m	15m	22.5m
R	0.65	0.70	0.81
Average Error	0.10	0.14	0.09
Relative Error	10.2%	15.2%	8.9%
Standard Error	0.136	0.174	0.108
Coefficient of Variation	0.138	0.191	0.111

Table 2. Statistics for the error between observed and simulation values for water table depth in subirrigation plots 5 and 6 at three locations between laterals.

Table 2 gives several other statistics between the observed and simulation results. LINKFLOW simulated the water table trends but the relative error was as high as 15%. This is partly due to error in the measurements and in the soil properties as noted in the range of values found by the auger hole tests. Despite this variation, these values fall into the typical range of standard error (0.1-0.4m) reported for DRAINMOD simulations (Fouss et al.,1987; Workman and Skaggs, 1989; and Kanwar and Sonaja, 1988).

Figure 20 graphs both simulated and observed values of water table depth with time for one observation point. The moisture contents in the root zone and the measured 15cm depth moisture content are compared for the same location in the field in Figure 21. Moisture content measured by neutron probe is not a point measurement but a mean value near and above that depth. Therefore moisture contents are only plotted to observe if observed and simulated behave in the same manner. Both Figures 20 and 21 showed similar trends with the simulated values having less fluctuation.

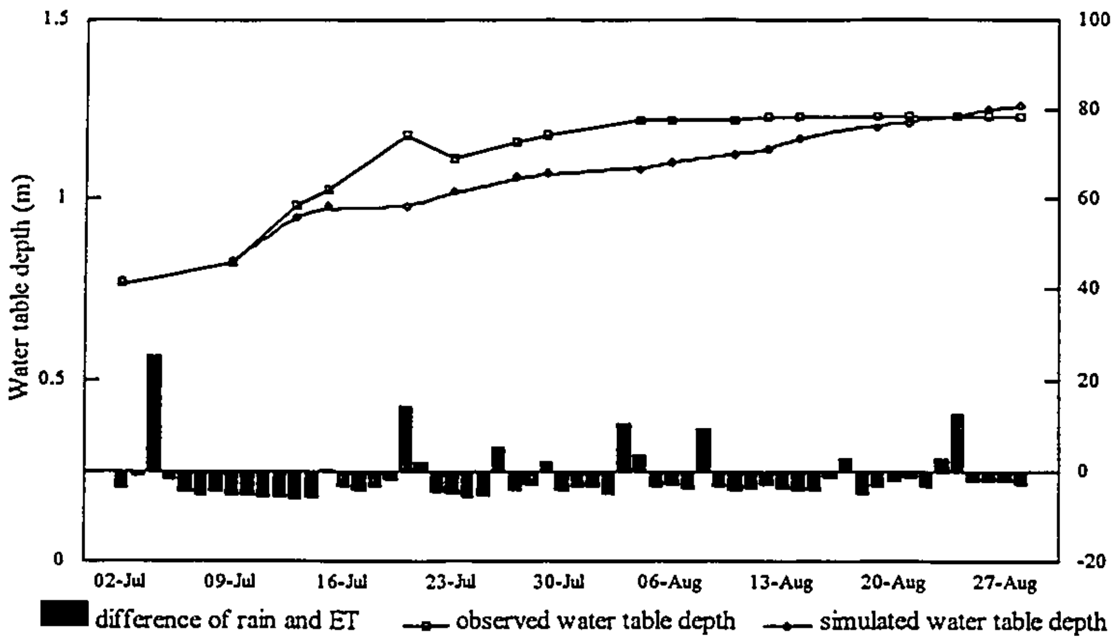

Figure 20. Depth to water table versus time for simulation and observation data in subirrigation plot 5 at mid spacing in the southern set of observation pipes.

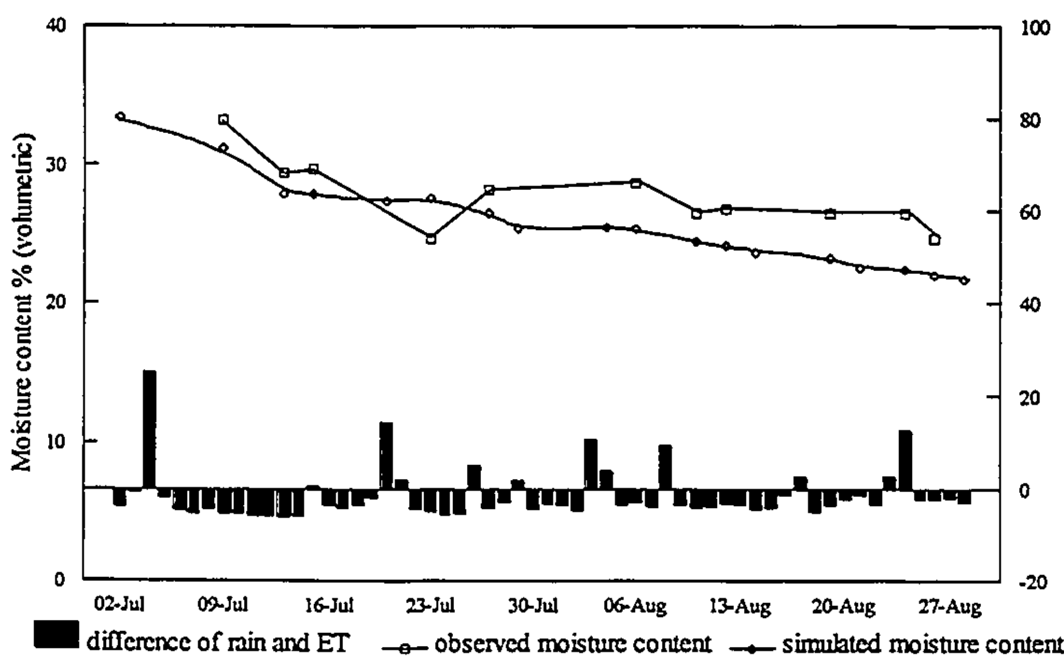

Figure 21. Moisture content in root zone versus time comparison for simulation and observation data in subirrigation plot 5 at mid spacing for southern set of observation tubes.

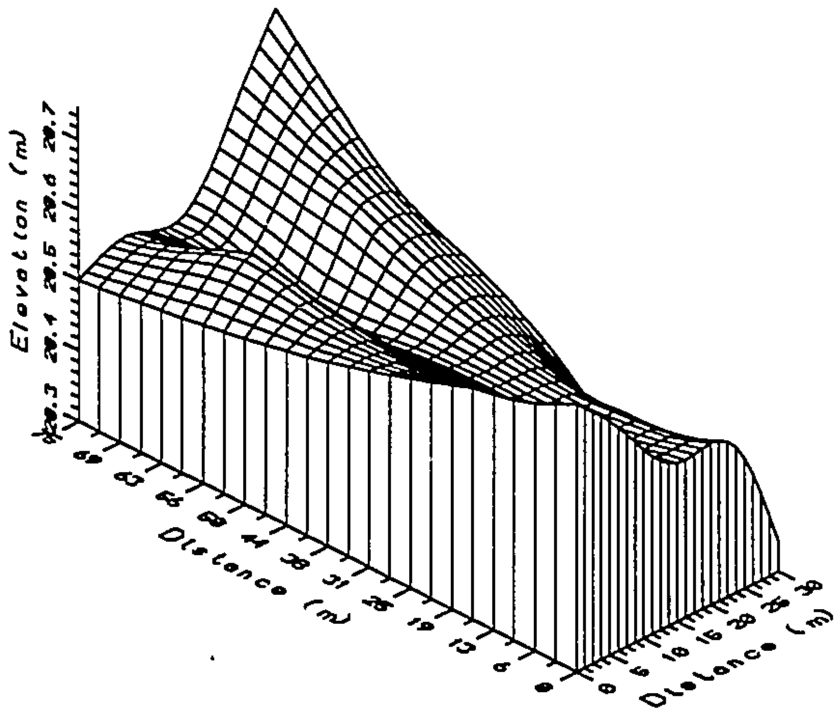

Figure 22. Soil surface elevations for plot 12 for subirrigation.

Plot 12 was subjected to the treatment of fresh water subirrigation. The plot was contained in the region shown in Figure 22. An area of higher surface elevation occurs at the top right (north-east) of the plot and the edge of a depression is situated on the bottom right of the plot. The total difference in elevation is approximately 25cm. Two rows of observation pipes were at distances 15 and 55m from the south end of the plot. The region shown above runs north - south with drains located on the east, west and south boundaries. This plot was at the north end of the field and was subject to seepage losses to adjacent regions. It had difficulty in maintaining a high water table during operation.

Figure 23 shows the relation between observations and results of simulation for depth to water table. Much of the scatter is due to readings in

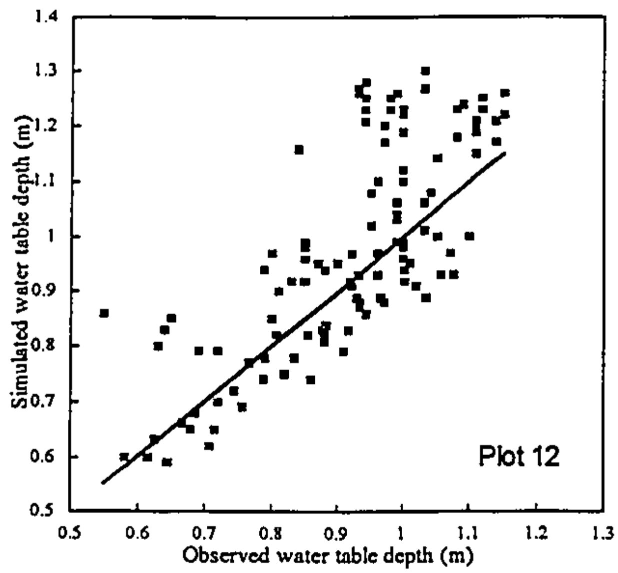

Figure 23. Comparing observed and simulation depth to water table in subirrigation plot 12. Solid line represents a perfect match.

the 7.5m from drain area where the relative error was 16.5%. There were better comparisons for other points as indicated by the high regression coefficient values "R" and the low coefficients of variation in Table 3. This anomaly may be associated with measurement error or inaccuracies in the soils information, also the effects of surface runoff and water accumulations in depressions will effect comparisons. Figures 24 and 25 show good agreement between simulated and observed water table depths and root zone moisture contents respectively over the time period.

Table 3. Statistics for the error between observed and simulation values for water table depth in subirrigation plots 12 at three locations between laterals.

	7.5m	15m	22.5m
R	0.7	0.91	0.89
Average Error	0.17	0.05	0.08
Relative Error	16.5%	5.0%	6.5%
Standard Error	0.202	0.071	0.095
Coefficient of Variation	0.194	0.066	0.075

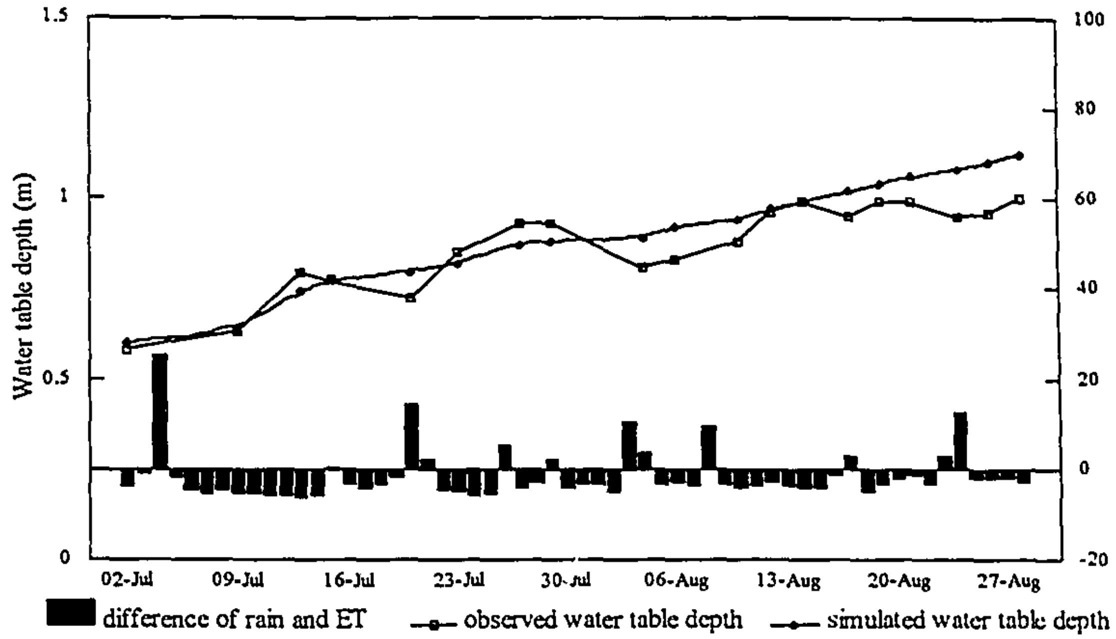

Figure 24. Depth to water table versus time comparison for simulation and observation data in subirrigation plot 12 at mid spacing in the northern set of observation pipes.

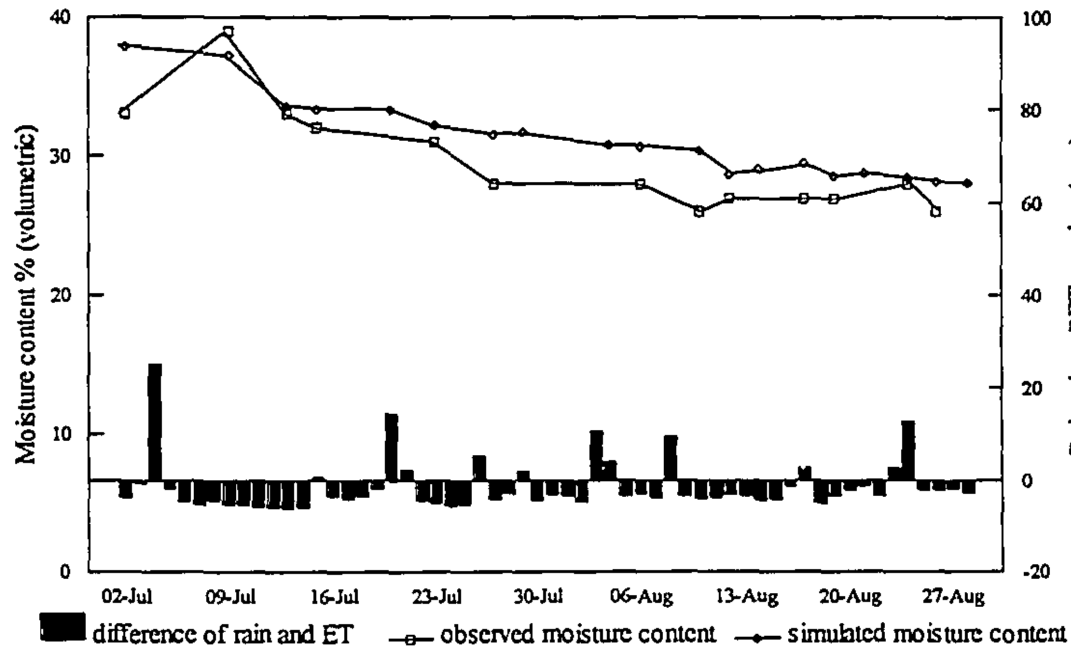

Figure 25. Moisture content in root zone versus time comparison for simulation and observation data in subirrigation plot 12 at centre spacing at the northern set of observation tubes.

4.2.4 Drainage Plot Comparison

Plots 1 and 2 were subjected to the treatment of conventional drainage. The two plots are contained in the region shown in Figure 26. The region had a slight depression running north-south down the center of the field. The total difference in elevation is approximately 20cm. The four rows of observation pipes were at distances 45, 85, 120 and 160m from the south end of the plot. The region shown runs north - south with drains located on the east, west and south boundaries. Results of auger holes tests reported by Soultani (1989) showed hydraulic conductivity values ranging between 0.6 and 2.2 m-day^{-1}.

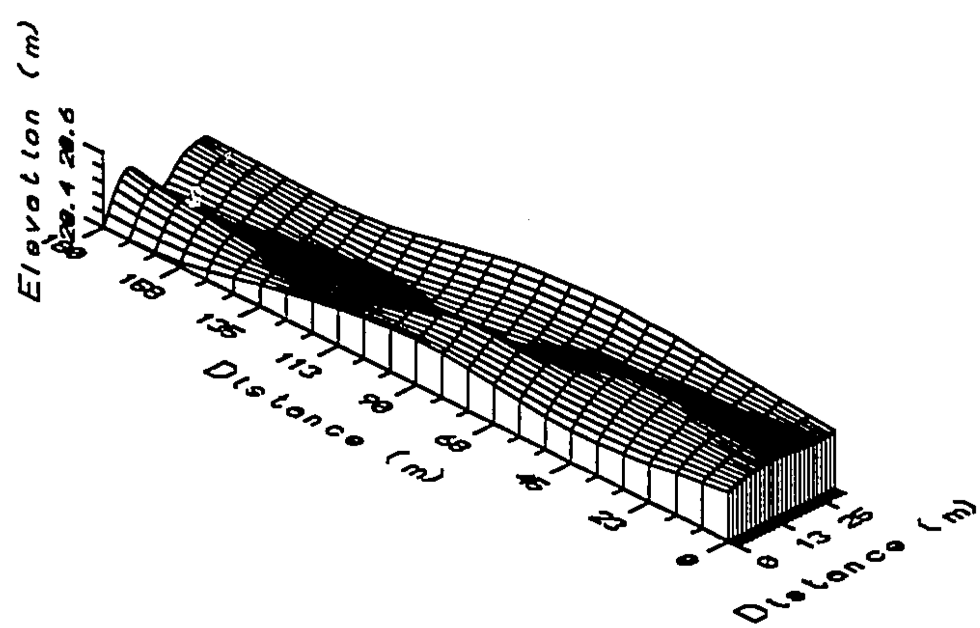

Figure 26. Soil surface elevations for plots 1 and 2 for drainage.

This treatment area sometimes benefited from high water levels in the outlet ditch next to the plots, and in those instances (such as occurred on July 20) the area operated as it would in subirrigation.

	7.5m	15m	22.5m
R	0.73	0.12	0.84
Average Error	0.09	0.27	0.10
Relative Error	8.0%	13.0%	9.5%
Standard Error	0.102	0.300	0.115
Coefficient of Variation	0.098	0.263	0.109

Table 4. Statistics for the error between observed and simulation values for water table depth in conventional drainage plots 1 and 2 for three locations between drain laterals.

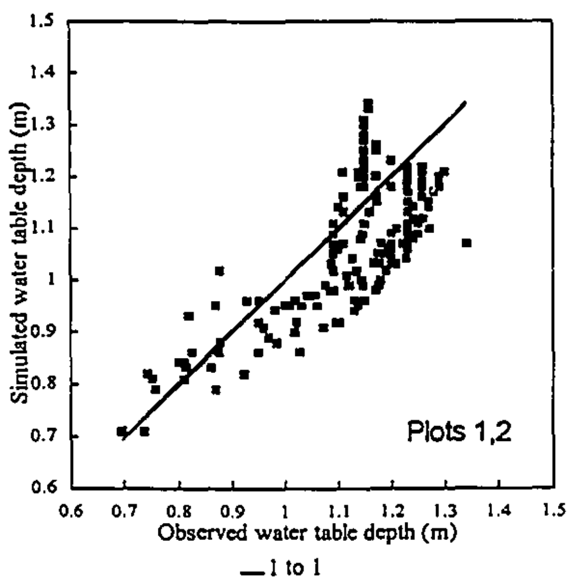

Figure 27. Comparing observed and simulation depth to water table in conventional drainage plots 1 and 2. Solid line represents a perfect match.

Figure 27 shows the simulated versus observed water table depths. The comparison between results and observations was not good for one area as reflected by the 23% error in the 15m column. The rest of the data compared well. The results suggest measurement and soil property description may have caused the error. Despite this, the error is well within the range that has been reported in other studies.

Figures 28 and 29 show the corresponding water table depths and moisture contents with time for two locations. The measured and simulated data compare well for the overall trend for the time period. One observation that can be made is that the simulation model did not show a similar response in moisture content change to individual rainfall events. These events are shown on the figures as the difference between rainfall and PET. One reason for the lack sensitivity in the simulation to these is the simulated moisture contents are an average value over the root zone while the measured value is for a point 15cm below the soil surface. However it is noted on Figure 29 that rainfall events did change the slope of the simulated line showing that the rainfall was used to meet some of the moisture losses over the root zone.

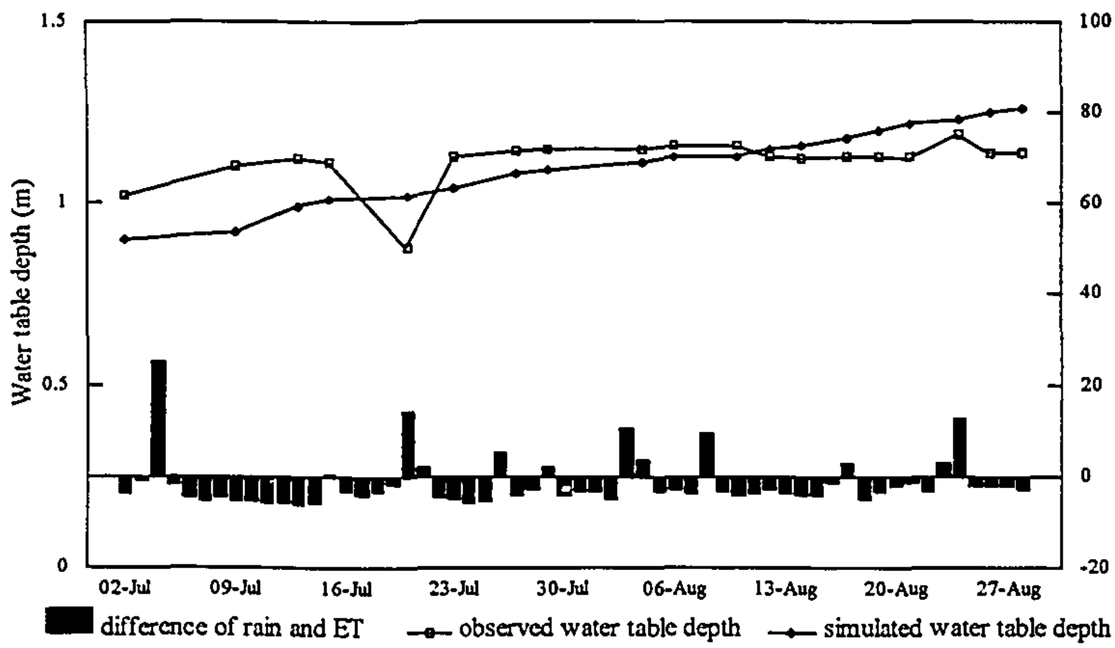

Figure 28. Depth to water table versus time for simulation and observations in drainage plot 1 at 3/4 spacing for southern observation pipes.

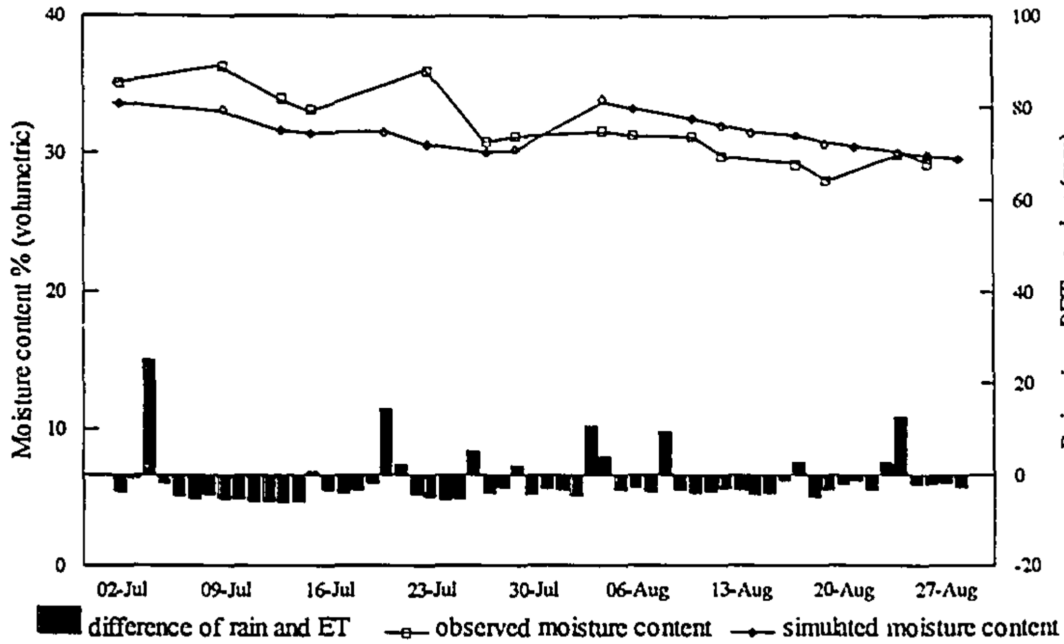

Figure 29. Moisture content versus time comparison for simulation and observation data in drainage plot 2 at mid drain spacing for the northern set of observation tubes.

4.2.5 Control Drainage Plot Comparison

Plots 13 and 14 were subjected to the treatment of controlled drainage. The two plots are contained in the region shown in Figure 32. The region is flat, with a total difference in elevation of approximately 10cm. The four rows of observation points were at distances 45, 85, 120 and 160m, respectively, from the south end of the plot. The region shown runs north - south with drains located on the east, west and south boundaries. This treatment area at times benefited from water flowing from the subirrigation plot 15 located on the higher land to the north.

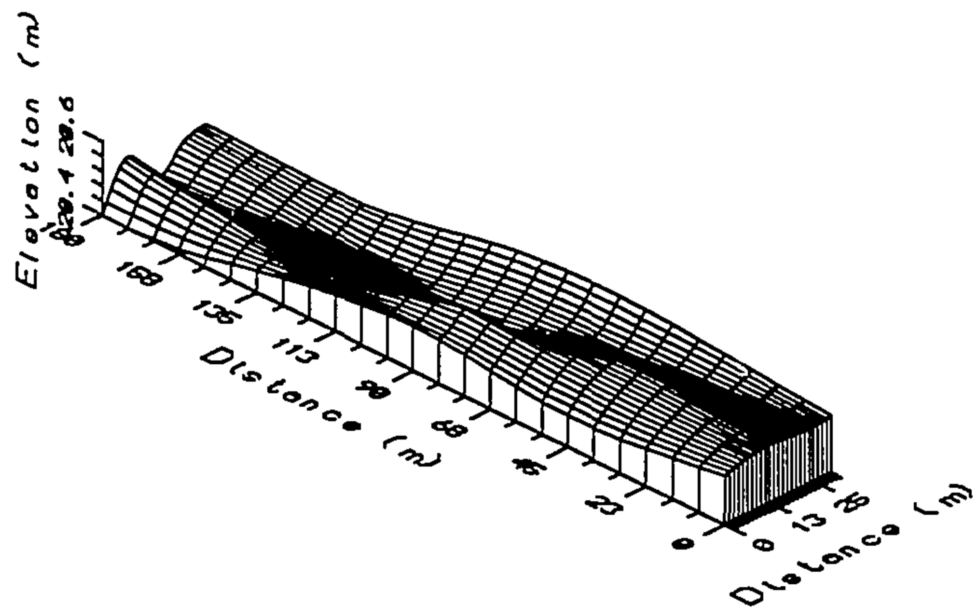

Figure 30. Soil surface elevations for plots 13 and 14 for controlled drainage.

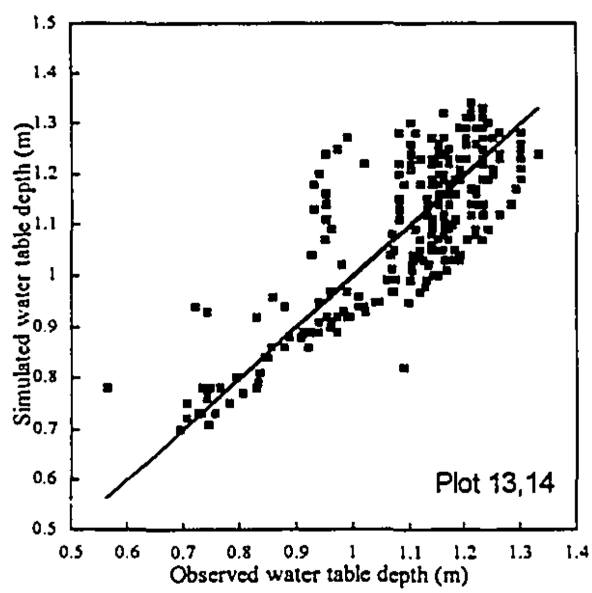

Figure 31. Comparing observed and simulation depth to water table in control drainage plots 13 and 14. Solid line represents a perfect match.

Figure 31 shows the simulated versus observed depths to water table for this controlled drainage plot. The data has a good comparison as reflected in the high regression coefficient values, relative errors of less than 10% and low coefficients of variation as indicated in Table 5.

	7.5m	15m	22.5m
R	0.81	0.78	0.85
Average Error	0.08	0.08	0.07
Relative Error	7.5%	7.8%	6.4%
Standard Error	0.099	0.110	0.085
Coefficient of Variation	0.088	0.105	0.078

Table 5. Statistics for the error between observed and simulation values for water table depth in controlled drainage plots 13 and 14 for three locations between drain laterals.

Figure 32 graphs the simulated and observed values at one location in the plot with time. The water table depth values compare well, however for the same location, the moisture content values do not compare as well (Figure 33). Some of the difference is due to the simulated value being an average root zone moisture content while the measured is at 15cm depth. Also, the effects of surface runoff or water ponding in depressions after rainfalls which LINKFLOW does not account for may contribute to some of the error. It appears that moisture content conditions in the root zone were not well simulated for this location.

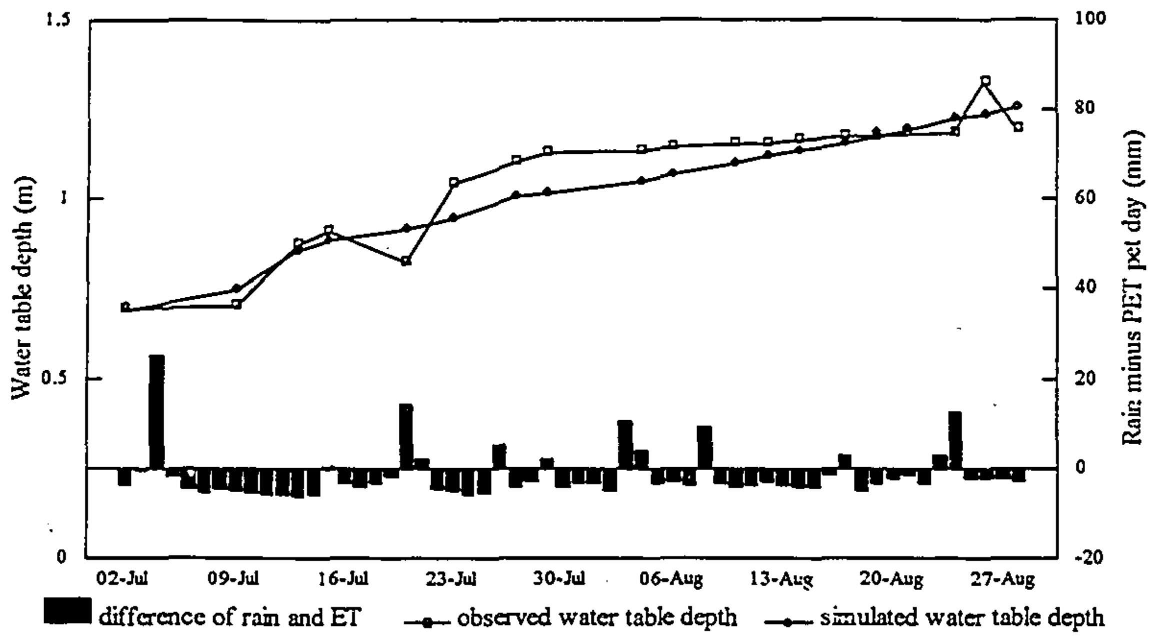

Figure 32. Depth to water table versus time for simulation and observations for controlled drainage plot 14 at centre spacing for the northern observation pipes.

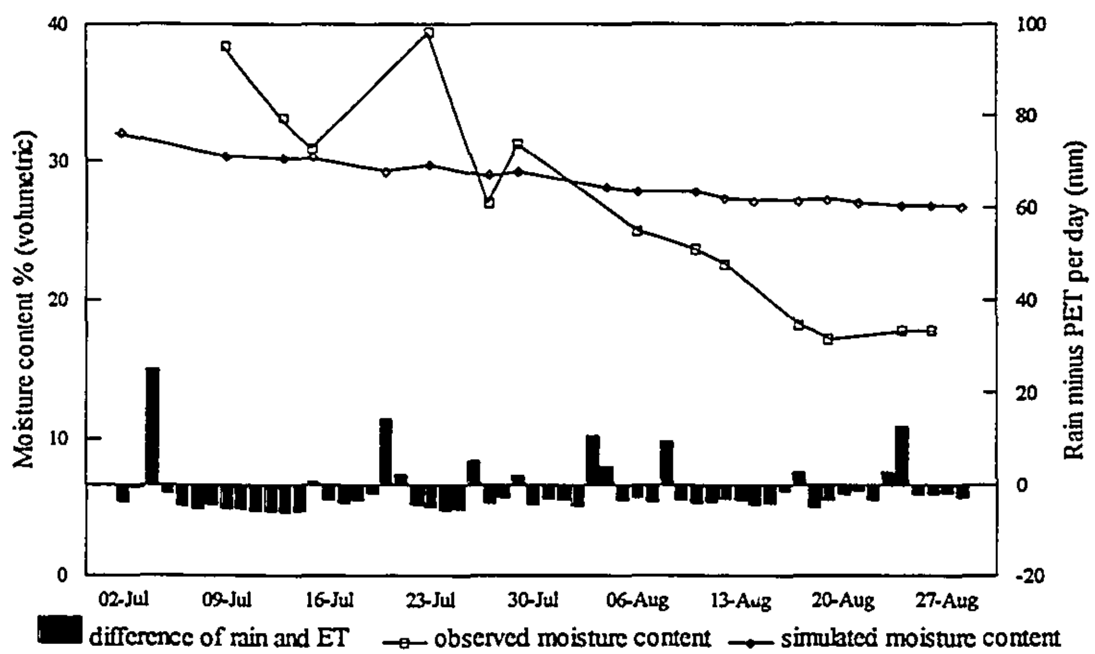

Figure 33. Moisture content versus time comparison for simulation and observation data in controlled drainage plot 14 at mid spacing for northern observation tubes.

4.3 Summary of Verification of LINKFLOW

This chapter found LINKFLOW could model the complex processes involved in water flow during water table management. However significant errors can occur due to variability in measurements and soil properties during the verification process, which indicates that for successful simulation with LINKFLOW, a good set of field data is important. The next section will examine further the effect of input information error on simulated water table depths.

4.4 Sensitivity Analysis of Input Parameters

The performance of LINKFLOW in simulating the movement of the water table depends on the accuracy of the input data. Field and laboratory measurements may be required to provide detailed soils and topographic data for a given field. These measurements require time and money, with the costs increasing with the level of detail required. It may be necessary to estimate values for soil parameters when data and resources limit conducting a full measurement program. It is important to know how error in the inputs will affect the results. To estimate this sensitivity, each of the inputs will be varied and the effect of these variations on the output will be noted. The inputs that greatly affect the output should have priority to the available resources when developing the input data set.

4.4.1 Procedure for Sensitivity Analysis

The sensitivity analysis of LINKFLOW was conducted on the water table management system described earlier in this chapter. The sensitivity analysis involved changing inputs, one at a time, by a set percentage and then comparing the results to the original output. The percentage change for each input from the original is the input error. Input errors of ±20%, ±50%, -90% and +100% were used with the main data inputs. These included the saturated conductivity, anisotropy factor (ratio of horizontal to vertical saturated hydraulic conductivity), unsaturated conductivity function, and the moisture retention function. Calculated properties from the unsaturated conductivity function were altered after their calculation, instead of changing the coefficients by the percentage error. The output error was found as the percent change from a simulation using the true value and one with the input error after an arbitrary 21 days of transient simulation.

Figure 34 graphs the results of the sensitivity analysis. Input error in the hydraulic conductivity caused the greatest error in determination of the water table height. For example an input error of ±20% results in an error in the estimation of the water table height of: ±2.2% due to the moisture characteristic function, ±0.1% due to the unsaturated conductivity function, ±6.7% due to the saturated conductivity value, and ±1.4% due to the anisotropy value. The ±6.7% error in saturated conductivity results in a ±1.5 cm error in the height of the water table over 15 days, however if the error in saturated conductivity was ±100% the resulting output error would be 30-60%. Unfortunately spatial hydraulic conductivity estimates are costly and difficult to obtain accurately for a field situation, but they still should receive the most attention when preparing the data set. The next factor which also is made up of the saturated conductivity is the anisotropy factor which caused the second greatest change.

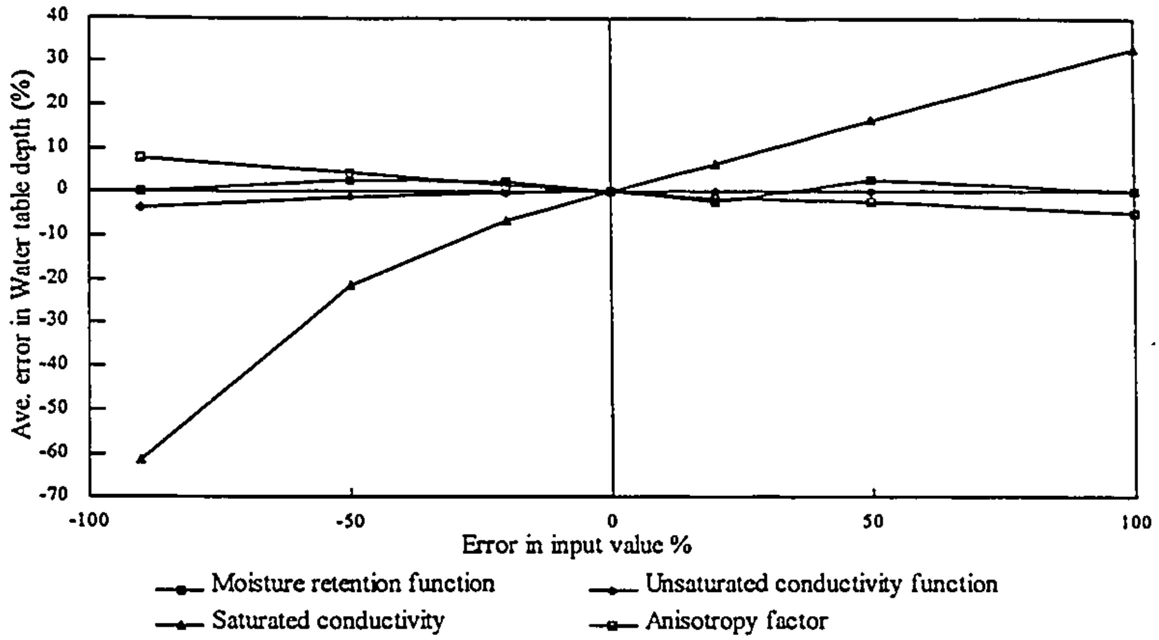

Figure 34. Effect of error in input parameters on resulting error to water table levels for example problem.

Anisotropy will be discussed further in Chapter 6. The unsaturated soil parameters for conductivity and moisture retention had the least effect in estimating the water table height for the example problem simulated. Output error from these factors has more impact on results such as average moisture content in the root zone or total water extracted from plant roots.

LINKFLOW has been shown to simulate the processes occurring during water table management. A sensitivity analysis showns where effort can be made to ensure the least amount of error by input data. Chapter 5 will use LINKINP and LINKFLOW for an example simulation to illustrate the operation of the program and its use in an investigation.

Chapter 5: Example Investigation

5.0 Example Investigation

In this chapter, LINKFLOW will be used to simulate subirrigation for a given soil profile to illustrate: the use of LINKINP in the preparation of a data set for LINKFLOW, considerations in LINKINP's use, and in examining the output from LINKFLOW.

5.0.1 Steps in Performing an Investigation Using LINKFLOW

a) **Problem definition** is necessary to aid in developing a data set for a ground water flow simulation. Identifying the problem and the investigation's objectives will affect: (1) how the finite difference grid is laid out to represent the flow region, (2) the collection of relevant field data, and (3) selection of appropriate operational parameters for LINKFLOW.

This sample investigation calculates the uniformity of water supplied to the root zone from the water table during a period of subirrigation over an area of a field. The region is bound by two lateral drain lines and by one main line. Simulations for two different lateral drain spacings will be compared for uniformity of water supplied to the crop. The soil properties are the same over the region, with the soil profile having decreasing saturated hydraulic conductivity with depth. The period of simulation will be for three weeks after the beginning of subirrigation.

b) **Site description** includes: weather, crop, topography, soils, and drain layout information. The greater the diversity of soil and topographic features over the region, the finer the grid will need to be to represent the region (since each block within the grid for the saturated flow model is considered to have homogeneous properties). A finer grid, requires more computer memory and computation time.

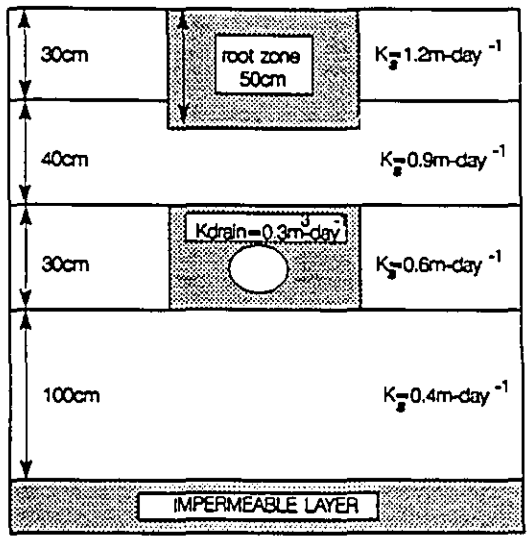

Figure 35. Soil profile with layer dimensions, saturated hydraulic conductivity and drain conductivity used in the example. (not to scale)

In this example, the region has a width equal to the spacing between the two lateral drains (15m and 30m), a length of 200 m, with a main drain at one end and none at the other end of the region. The soil profile properties are shown in Figure 35. The drains supplying subirrigation water have a hydraulic head of 19.75m inside them. The land surface elevation is 20.00m, and the initial water table elevation is 19.25m. The crop has a potential evapotranspiration rate of 5mm-day^{-1}, a fixed root zone depth of 50 cm, a permanent wilting point of -2.5 m, and at 50% AWC the pressure head is -0.8m. The permanent wilting point in this example is greater than the typical -15m suction used for permanent wilting point. The -2.5 m is based on a permanent wilting point moisture content of 12% which is in the recommended range sited by Schwab et al. (1993) for a sandy loam. The moisture retention curve and conductivity function are shown in Figure 36 are based on laboratory results for a sandy loam (MacKenzie,1992) and are assumed to represent the unsaturated soil properties over that flow region. Currently every spacial node of the saturated model can have different soil properties. The unsaturated model at this stage of development can only use one set of soil properties. Therefore the selection of representative properties in the unsaturated zone is important. The thickest soil layer in the top 0.6m of the major soil type is recommended. The coefficients for these soil properties were found by entering pressure head, moisture content and conductivity data into the program SOIL (El-Kadi, 1984). Coefficients for Van Genuchten (1978a) relation (equations 40,41,42,43) are used to describe the unsaturated hydraulic conductivity as 'K_{sat}' equal to 1.1 m-day^{-1}, 'n' is 3.6 (dimensionless), a residual moisture content 'θ_r' of 0.078 and saturated moisture content of 0.43 (cm^{3}cm^{-3}). In the moisture retention relation, 'α' equals 0.01678 (cm^{-1}), and 'n' equals 2.674 (dimensionless). The drain conductivity constant for the drain soil interface is 0.4 m^2-day^{-1} per m of pipe, calculated from field measurements by Bournival et al. (1986).

c) **Preparation for data input** involves a preliminary sketch of the field and assigning a grid to define the region. It is important to keep grid spacing small in areas where high hydraulic gradients may exist, such as near drains, and at the same time, not make the grid too fine which increases computational requirements. Figure 37 shows the initial grid layout from the plan view. The soil profile is divided into the four layers as defined by hydraulic conductivity information in Figure 35. The grid for the saturated flow model is composed of blocks laid out in an 8 X 9 X 4 matrix, so there are 288 cells in the saturated model as depicted in Figure 38. After some initial simulations using this grid, it was found that it was not fine enough, resulting in the saturated flow component of the model having convergence problems.

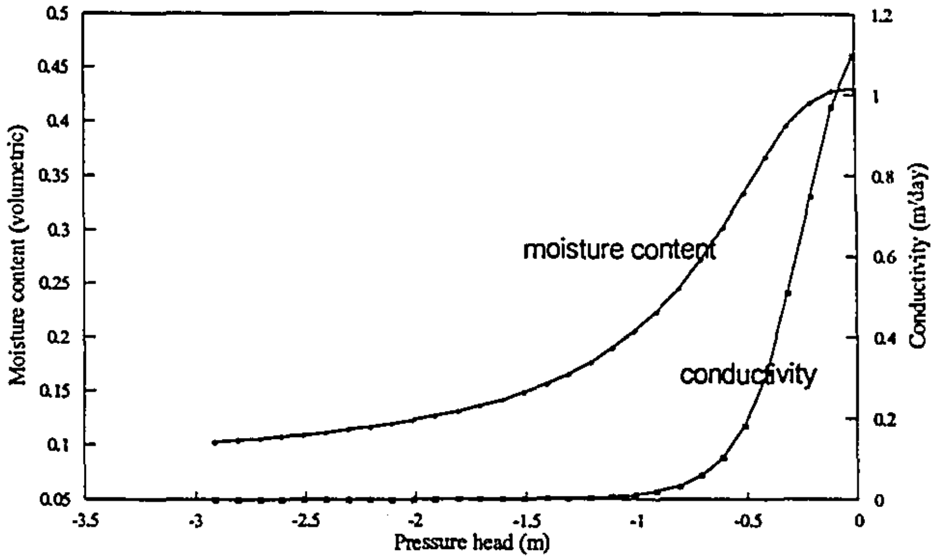

Figure 36. Moisture retention and conductivity relation used in case study.

The grid size was increased to 11 X 13 X 4 and the model performed satisfactorily. In using the program, several trial runs may be necessary to find a workable combination of parameters such as grid spacing, time step multiplier and the number of time steps. Once experience has been developed for a particular type of problem, workable values can be found quickly and do not need to be changed in future simulations for similar systems. In the revised grid layout, 572 cells comprise the saturated flow grid, which doubles the execution time of the program over the initial grid.

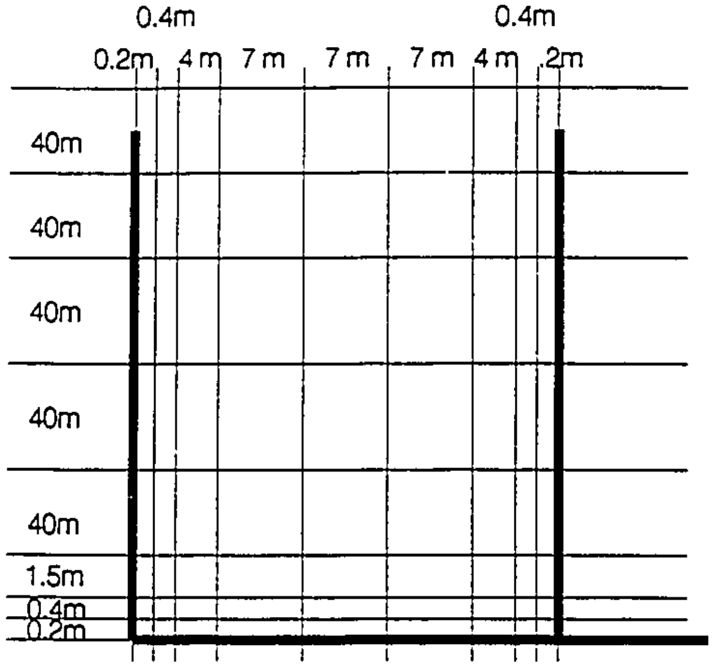

Figure 37. Initial layout and spacing of grid in the saturated zone at 30m drain spacing. The heavy lines represent drain locations and narrow lines the mesh of the grid. (not to scale)

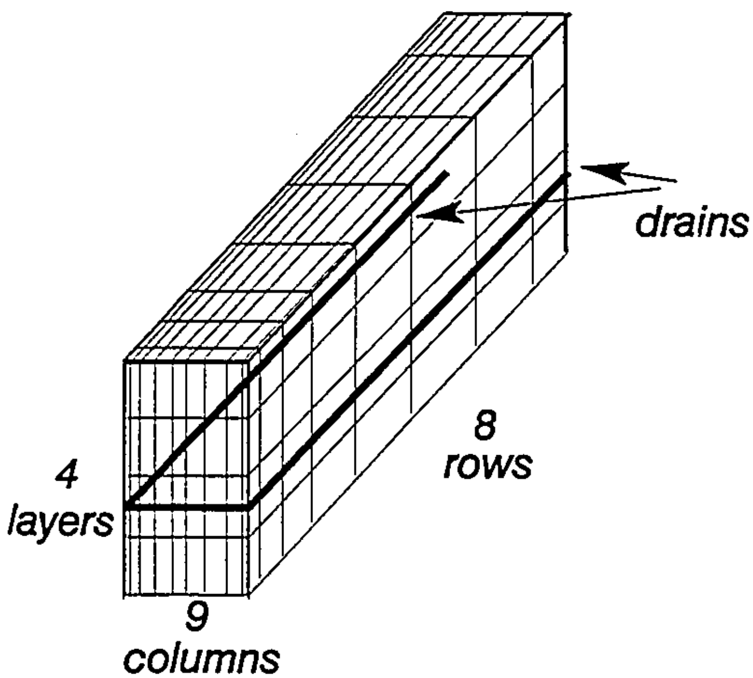

Figure 38. The saturated grid layout sketched to depict layers,columns, and drain location (not to scale).

It is possible to input soil, topographic, and initial hydraulic conditions information for each cell; however, this was not required in this example since properties are assumed to be uniform over the region. LINKFLOW calculates hydraulic heads in the center of each grid cell (block-centered nodal system). This should be kept in mind if there is a requirement for head information at certain locations (such as during calibration or verification). The drain lines are located in the center of the third layer down from the soil surface.

d) **LINKINP** will organize all the input data into the proper format for operation of LINKFLOW. To input data, the option **Input for simulation option** is selected from the main menu. The program then requests the name of the data set (this may be typed or selected using the mouse from a list of current files), or if the user only pushes **enter**, a default set of data is loaded. The screen will appear as in Figure 39, and the user is expected to update data by choosing each option down the page, using a pointing device such as a mouse, either typing in values, or selecting values from a range of possible inputs.

The first page (Figure 39) collects the information to define the grid in the saturated flow model. In this example, the numbers entered were: **rows** at 11, **columns** at 13, and **layers** at 4. Six stress periods which are the major time increments between printouts were selected, and under the command **Info for each stress period**, information concerning the time length of each stress period, the number of time steps and a multiplier factor was entered for each stress period. In addition to being a printout interval, a stress period is the time period during which a constant external hydrologic stress is applied to the model (such as a rainfall event or potential evapotranspiration rate).

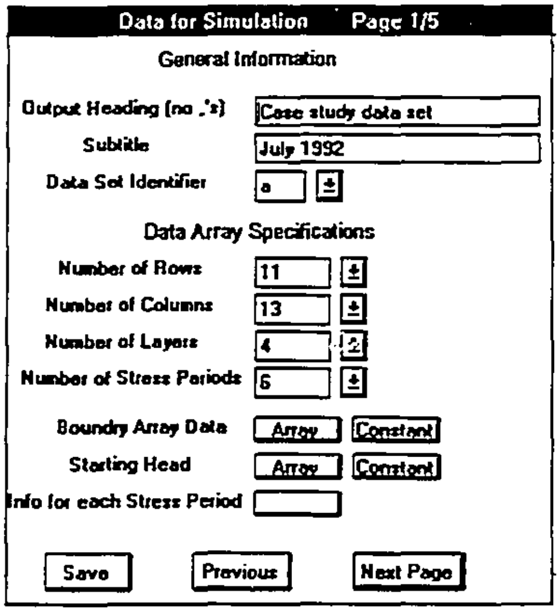

Figure 39. First page of data input in LINKINP program. Note that blocks on the page without data are command buttons to select new data entry forms.

In this simulation, the stress periods were the time intervals for printouts (.5,1,4,10,15,21 days of simulation). The **boundary array data** selection is for cases of irregularly shaped regions and does not apply for this example. In case of an irregularly shaped area, arrays for each layer that currently contains '1' for each active cell can be changed to '0' to turn off a cell. By turning off cells outside the region an irregular shaped area can be approximated. The **starting head** is the initial water table level and must be entered for each layer (a value of 19.25m in this example). Once values have been entered for this page, the **Next page** button is selected and the program goes to page 2. The user may also go back to a **previous** page or **save** the current data. It is not necessary to **save** until the end of the input program, but saving is highly recommended when large data sets are being created to avoid lost time in case of computer problems. Note that the command buttons (blocks on the LINKINP pages without data) when selected present new forms for the user to enter information. Since the program contains about thirty forms only the main ones are shown here in the interest of space.

Figure 40 shows page 2 of LINKINP where the dimensions for **rows**, **columns**, **layers** of the grid are entered. These values are each contained in one-dimensional arrays that require a value for each cell along a column, row and layers respectively.

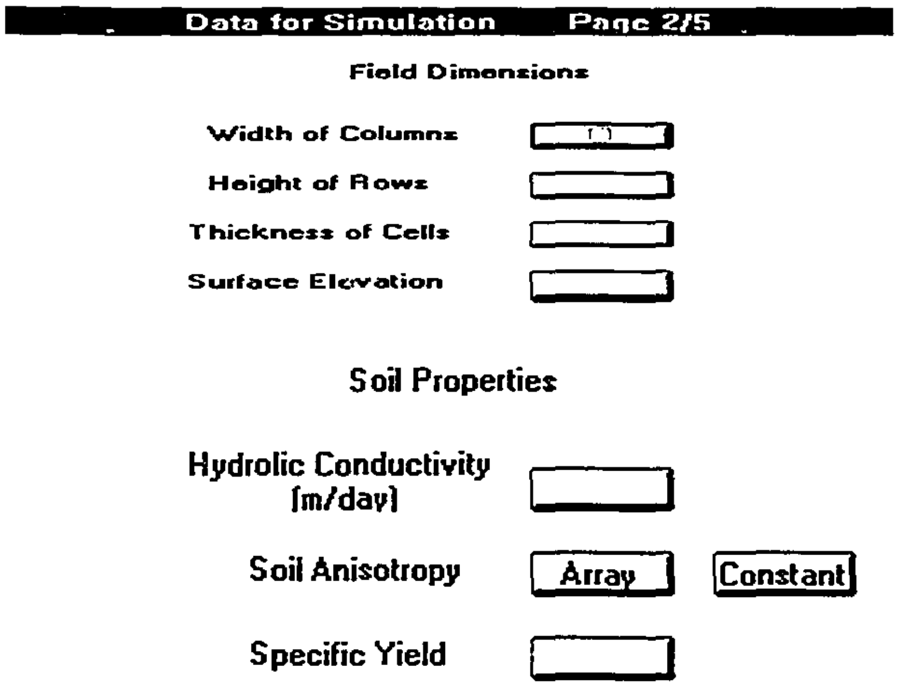

Figure 40. Page 2 of LINKINP program. Boxes on this page are control buttons to select various data entry forms.

The **surface elevation** may be entered: as an array to reflect the topographic differences such as what is done in the field verification in Chapter Four, or as in this example a single value (20.0m) for all surface cells. The **soil properties** at the bottom of page 2 include **hydraulic conductivity, soil anisotropy** and **specific yield** which are values for the saturated flow model. These properties may be entered as an array with a value for each cell in the model (572 cells in this example), or as a constant for each layer. Note the **specific yield** entered is only used by the model if the water table is at the surface. Once it drops below the surface, the unsaturated model will calculate values for the specific yield.

Figure 41 contains page 3 of LINKINP on which information is assembled concerning the layout and operation of the drains. First, there is the **number of nodes** or cells in the grid that will be used to represent the drains (2 columns of 11 nodes and one row with 13 minus 2 nodes equals 33). The **'K-drain'** value is a constant for all locations (0.4 m^2-day^{-1}-m^{-1}). The **mode of drain operation** is subirrigation selected from a choice of: drainage; subirrigation; changing modes; and automated control by water table or moisture stress level. **Location of nodes** prompts the user to enter the layer, row, column number for each of the 33 drain locations, and a direction indicator as to whether the drain is along a column or row in the grid. LINKINP calculates drain conductivities that are the products of the K_{drain} times the length of drain in a cell. Therefore, if the K_{drain} value is changed after this option, the location of nodes will need to be reentered to update these calculations. The final input on this page is the **level of head** in the drains during each stress period. A constant value of 19.75m is used in all stress periods for this example.

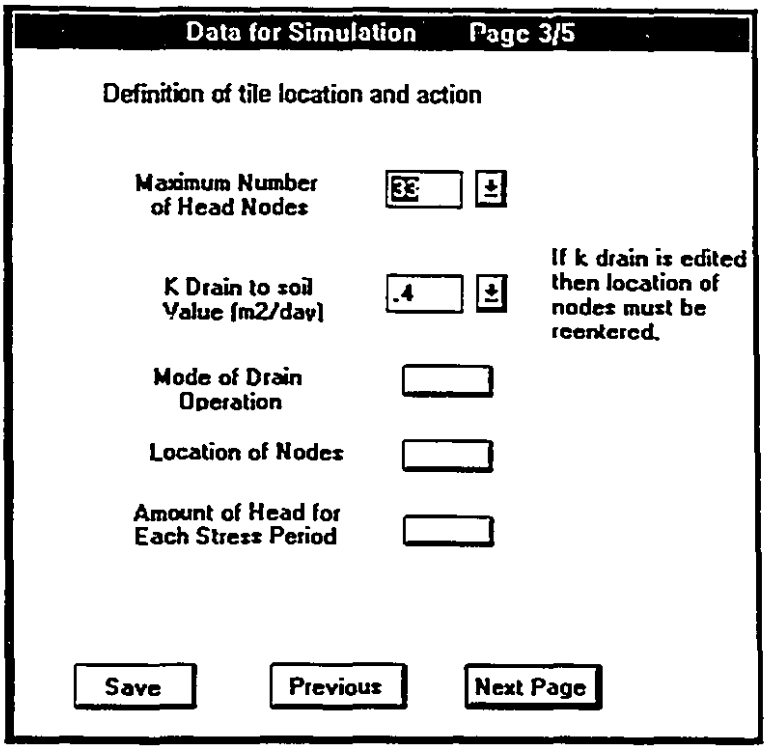

Figure 41. Page 3 of LINKINP program. Boxes without values are control buttons to select various data entry forms.

Figure 42 contains page 4 of LINKINP, where information needed for the unsaturated flow model is entered. The **row used for unsaturated model** refers to a row in the saturated flow model that the grid is linked to when a single row has been selected in the linkage option. A value is entered even if the linkage is for all cells. The **time increment** is the size of time step in days used in the calculations of the unsaturated component. **Tolerance for pressure change** (m) is for determining if the model is converging on solutions. Generally, this and the previous value do not need to be changed. Pressure head at **permanent wilting point** and at **50% available water content** (AWC) are found from the moisture retention curve.

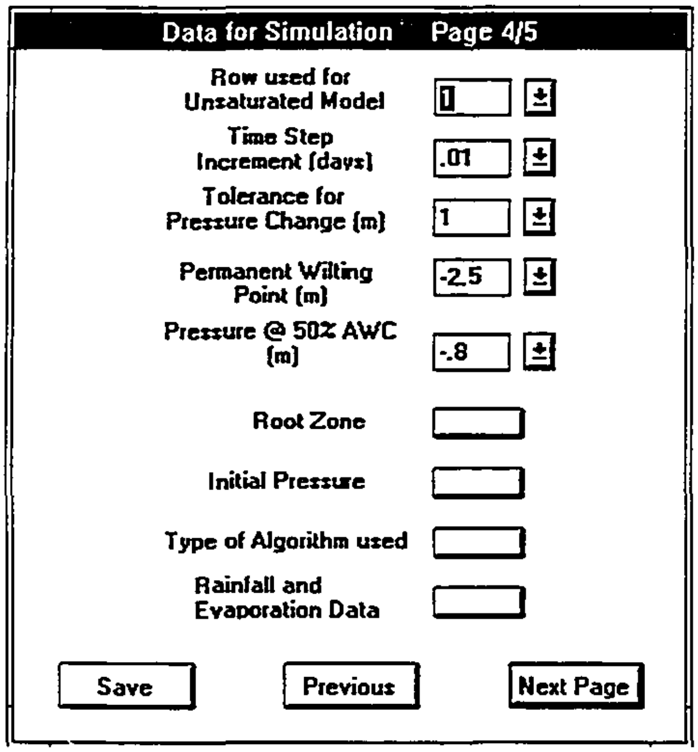

Figure 42. Page 4 of LINKINP program. Empty Boxes are control buttons used to select additional data enter forms.

Root zone allows the user to select either a changing root zone depth, or as used in this example, a constant root zone depth (50cm). The **type algorithm** selects the empirical relations to be used to describe the moisture retention and conductivity relations. The choice is between Hoover's relation and Van Genuchten's. The **rainfall, potential evapotranspiration** and **printout** flag are entered for each stress period in the final option.

Figure 43 displays page 5 of LINKINP and the remaining information for the model. The first three items made up of **Maximum number of iterations, acceleration parameter,** and **head change criterion** (m) are needed for the successive overelaxation procedure in the saturated flow model. These are normally changed only to optimize performance for that component of the model. The **starting hour of the day** is the time of day the simulation uses to begin. This aids in setting up the simulation to give outputs at a certain time of day (i.e., 12 noon). The **type of linkage** refers to the number of unsaturated flow columns that will be active during a simulation. The more unsaturated model columns active, the longer the simulation will take, so the user needs to select the number of columns needed for the problem being solved. In this example, alternating rows and columns are selected as a compromise between detailed spatial analysis and computation time. Under **graphical output**, the type of data saved for graphical analysis is selected. In this example, the depth to water table values are stored.

Selecting **Done** on page 5, moves to a final window requesting the name of the data set and then saves the data to disk. After completing a session, the program creates a file called START.PRN that contains the name of the new data set. When LINKFLOW is executed, it will look for START.PRN that contains the file name for the first data file. One may have several sets of data in the same directory, but only the data set named in START.PRN will be used when LINKFLOW is executed.

e) **LINKFLOW** can be selected from the first menu in LINKINP or run independently as an executable file. LINKFLOW should be present in the same directory as the one where the data files are located. No interactive input is required, and the program will show status on the screen of the amount of time that has been simulated and the actual length of time the computer has been working. When LINKFLOW is run from LINKINP, the program returns to LINKINP when LINKFLOW has finished execution. The data sets may then be edited and output examined from LINKINP.

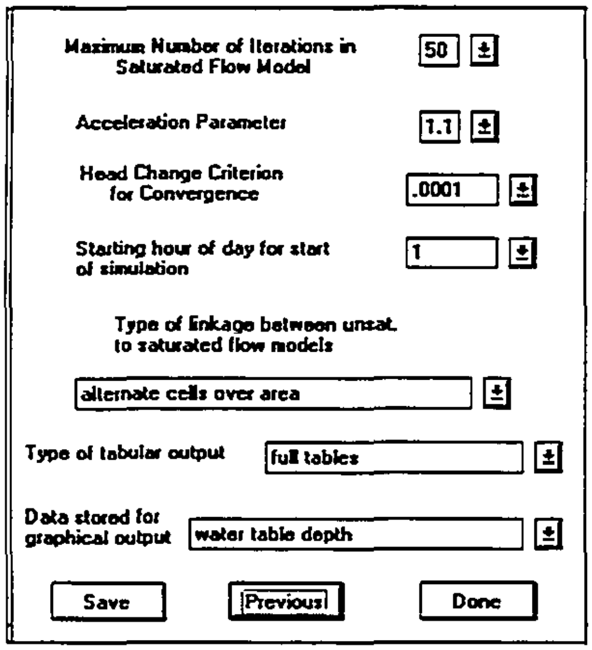

Figure 43. Page 5 of LINKINP program.

f) **Examining the output** data can be done from LINKINP by selecting that choice on the first menu, which will give a choice of graphic or text output. Selecting the desired choice, the output data can be viewed, printed or edited.

5.0.2 Obtaining Results from the Simulation

Output was selected for the first and last stress periods (major time increments) for the simulation of subirrigation with 30m drain spacing; the output with complete input information is given in the Appendix B. The elevation of the water table versus time is shown in Figure 44 for two locations in the region for the two drain spacing. The 30m spacing was beginning to raise the water table at mid spacing after 21 days of simulation. The water table rose within a week for the 15m drain spacing. Near the drain, there was little difference in the water table levels for the two drain spacings since flow was restricted by horizontal conductivity. Figure 45 shows the moisture content for the root zone in the same locations as the water table elevation varying with time. Moisture content with the 30m drain spacing plot decreased over the 21 days of simulation at mid spacing. The moisture content reflected the same trend as the water table elevations. The water table depths over the area were viewed using the contour package in the program SURFER.

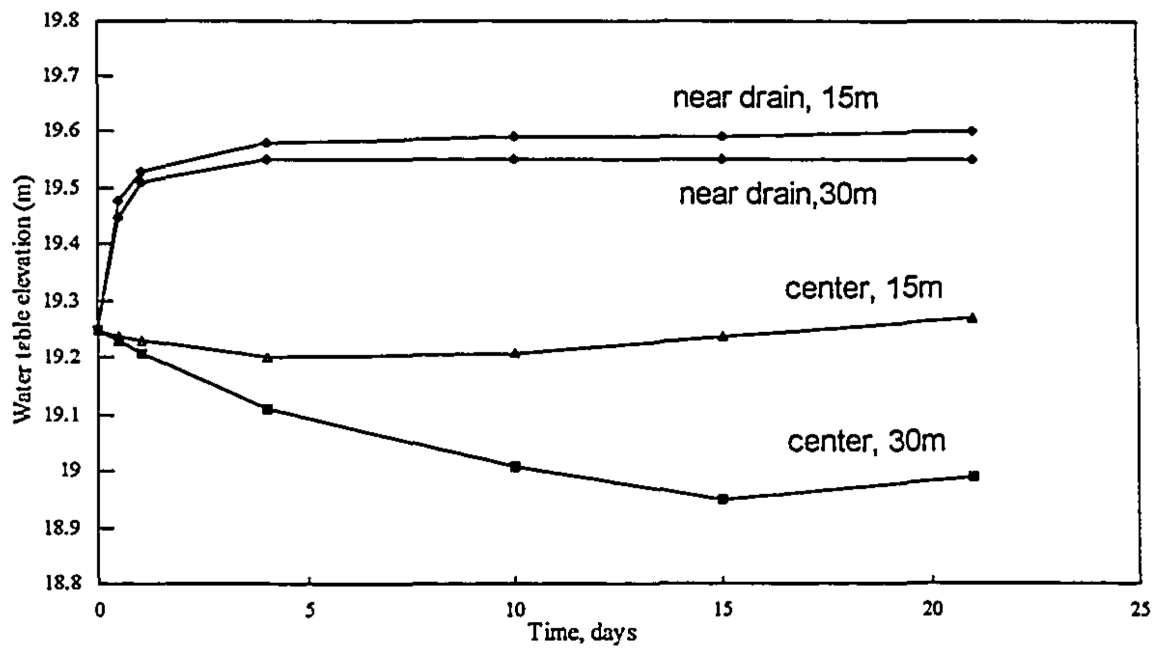

Figure 44. The change in water table elevation with time for locations near the drain and at mid spacing for 15m and 30m spacings.

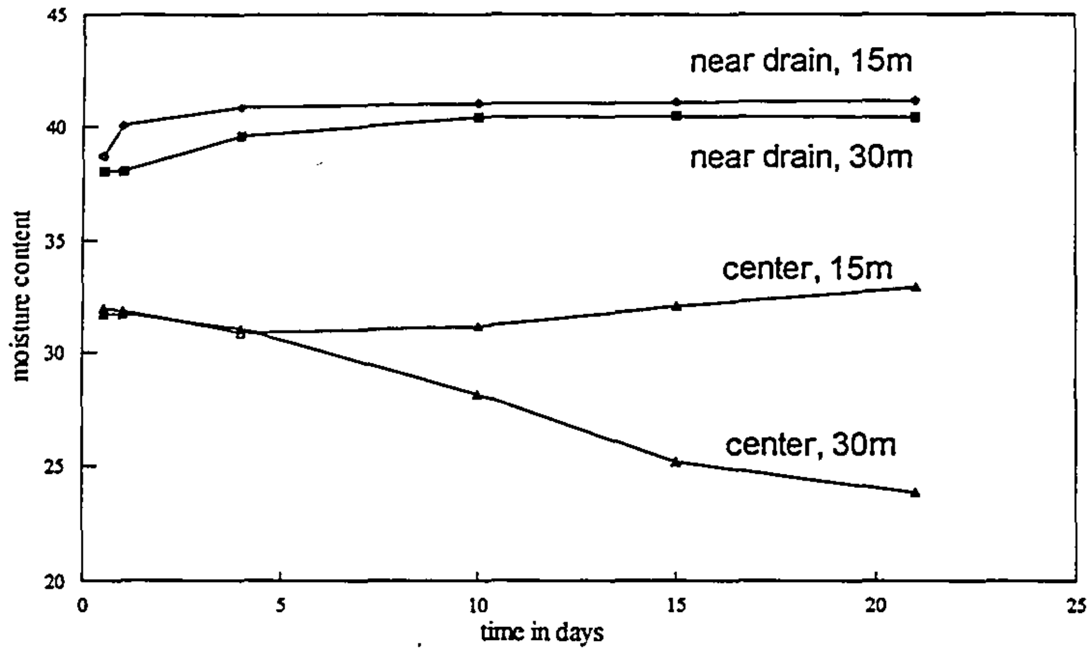

Figure 45. The moisture contents with time for locations near drain and mid spacing for 15m and 30m drain spacing.

The plots shown in Figure 46 to 51 reflect the spatial movement of the water table depths with time (it should be noted that the moisture content in the root zone or for the WET factor could have been selected instead of depth). The contours are at 0.05m interval on all plots and the drains are on the left, right and bottom of each plot. The most change in the location of the contours occurred early in the simulation. The similarity in the contour plots for the 10 and 21 day plots for both drain spacings suggest that steady state flow condition was being approached. Irregular curves in the contours on the upper left corner of the 30m spaced plots reflect some problems in the "grid" operation of the SURFER package; however this was not evident in the 15m spaced contour plots.

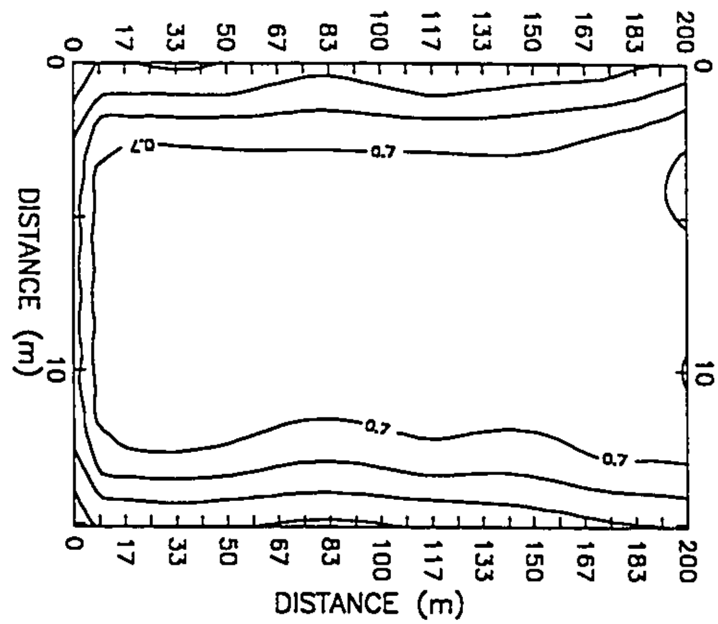

Figure 46. Contour lines (at 0.1m spacing) for depth to water table (m) after 1 day of subirrigation for 15m spacing. Note the vertical axis is scaled 10 times the horizontal.

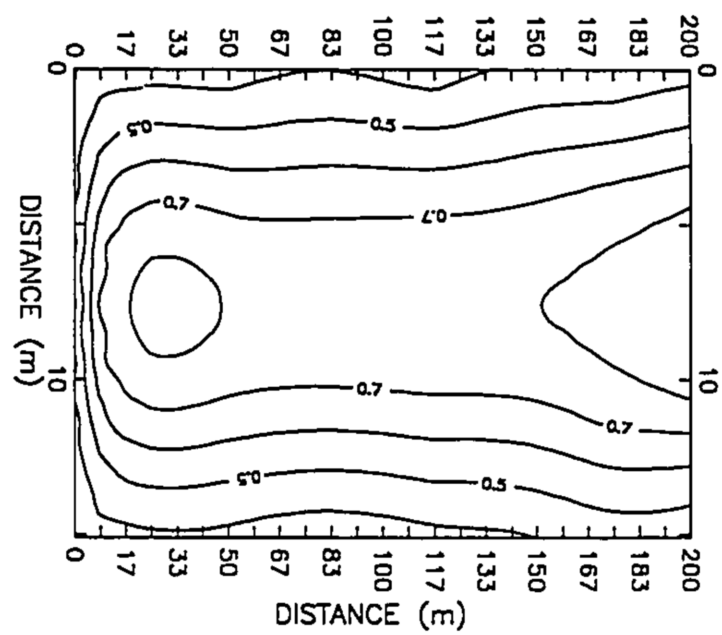

Figure 47. Contour lines (at 0.1m spacing) for depth to water table (m) after 10 days of subirrigation for 15m spacing. Note the vertical axis is scaled 10 times the horizontal.

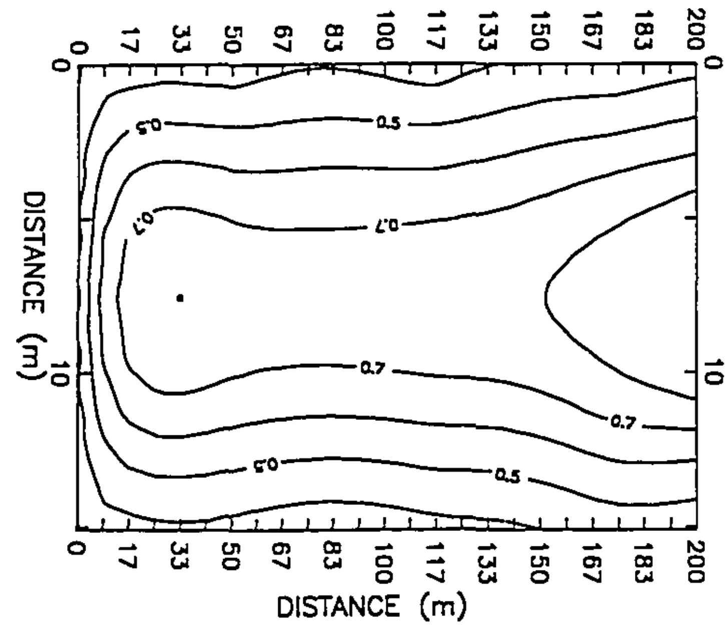

Figure 48. Contour lines (at 0.1m spacing) for depth to water table (m) after 21 day of subirrigation for 15m spacing. Note the vertical axis is scaled 10 times the horizontal.

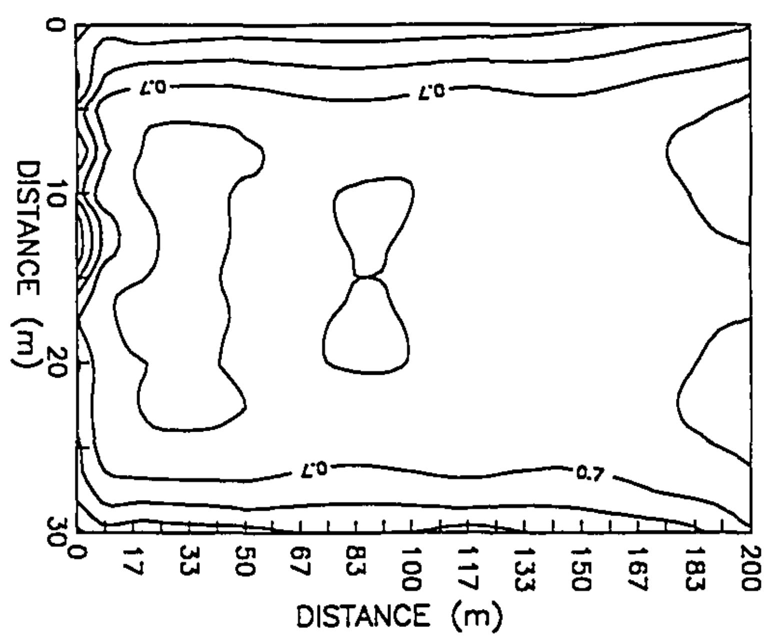

Figure 49. Contour lines (at 0.1m spacing) for depth to water table (m) after 1 day of subirrigation for 30m spacing. Note the vertical is scaled 5 times the horizontal.

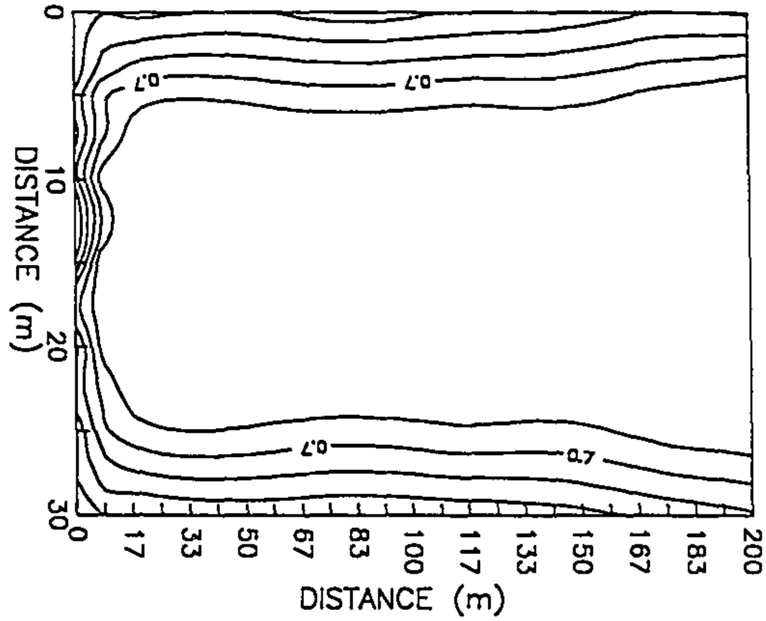

Figure 50. Contour lines (at 0.1m spacing) for depth to water table (m) after 10 days of subirrigation for 30m spacing. Note the vertical is scaled 5 times the horizontal.

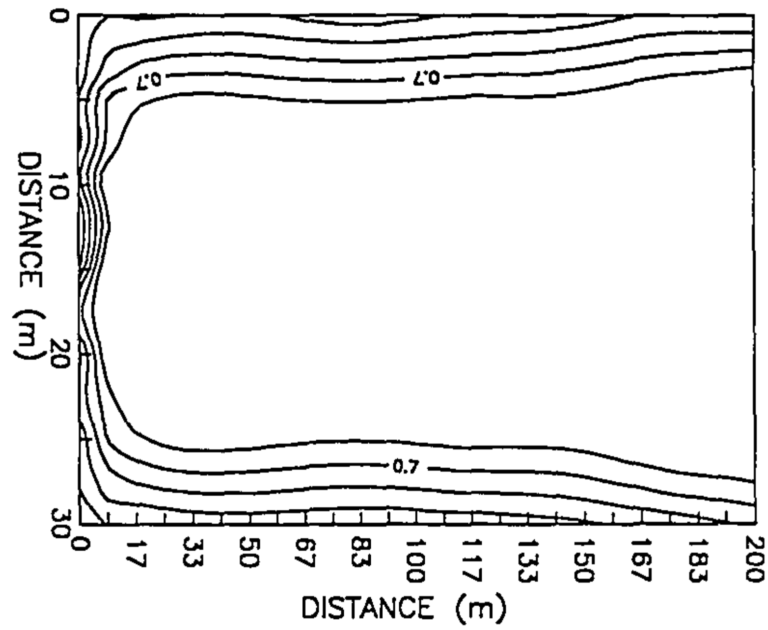

Figure 51. Contour lines (at 0.1m spacing) for depth to water table (m) after 21 days of subirrigation for 30m spacing. Note the vertical is scaled 5 times the horizontal.

The affect of subirrigation on the root zone is illustrated in Figures 52 and 53, where the WET values (as defined by equation 44 and simplified into four categories) and the area affected is plotted versus time. The four categories for WET were: severe stress where the WET value is less than -0.5 (very dry), low stress where the WET value is between -0.5 and 0.0 (dry), no stress where WET is 0.0 and aeration stress when WET is greater 0.0 (aeration less than 7%). There was a marked difference in results with the two drain spacings. The 15m spacing in Figure 52 showed no severe or low stress conditions and had significant areas of aeration stress. The 30m spacing in Figure 53 had no severe stress, limited aeration stress and a significant amount of low stress (47% after 21 days).

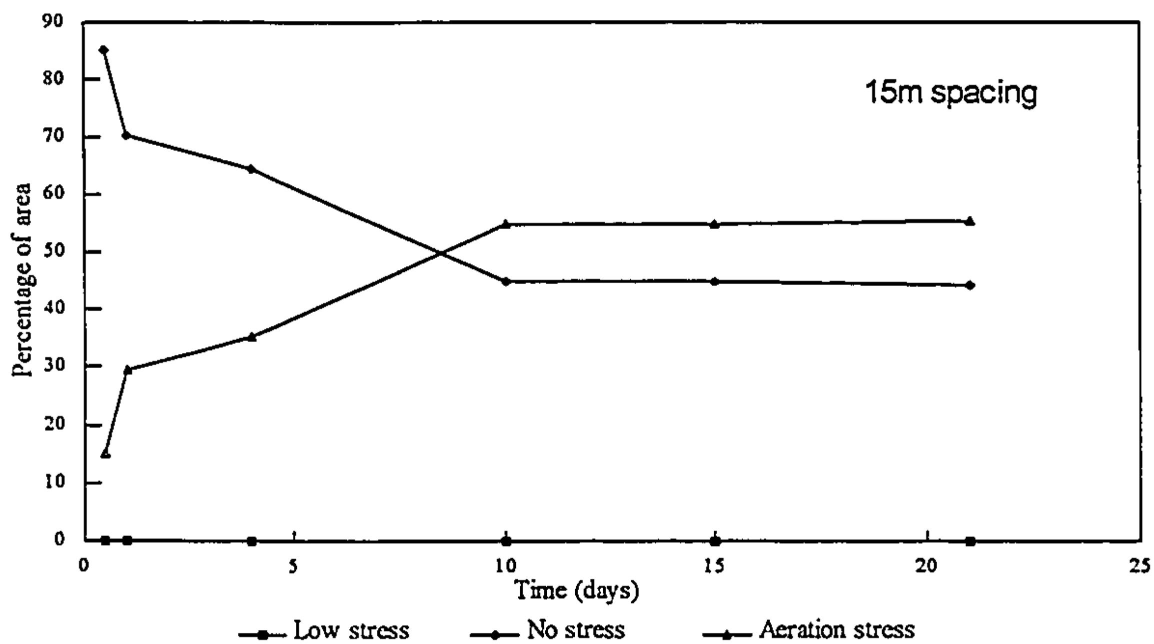

Figure 52. Level of WET in the 15m drain spaced plot over the 21 days. The low stress is zero for this simulation.

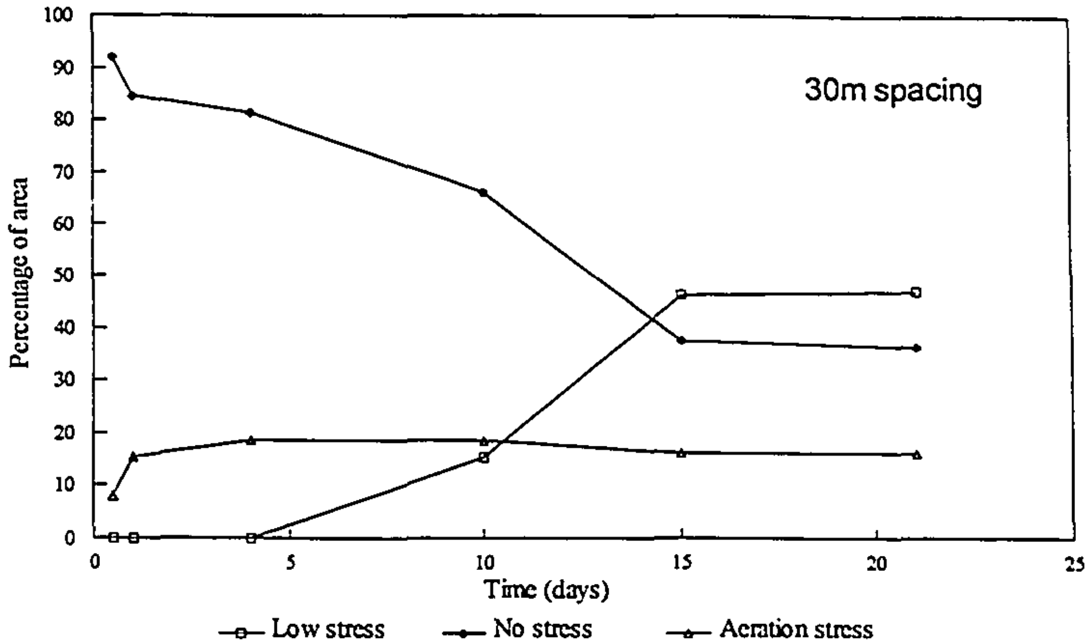

Figure 53. Level of WET in the 30m drain spaced plot over the 21 days.

These results reflect the situation for one combination of inputs for these two spacings. Changing head levels in the drain would alter the results. The water levels in 30m drain spacing case would react sooner if a higher head in the drain lines was used. An evaluation of the dynamics of the system would require several simulations for a range of system parameters.

The water budgets given in the output given in Appendix B shows that after a half day, a discrepancy of 2.43% was found for total flows and a 13.56% for the rates of flow in the current time step. These numbers changed to 0.51% and 0.46% after the 21 days of simulation. The larger differences noted for the earlier point in simulation are due to the initial high flows that occur as subirrigation begins, also after 21 days the percent difference is calculated using a much greater total accumulated flow. The 13.56% difference is not of great concern since the flow caused by evapotranspiration are calculated diurnally and creates an imbalance during the day.

This chapter illustrated the use of LINKFLOW and LINKINP for a simulation problem. Some of the original features of the program in the method of data entry, the graphical output showing the spatial effect of water table management and the treatment of a transient water movement in a heterogeneous soil were demonstrated. The next chapter will apply LINKFLOW to examine two unique soil conditions and simulation of automated controls that other models can not treat.

Chapter 6: Applications of LINKFLOW

6.0 Application

LINKFLOW will be applied in this chapter to investigate the impact of specific soil conditions on subirrigation and drainage, plus simulations of automatic control systems will be demonstrated. One soil condition is a further examination of the effect of anisotropy and how it can effect water movement in the field. The next case examines the influence of clay lenses at different depths and coverage of the field and through simulations to find their effect on subirrigation and drainage. The last section deals with the automatic head control which can be simulated using LINKFLOW.

6.1 Anisotropy

Soils are commonly assumed to be homogeneous and isotropic when considering water movement occurring during water table management systems. In some cases, a layered soil is considered as consisting of several homogeneous and isotropic soil layers. In many cases, the assumption of isotropy oversimplifies the field situation and may give misleading results. LINKFLOW can be used to simulate flows for the soil condition where the saturated hydraulic conductivity is considered anisotropic. The directional dependency can occur in surface soils due to cracks and worm holes creating higher vertical conduction than horizontal. Soils developed from sediment deposits or soils subjected to high over burden pressures will often exhibit greater horizontal than vertical conductivities (Maasland, 1957). Rogers and Selim (1989) investigated the effect of anisotropy on terraced soils with drainage tile. They found that anisotropy greatly affects the size of the flow region and the flow rate.

The effect of anisotropy on water table movement has been characterized by varying the degree of anisotropy "R'" (Equation 68) while maintaining constant values of equivalent conductivity "K" (Equation 67) (Selim, 1987). Equivalent hydraulic conductivity (m-day^{-1}) can be defined as:

$$K = (k_v k_h)^{\frac{1}{2}} \qquad (66)$$

where k_v is the vertical and k_h horizontal conductivities in m-day^{-1}. The degree of anisotropy is described by:

$$R' = \left(\frac{k_h}{k_v}\right)^{\frac{1}{2}} \qquad (67)$$

In the sensitivity analysis of chapter four above, the anisotropy factor (ratio of horizontal to vertical saturated conductivities) was varied to determine the sensitivity of water table levels to error in this parameter. Horizontal conductivity and anisotropy are input information to LINKFLOW, while the vertical conductivity is calculated from these. Therefore, in the sensitivity analysis, as different values for the anisotropy factor were used, it resulted in new values of vertical conductivity with no change to the horizontal conductivity. The variation in anisotropy caused a change in the overall conductivity of the soil. The investigation in this section will have simulations compared for different levels of equivalent conductivity (0.25, 0.5, 1.0, 2.0m-day^{-1}) and a range in degree of anisotropy values from 0.1 to 5.0. The soil is considered homogeneous and the input information is the same as used in previous simulations except for the conductivities shown in Table 6. The average rates of water supplied from the subirrigation drains and the depths to water table at mid spacing will be used to compare simulations.

$K = [k_v k_h]^{1/2}$	$R' = [k_h/k_v]^{1/2}$	k_v	k_h
0.25	0.1	2.5	0.025
0.25	0.5	0.5	0.125
0.25	2	0.125	0.5
0.25	5	0.05	1.25
0.5	0.1	5	0.05
0.5	0.5	1	0.25
0.5	2	0.25	1
0.5	5	0.1	2.5
1	0.1	10	0.1
1	0.5	2	0.5
1	2	0.5	2
1	5	0.2	5
2	0.1	20	0.2
2	0.5	4	1
2	2	1	4
2	5	0.4	10

Table 6. The combinations of R' and K with associated horizontal and vertical saturated hydraulic conductivities (m-day^{-1}) used for the simulations.

Flow from the drains during subirrigation and the resulting height of the water table after 21 days of transient simulation were compared in Figures 54 and 55. Figure 54 shows the average rate of water supplied versus the degree of anisotropy for the different values of equivalent conductivities. Flow rate during subirrigation increased significantly (86% for K=0.25m-day^{-1}) as the degree of anisotropy increased from 0.01 to 1 and then showed little change in flow rate (3% for K=0.25m-day^{-1}) for higher degrees of anisotropy from 2 to 5.

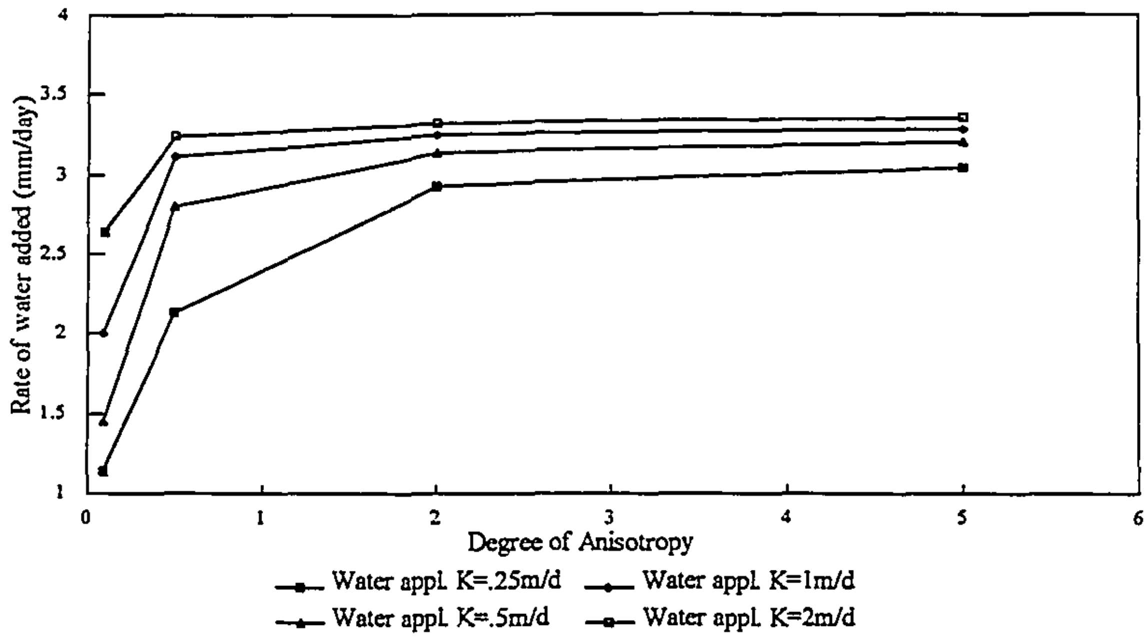

Figure 54. Influence of the degree of anisotropy on predicted rates of water supplied during subirrigation. Note data plotted for values of constant equivalent conductivity.

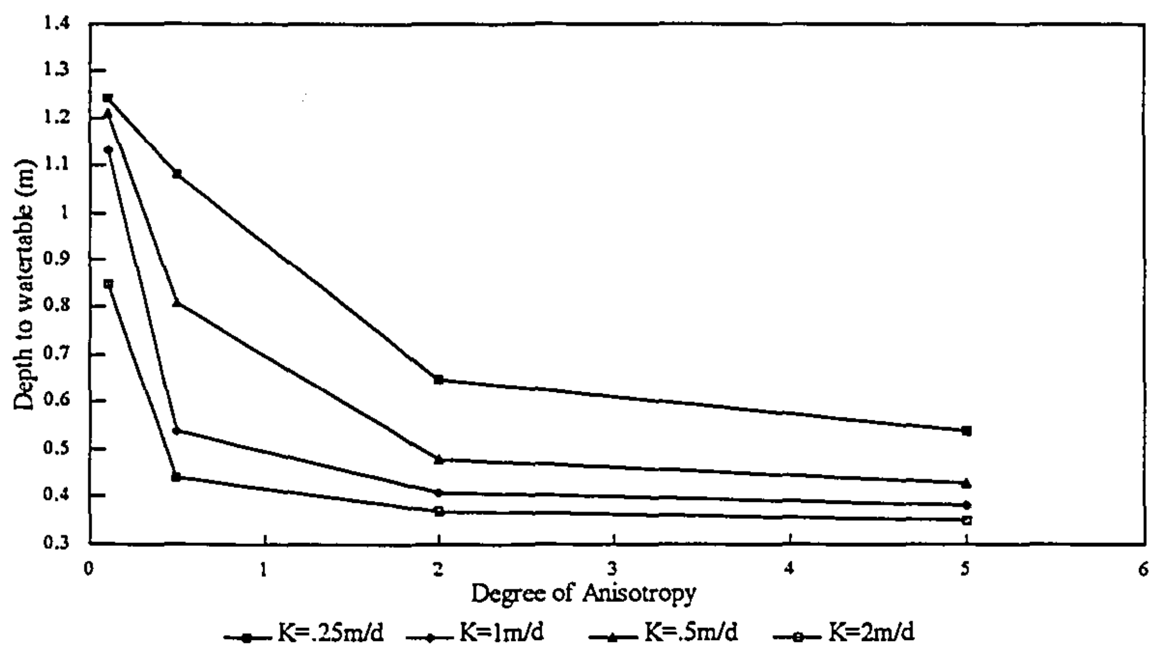

Figure 55. Influence of the degree of anisotropy on predicted water table depths at mid spacing. Note data plotted for values of constant equivalent conductivity.

Increasing the equivalent conductivity value directly raised the rate of flow from the drains. A 136% increase in flow rate occurred when $R'=0.01$ and K changed from 0.25 to 2m-day^{-1}. At a higher R' value of 5, the rate of water added changed by 13% for the same change in K. In general, the effect of the degree of anisotropy on flow rate was most pronounced when the degree of anisotropy value was below one. The depth to the water table at mid spacing (Figure 55) in the center of the region shows a similar response with the water table rising closer to the surface as the degree of anisotropy increased. These results agree with Rogers and Selim (1989) who found that higher K and R resulted in the greatest flows. This seems reasonable since as these values become higher, the horizontal conductivity will increase, and since horizontal is the direction of greatest distance for the flow then the systems performance improves. The effect of constant horizontal conductivity can be determined by selecting R' and K for a k_h value from Table 6 (ie k_h=0.5m-day^{-1}, K=0.25 & $R'=2$ and K=1 & $R'=0.5$) and using these in Figure 54. The water flow from drains will then decrease as the degree of anisotropy increases. This results in less rise in the water table when subirrigating. For example, drain flow decreases by 6.4% for R' changing from 0.5 to 2 and the associated water table rise at mid spacing was 17% less. The error in designing subirrigation and drainage systems spacing with conventional methods which neglect anisotropy will tend to exceed performance where the R' values are less than one. When the R' values are greater than one, the system will tend to be under-designed and not perform up to expectations. To study this effect on a designed system, further simulations were run with a constant horizontal conductivity and varying R' in the next section.

6.1.1 Effect of Anisotropy on Drain Spacing

To examine the effect of anisotropy and drainage spacing on a subirrigation and drainage system's performance, three drain spacings and a range of anisotropy combinations were simulated used LINKFLOW. To start with a reasonable spacing, the steady state spacing equation of Ernst (Ernst, 1975) was used to calculate a spacing of 15m for a soil profile 2m deep, with 10cm diameter drains at 85cm depth and a horizontal conductivity of 1 m-day^{-1}. Two other drain spacings of 10m and 20m were selected arbitrarily around 15m in an effort to establish the trends. In this example, the horizontal conductivity is held constant in all simulations and when the anisotropy is changed, it really means the vertical conductivity value is altered. Since typical designs use only the horizontal conductivity, these simulations will illustrate the potential effect vertical conductivity in anisotropic soils has on system performance. The drainage simulation allows 24 hours for a saturated profile to drain and measures performance of the drainage system in terms of the depth to which the water table is lowered over the time period and the rate of drainage water removed. To ascertain the influence of evapotranspiration on this case, a set of simulations were run with a PET of 5mm-day^{-1} and another at 0 mm-day^{-1}. The zero PET is the worst case since all water will need to drained by the drainage system. Depending on the crop, a satisfactory drainage performance would be in the order of 35cm for tolerant crops and 50 cm for sensitive crops in 24 hours (Smedema and Rycroft,1983). LINKFLOW was run for each drain spacing, each R' value and for drainage and subirrigation for a total of 45 simulations.

Figure 56 shows the drop in the water table over the 24 hour period caused by a constant PET of 5mm-day^{-1}, three drain spacings and for different degrees of anisotropy. The lowest value of the degree of anisotropy is 0.01 and not zero as it appears in the graph. Unlike when the equivalent conductivity was held constant, here it is evident that higher anisotropy will decrease the systems performance. None of these spacings would be suitable for a crop sensitive to flooding. The 15m spacing is adequate for tolerant crops except at the higher values of anisotropy. If the degree of anisotropy is five or greater, the 10m spacing would be necessary. Note that a degree of anisotropy of five means that the vertical conductivity is 1/25 of the horizontal conductivity. This is a reasonable range as Maasland (1957) reported on cases of the horizontal conductivity being up to 40 times greater than the vertical. Figure 56 illustrates the same trends for the average drainage rate. The 10m spacing was the only one to perform at 10mm-day^{-1} or better which was the criteria used in the steady state relation. However, this is not a critical factor since the simulation is for a falling head situation while the steady state situation is not. Figures 58 and 59 show the same relations but with the PET equal to zero. A PET equal to 0 mm/day is used for the drainage simulations over the 24 hours simulation period. Only the 10m spacing could lower the water table quickly enough for tolerant crops and even then the degree of anisotropy should be less than 2.

One observation that is clearly shown in this simulation is that the vertical conductivity can make a significant difference to the performance of the drainage system, particularly if it is less than the horizontal conductivity. If a drainage design was done by current methods which assumes an anisotropy factor of one, then the drainage rate for 15 m spaced drains is 9 mm-day^{-1}

(Figure 59), however, if the R' was 5 then the system will only handle 6.7 mm/day, a 25% reduction. Thus, the soil profile will drain slower than expected, and may cause unexpected delays in planting, reduced crop yields and vehicle trafficability.

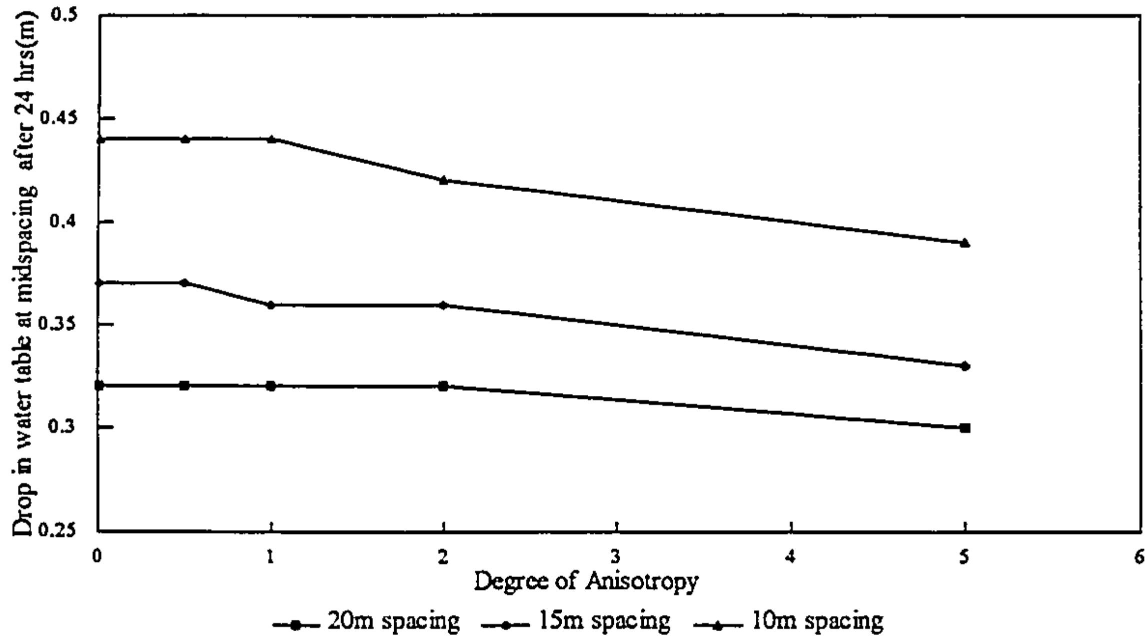

Figure 56. The drop in the water table at mid spacing after 24 hours of drainage for three drain spacings versus the degree of anisotropy in the soil. The PET is 5mm-day^{-1}.

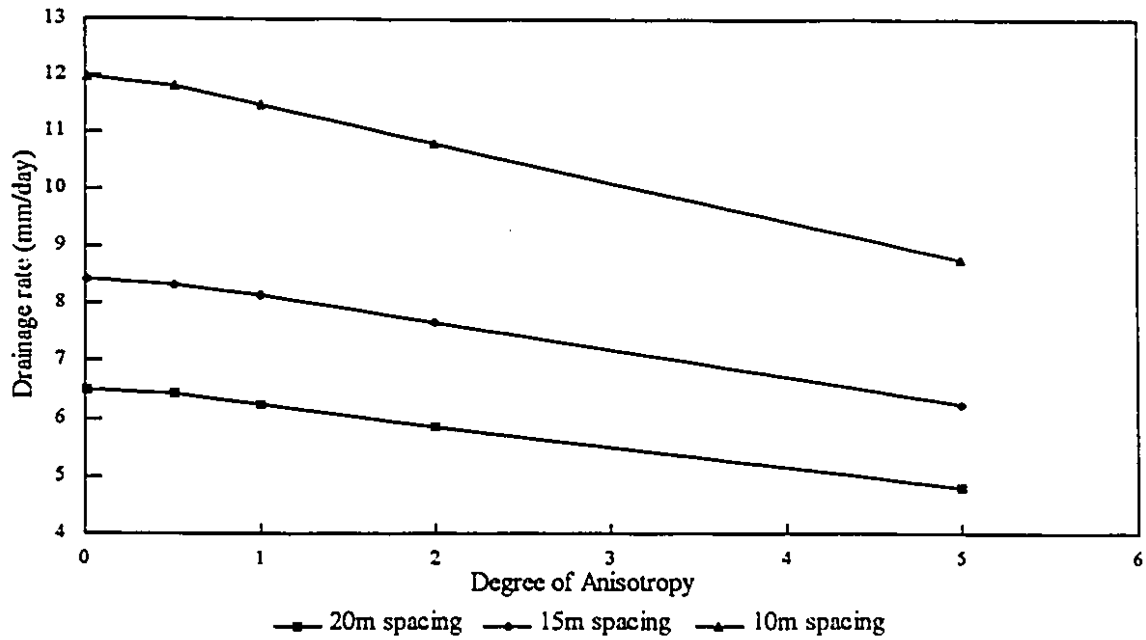

Figure 57. The average drainage rate after 24 hours of drainage for three drain spacings versus the degree of anisotropy in the soil. The PET is 5mm-day^{-1}.

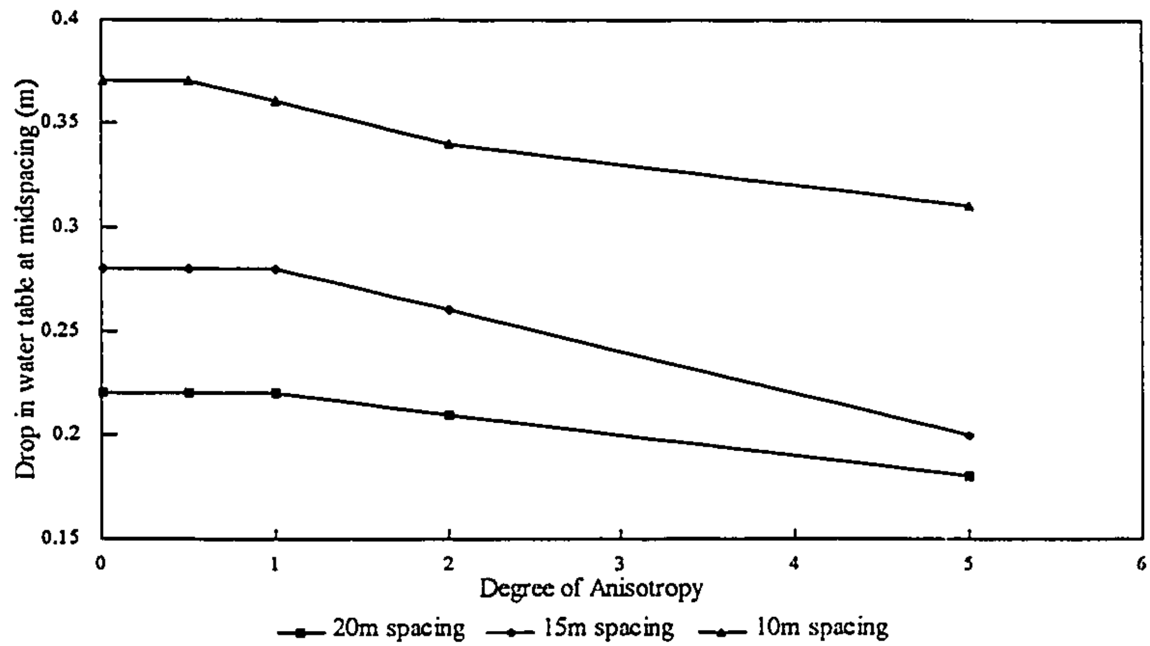

Figure 58. The drop in the water table at mid spacing after 24 hours of drainage for three drain spacings versus the degree of anisotropy in the soil. The PET is 0mm-day^{-1}.

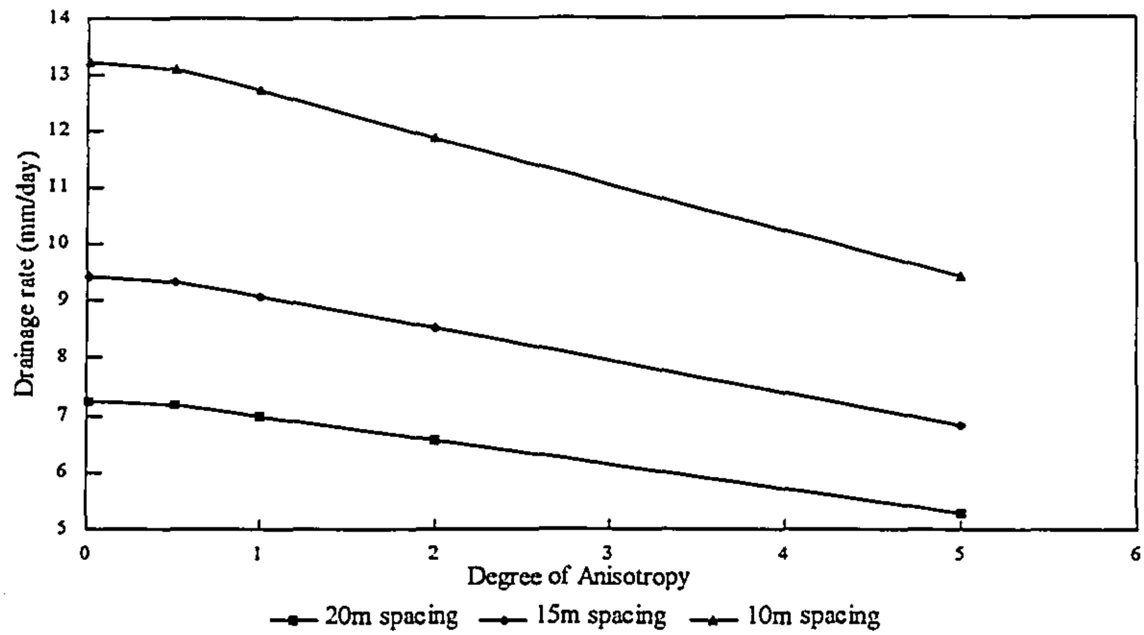

Figure 59. The average drainage rate after 24 hours of drainage for three drain spacings versus the degree of anisotropy in the soil. The PET is 0mm-day^{-1}.

During subirrigation, the amount that the water table can be raised over a 7 day period is an important system characteristic. A 5cm rise at mid spacing over a week was the criteria selected as a performance goal. This assumes the system can supply a 6mm-day^{-1} PET including a safety factor of 1mm-day^{-1} which added together over 7 days is 5cm. This value would vary with soil, crop, and climatic factors, but serves as a goal for the system discussed here. The following input information was used in these simulations, the PET equals 5 mm-day^{-1}, drain spacing of 10, 15 and 20m, and the degree of anisotropy was varied between 0.01 and 5. From Figure 60, it can be said that the 15m spacing would meet the performance goal if the degree of anisotropy stayed around 1 or less, otherwise the 10m spacing would be more suitable. Figure 61 reflects the performance in terms of the average rate of subirrigation water supplied over the 7 days. Again, the trend is that the high anisotropy (which means lower vertical conductivities) has a significant detrimental effect on the supply of water to crop. The unsaturated hydraulic conductivity was adjusted accordingly for the different degrees of anisotropy to coincide with the vertical saturated conductivity. Therefore as the degree of anisotropy increased, the vertical saturated hydraulic conductivity decreased and the unsaturated conductivity was decreased by the same factor as well.

If a subirrigation design was done by current methods which assumes an anisotropy factor of one, then the subirrigation rate for 15 m spaced drains is 6.6 mm-day^{-1} (Figure 61), however, if the R' was 5, then the system will only handle 5.4 mm-day^{-1}, a 18% reduction. On the other hand, if the R' was 0.01 then the subirrigation rate showed little change.

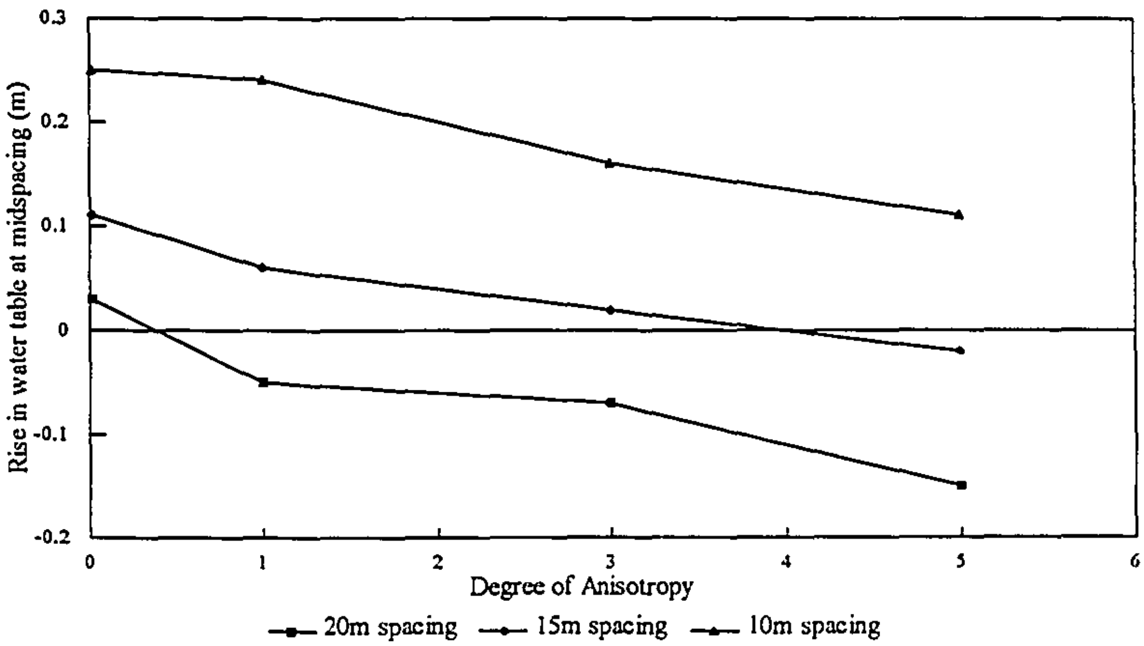

Figure 60. The rise of the water table at mid spacing after 7 days of subirrigation for three drain spacings versus the degree of anisotropy in the soil. The PET is 5mm-day^{-1}.

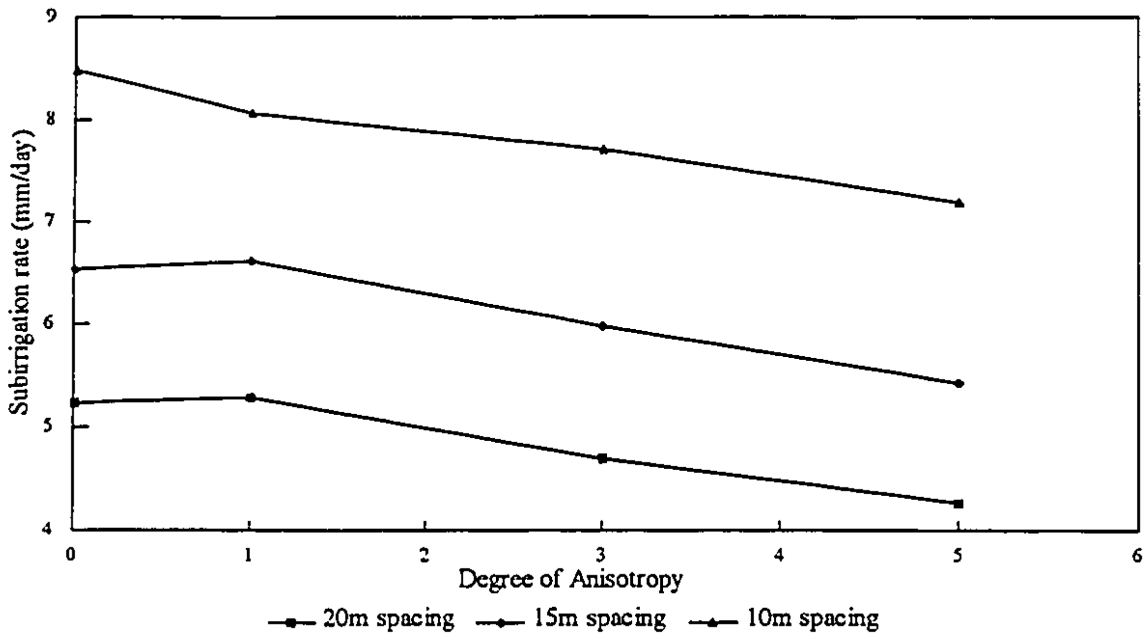

Figure 61. The average rate of subirrigation after 7 days of subirrigation for three drain spacings versus the degree of anisotropy in the soil. The PET is 5mm-day^{-1}.

A combined drainage-subirrigation system would require the 10 m spacing to be able to meet the drainage criteria for R' values of less than 2 and perform in subirrigation over the range of R' values. This example illustrates that designers should take these factors into consideration when planning water table management systems if the soil is suspected to have anisotropic behaviour. And, most soils are anisotropic.

Next, application of LINKFLOW to investigate the effect of clay lenses on the performance of a water table management system is discussed.

6.2 Lenses of Low Conductivity in Soil Profile

Some sedimentary soils have lenses or pockets of clay with low hydraulic conductivity in layers within the soil profile. It is difficult to accurately map these pockets and incorporate them into calculations for the design of a subirrigation or drainage systems. It is known that the presence of layers or lenses of clay can have a large effect on the performance of a subirrigation system (Galganov, 1991). LINKFLOW will be used to evaluate the impact of clay lenses on the performance of a subsurface drainage and subirrigation system. This is a unique application for LINKFLOW that no other model can do. In addition the effect of backfilling more conductive material around the drain when it is installed in a layer with low hydraulic conductivity is investigated. A subirrigation case will be examined first to find the amount of water delivered to the field from the drains and subsequent water table rises are compared for different surface areas with lenses.

The subirrigation system layout is the same as that used in the example problem of Chapter 5 with the 15m drain spacing. The soil is homogeneous and isotropic with a saturated hydraulic conductivity of 1 m-day^{-1}. Two types of lenses will be tested, with saturated hydraulic conductivities of 0.1 and 0.01 m/day. The lenses are assumed to have a thickness of 30 cm. They may be of different sizes, encompassing areas from 0% to 100% of the total surface area. The lenses are spaced over the region, with larger lenses in the center between drains since this is where the larger cells are located in the grid as shown in the Figure 62. Note that the thin lines on the figure represent the grid. One set of simulations will have the lenses at a depth just above the drain and the second set of simulations will have lenses at the same depth as the drain.

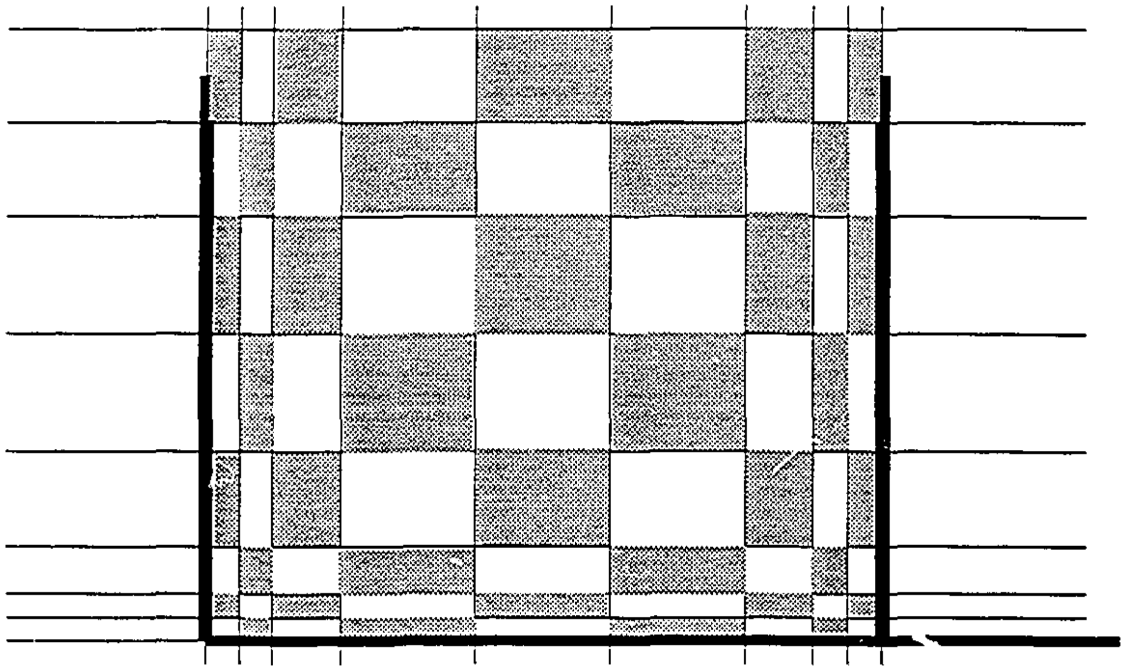

Figure 62. Lenses are areas of low hydraulic conductivity within a soil layer (shaded areas). The heavy lines represent the drains. Note this would represent 50% lenses present.

Figures 63 to 66 graph the results from initial simulations for subirrigation with the different areas of lenses. Figures 63 and 64 are for lenses with a hydraulic conductivity of 0.1m-day^{-1} while Figures 65 and 66 are for a 0.01m-day^{-1} hydraulic conductivity.

The lenses at the same depth (Figures 63 and 65) as the drain showed the greatest effect on drain outflow and water table depth for the range of areas of lenses used. Areas greater than 40% showed the largest changes to flow characteristics for both types of lenses. As expected, changes were most pronounced for the lenses with a lower saturated conductivity (Figure 65). The conductivity of the lenses did affect the flow rate as shown in Figures 63 and 65. There was a decrease in flow for the lower conductivity lenses and corresponding water table rise compared to the higher conductivity lenses case. When the lenses were present at areas greater than 50%, the overall performance was most affected.

Figures 64 and 66 for the lenses above the drain depth showed little change over the range of areas. Therefore, higher lens areas, lower lens conductivity, and lens positioned near the drain were the main factors found to reduce system performance. Of these factors it appears that having the lens around the drain will cause the largest change in flows in the system. In this case, it appears that if clay lenses with low conductivity are present at drain depth with enough lenses to exceed 50% of the area, the design drain spacing will need to be halved to provide the same performance, because the flow rate and water table rise would be substantially decreased.

Further simulations be presented in for the next section to show to what degree lenses with low conductivity at drain depth will affect the performance of a drainage and subirrigation system with three drain spacings. In addition, they will verify whether the 50% lens area is really a point of change in the performance of a system or simply a result of the earlier simulation having too many lenses near the drain at the 50% lens area.

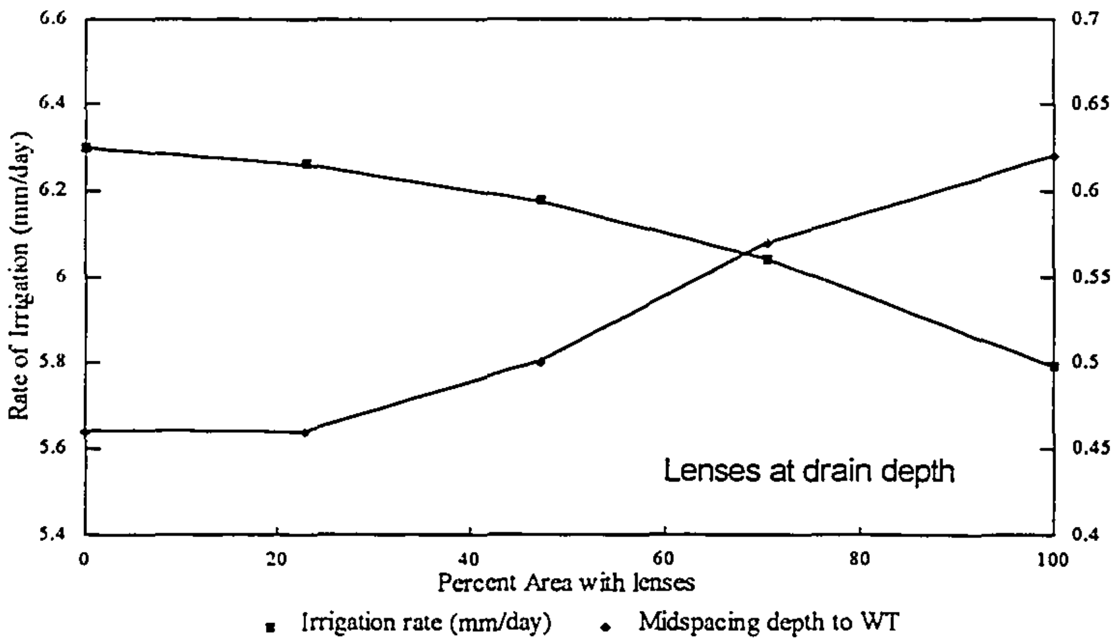

Figure 63. Effect of area of field with lenses (K=0.1m-day^{-1}) on water supplied from drains and water table depth at mid spacing. The lenses are located at the same depth as drain.

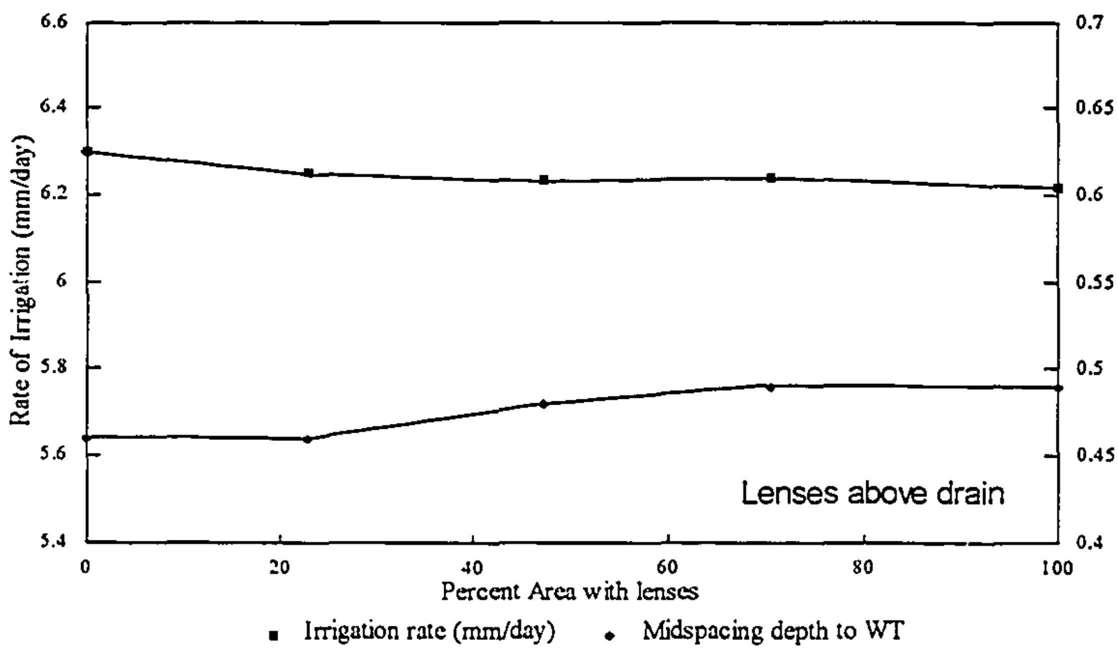

Figure 64. Effect of area of field with lenses (K=0.1m-day^{-1}) on water supplied from drains and water table depth at mid spacing. The lenses are located above the drain.

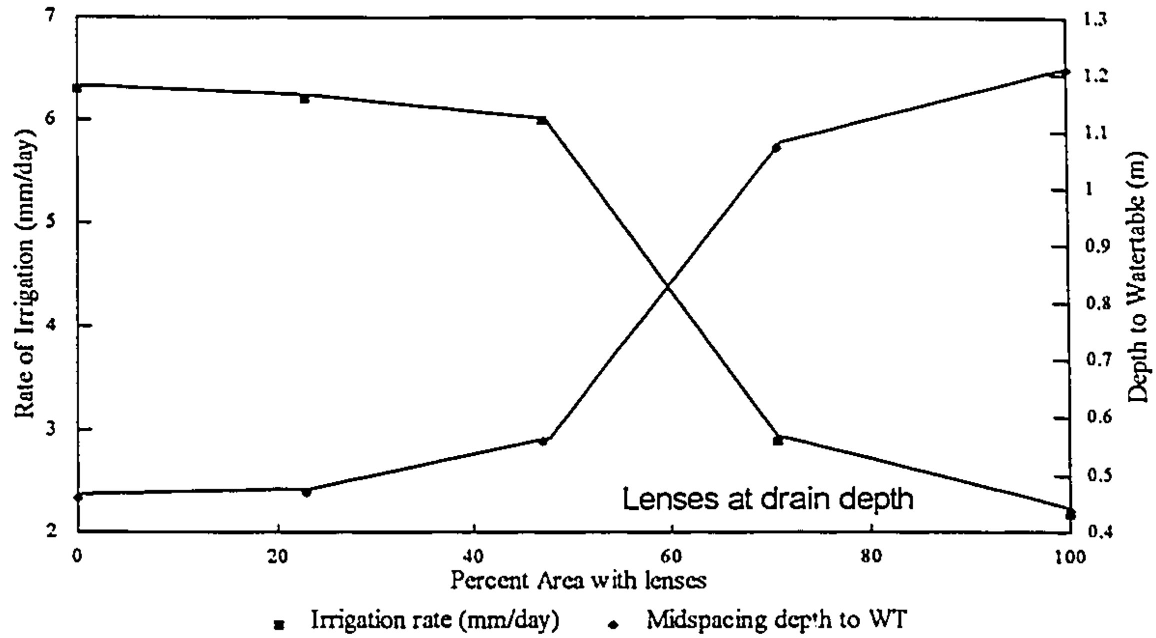

Figure 65. Effect of area of field with lenses (K=0.01mm-day^{-1}) on water supplied from drains and water table depth at mid spacing. Lenses are located at the same depth as drains.

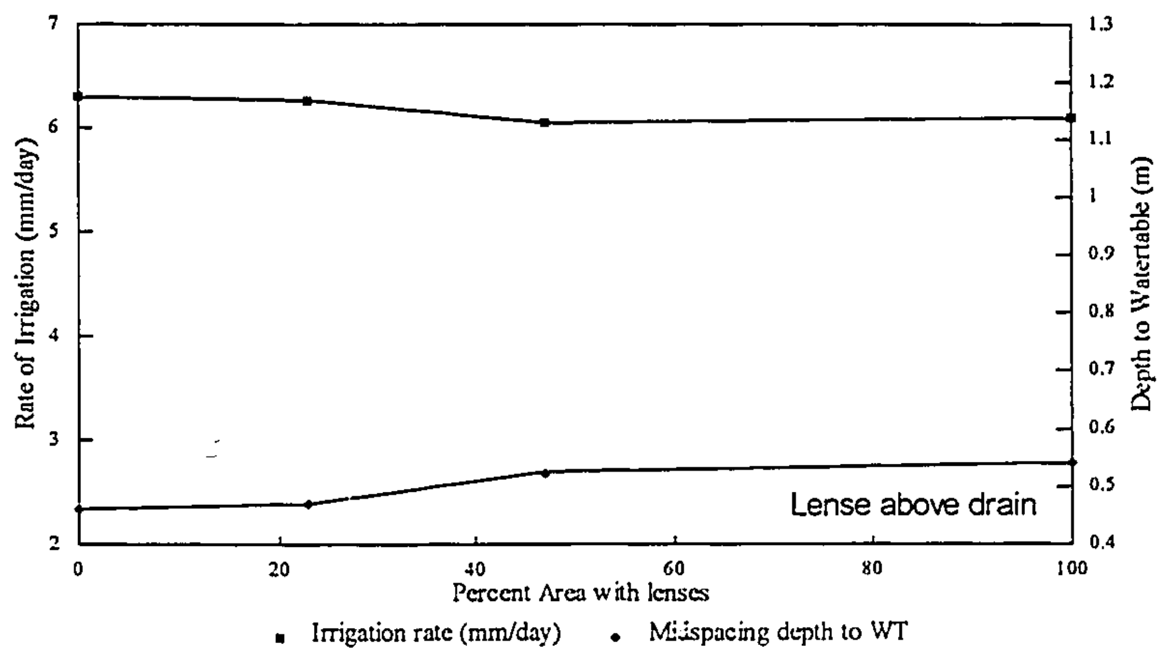

Figure 66. Effect of area of field with lenses (K=0.01m-day^{-1}) on water supplied from drains and water table depth at mid spacing. Lenses are located in a layer above the drains.

6.2.1 Effect of Clay Lenses and Drain Installation on Drain Spacing

The effect of clay lenses and how the drain is installed for different drain spacings are examined next for the subirrigation and drainage operation. The simulations are again done for different percentages of surface area having a clay layer present in the field. The lenses are 30cm thick and are located at the same depth as the drains over the field. In one set of simulations, the clay lens (K_s=0.01m-day^{-1}) will have the drains installed through them with "backfill" around the drain to allow flow to and from the drain at a higher conductivity (K_s=1m-day^{-1}). Another set of simulations represent the case which can happen in sensitive clays (Broughton et al., 1991) is that of "no backfill" and the drain is surrounded by the low conductivity lens. The results of both sets of simulations for the drainage case are given first for the drop in water table at mid spacing and the drainage rate versus the area with lenses for the three drain spacings. The drainage case uses a PET of 0 mm-day^{-1} and subirrigation cases use 5 mm-day^{-1} during the simulation.

Figures 67, 69 and 71 show the effect of dropping the water table by the presence of clay lenses on the three different spacings. In terms of performance, only the 10m spacing with backfill around the drain and less than 30% lenses in the field would meet the 35cm water table drop in 24 hours. It should be noted that the relatively low R^2 values (square of linear regression coefficient) for the lines of best fit of some of the "without backfill" cases is partially due to variability caused by the placement of the lenses. As suspected earlier, the trends observed in Figure 65 in the last section where a dramatic change occurred in performance at 50% lenses presence was due to the selection process for the lens locations. The latest simulations in drainage performance appear to have a linear relation with changing lens areas. The number of lenses around the drains matched the overall field percentage since even a small sized lens on the drain had a much greater impact than a large lens away from the drain. It was observed that the water table depth over the field fluctuated in the presence of the lenses. There was less scatter in the linear relations between drainage rate and the percentage of lenses in the field shown in Figures 68, 70 and 72. The drainage rate is an average for the field through the drains over the 7 day period and is not subject to the local effects of lenses as the water table depth was. Figure 73 compares the line of best fit for the three spacings and two installation situations. It is clear that the higher the presence of clay lenses, the greater the benefit from ensuring that the drains are "backfilled" with conductive material. The largest difference in performance occurred for the 10m spacing where the drainage rate increased by 107% between the case "without backfill" and the "backfill" case when the region is 100% lenses.

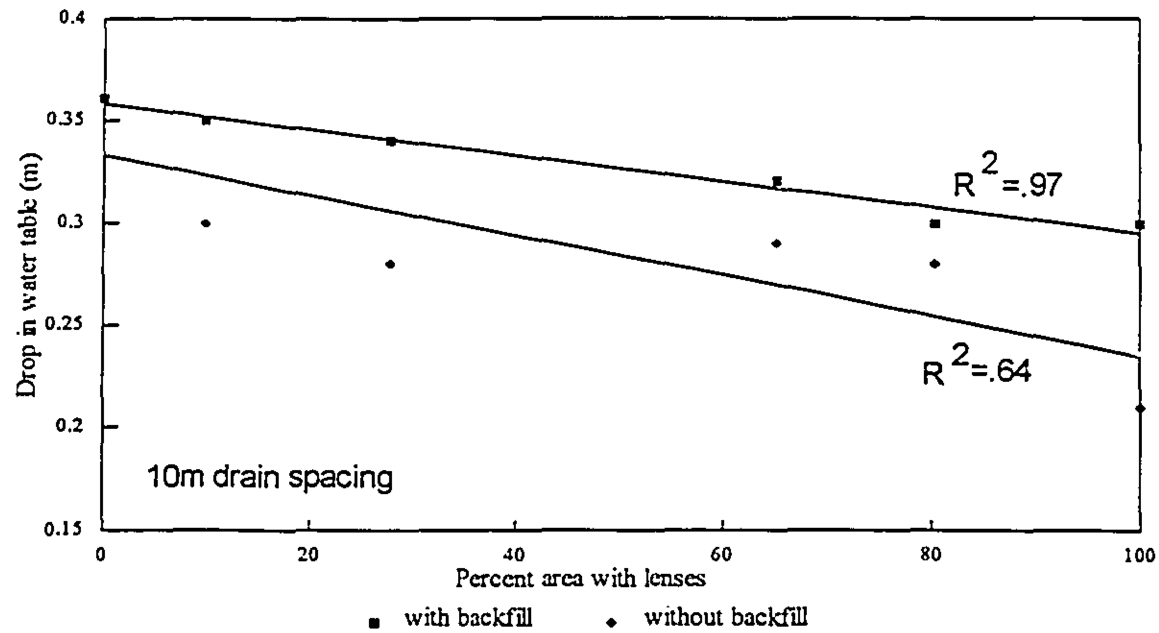

Figure 67. Drop in water table at mid spacing after 24 hours drainage for different areas of low conductivity lenses. The drain spacing is 10m for the conditions of backfill and no backfill.

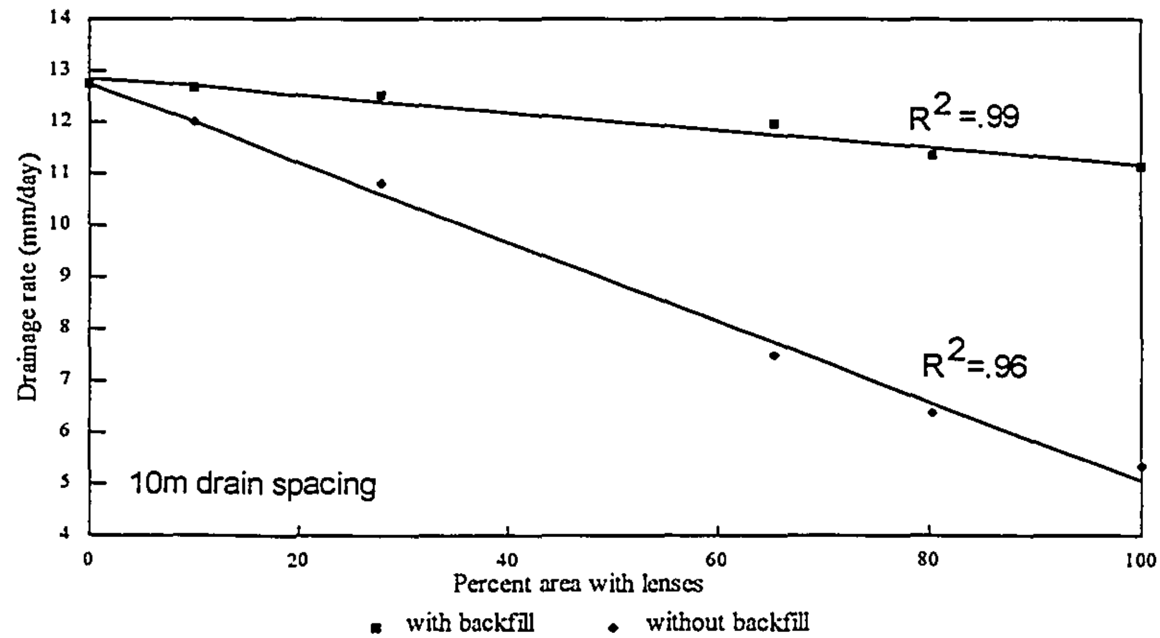

Figure 68. The average drainage rate over 24 hours of drainage for different areas of low conductivity lenses. The drain spacing is 10m for the conditions of backfill and no backfill.

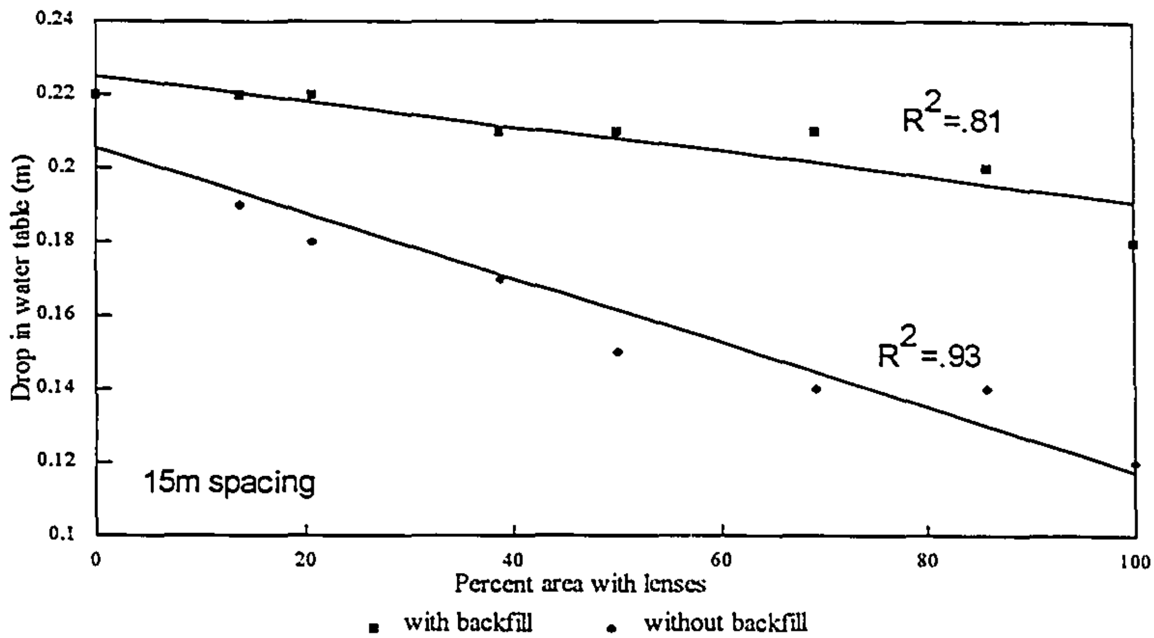

Figure 69. Drop in water table at mid spacing after 24 hours drainage for different areas of low conductivity lenses. The drain spacing is 15m for the conditions of backfill and no backfill.

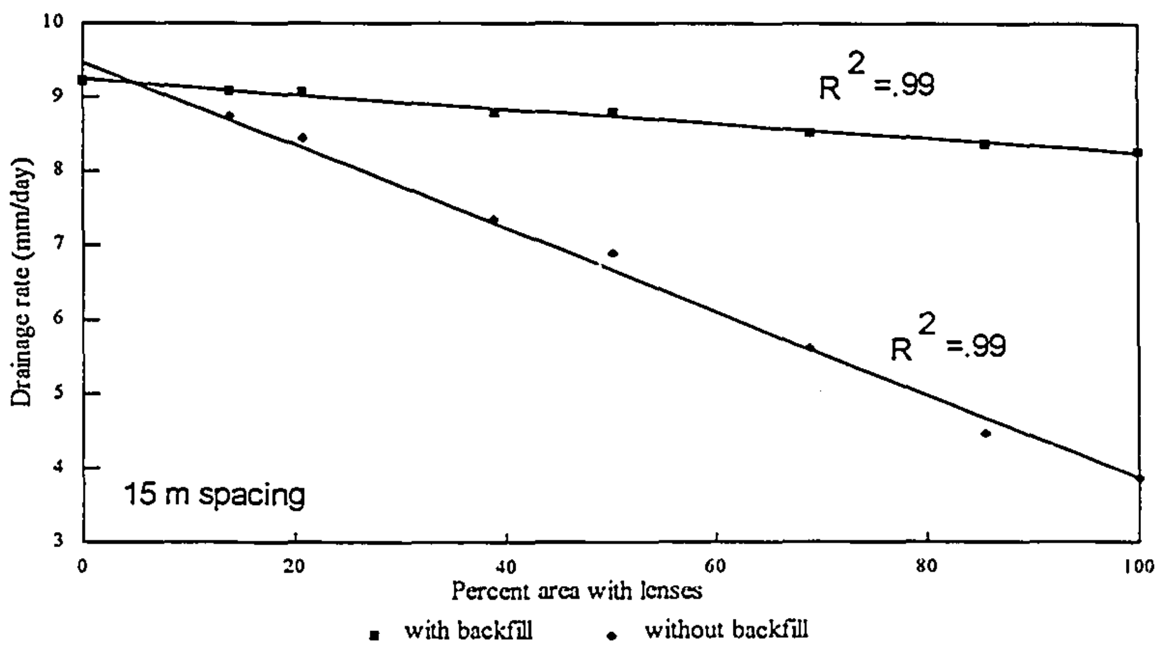

Figure 70. The average drainage rate over 24 hours of drainage for different areas of low conductivity lenses. The drain spacing is 15m for the conditions of backfill and no backfill.

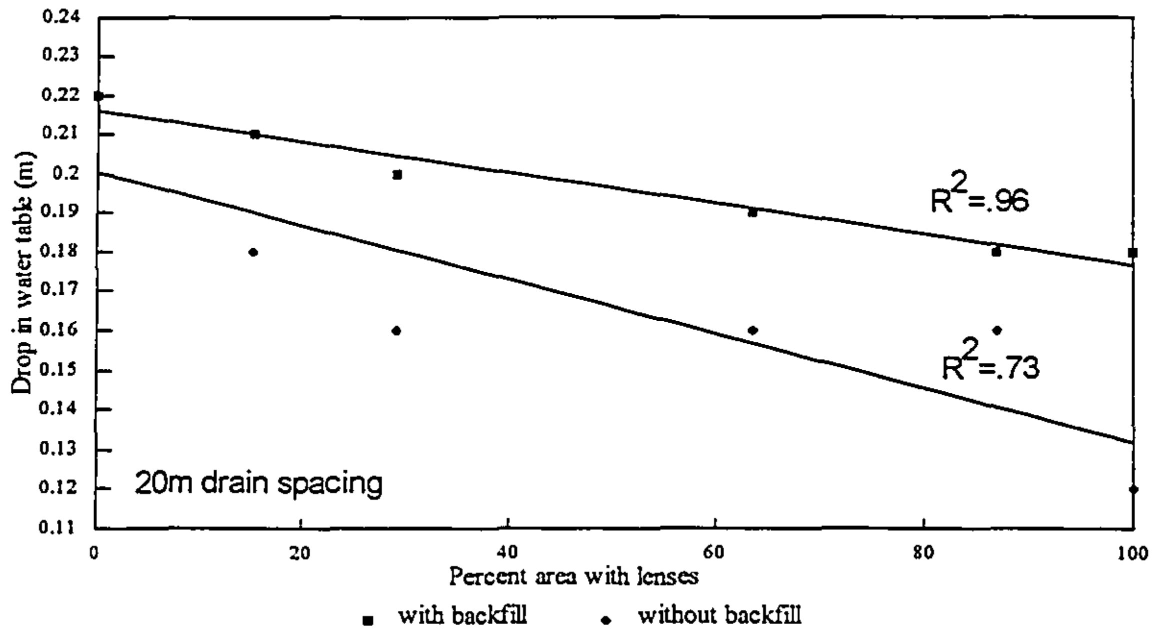

Figure 71. Drop in water table at mid spacing after 24 hours drainage for different areas of low conductivity lenses. The drain spacing is 20m for the conditions of backfill and no backfill.

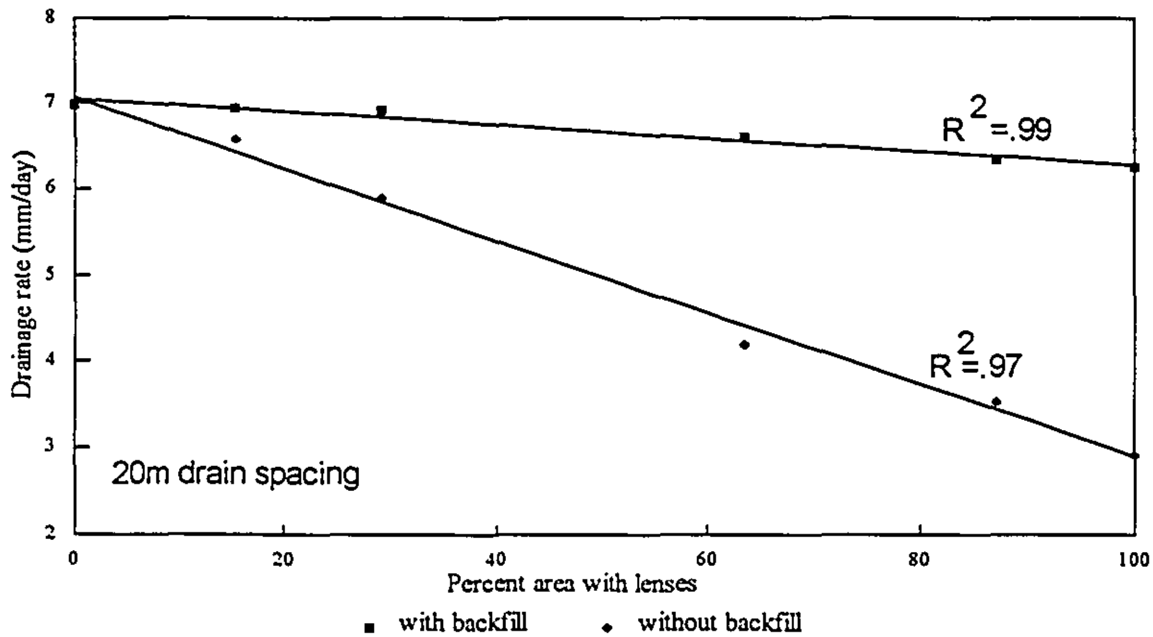

Figure 72. The average drainage rate over 24 hours of drainage for different areas of low conductivity lenses. The drain spacing is 20m for the conditions of backfill and no backfill.

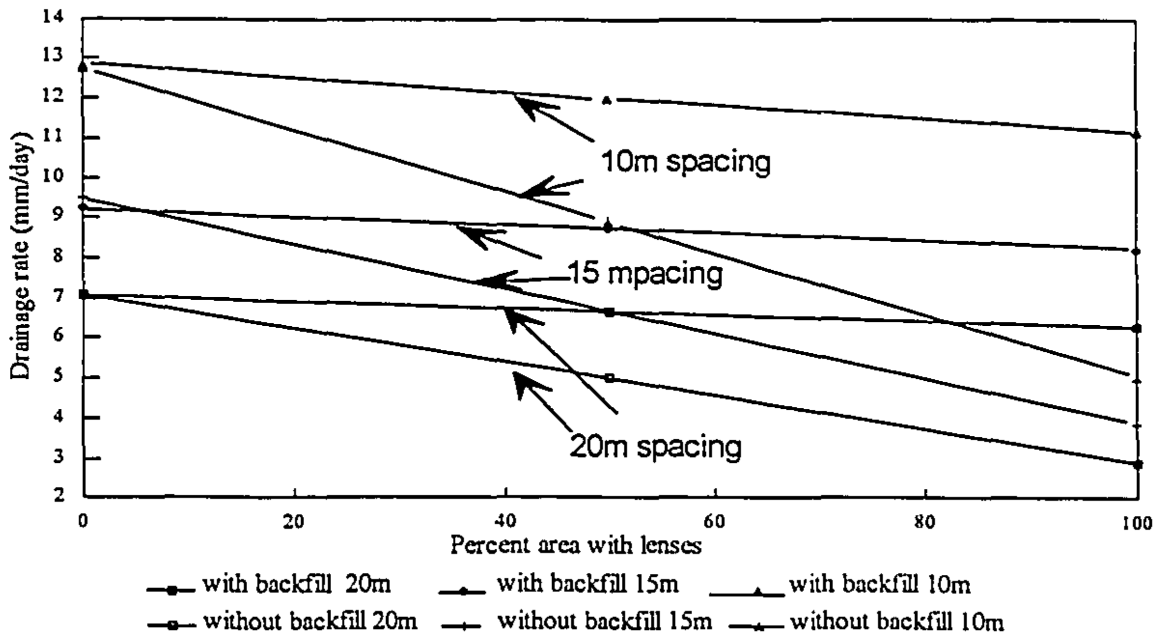

Figure 73. Summary for lines of best fit of the drainage rates for all the drain spacings is given for the conditions of backfill for different areas of low conductivity lenses.

The water table rise due to subirrigation for the two conditions of installation and varying proportions of areas with clay lenses is shown in Figures 74, 76 and 78 for 10m, 15m and 20m spacings, respectively. Only the 10m spacing for the range of lens areas "with backfill" and up to 65% lenses for the case of "without backfill" could meet the criteria of a water table rise of 5 cm over the 7 days. The 15m spacing could just do it if there were no lenses present. The lines of best fit of the data clearly show that the case "without backfill" will have the greatest effect on the subirrigation system performance as the presence of lenses increase. To illustrate this further, the 10m drain spacing shows a 41% decrease in water table rise between 0% and 100% lenses. The corresponding decrease in water table for the "without backfill" is 135% decrease (the water level fell). Figures 75, 77 and 79 show the subirrigation rate for the three spacings versus the area of lenses. The same relationships occurs with the case "without backfill" having the greatest effect on system performance as the area of lenses increase. Figure 80 combines the lines of best fit for the spacings and their rates of subirrigation. Only the 10m spacing can exceed the 5mm/day demand of water table rise. However, in practice, systems can be assisted by periods of rainfall or at least periods of low evapotranspiration (such as early in the growing season) so that the water table can be brought up to desired levels without over designing the system. Further simulations with appropriate weather data can be done to assure this.

The last application for LINKFLOW in this chapter is simulating automatic controls for a subirrigation systems which is another unique program capability.

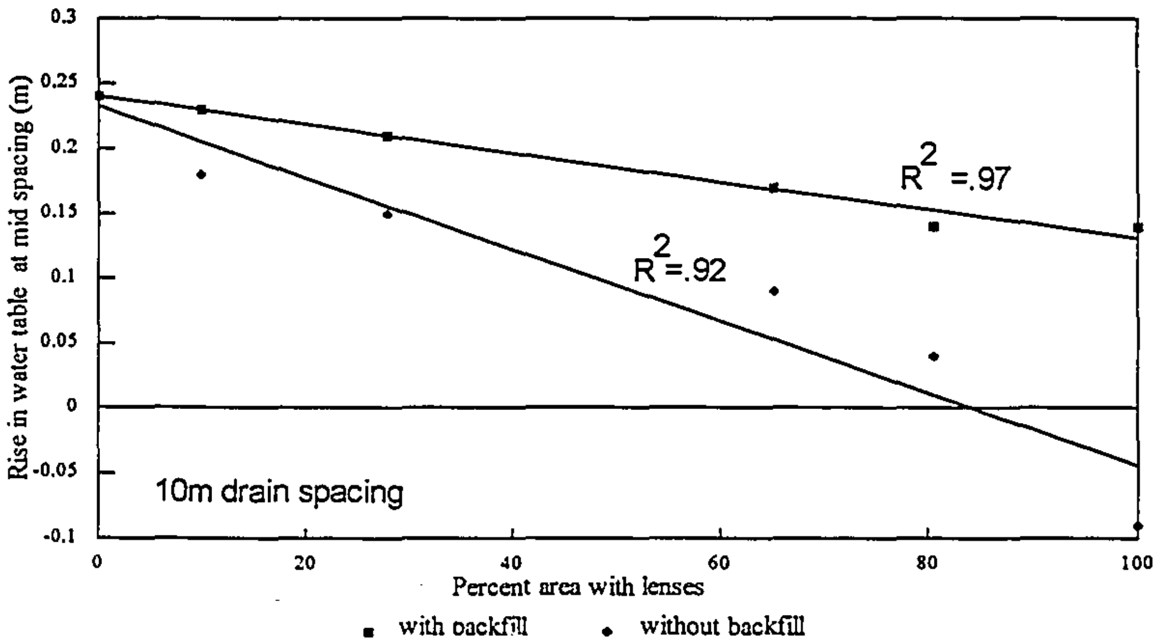

Figure 74. Rise in water table at mid spacing after 7 days of subirrigation for different areas of low conductivity lenses. The spacing is 10m for the conditions of backfill and no backfill.

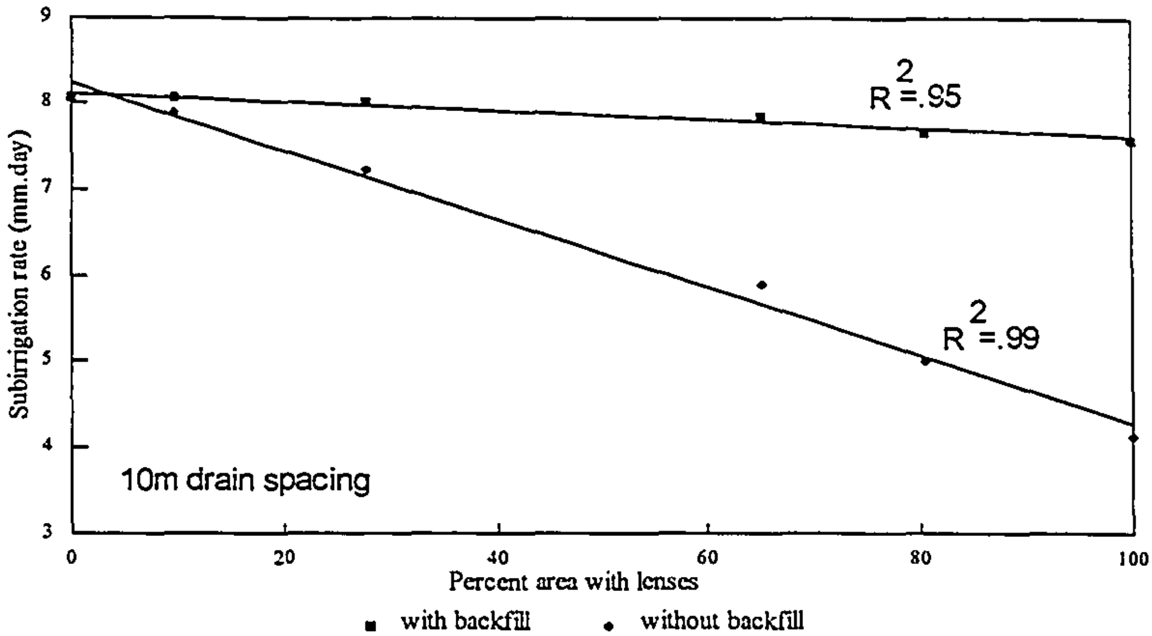

Figure 75. Rate of subirrigation after 7 days for different areas of low conductivity lenses. The spacing is 10m for the conditions of backfill and no backfill.

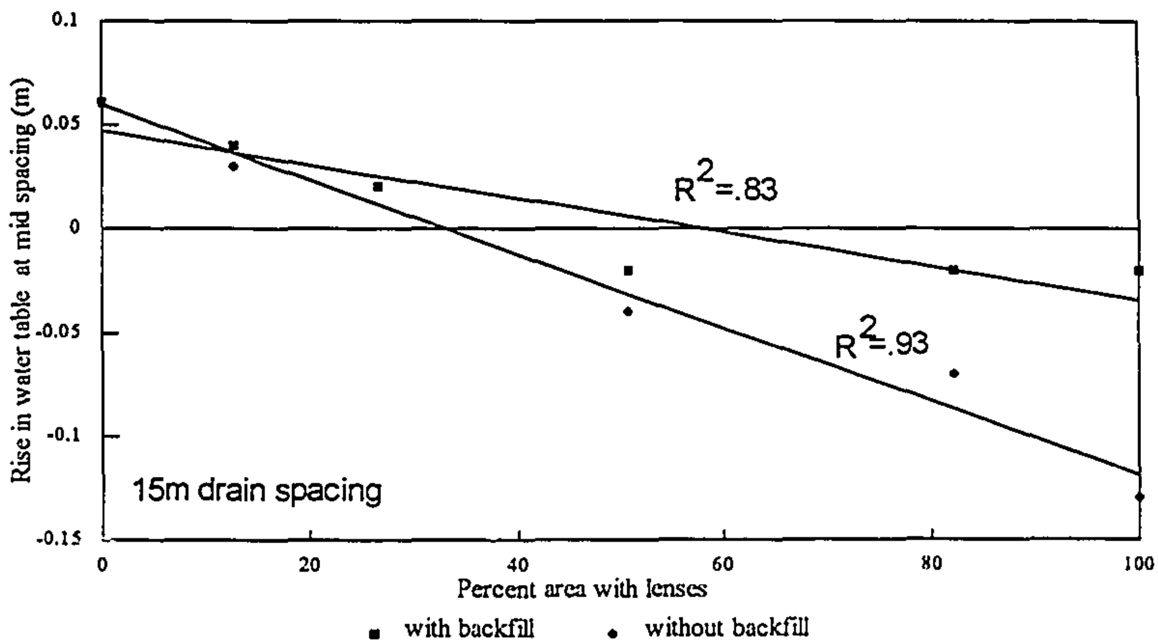

Figure 76. Rise in water table at mid spacing after 7 days of subirrigation for different areas of low conductivity lenses. The spacing is 15m for the conditions of backfill and no backfill.

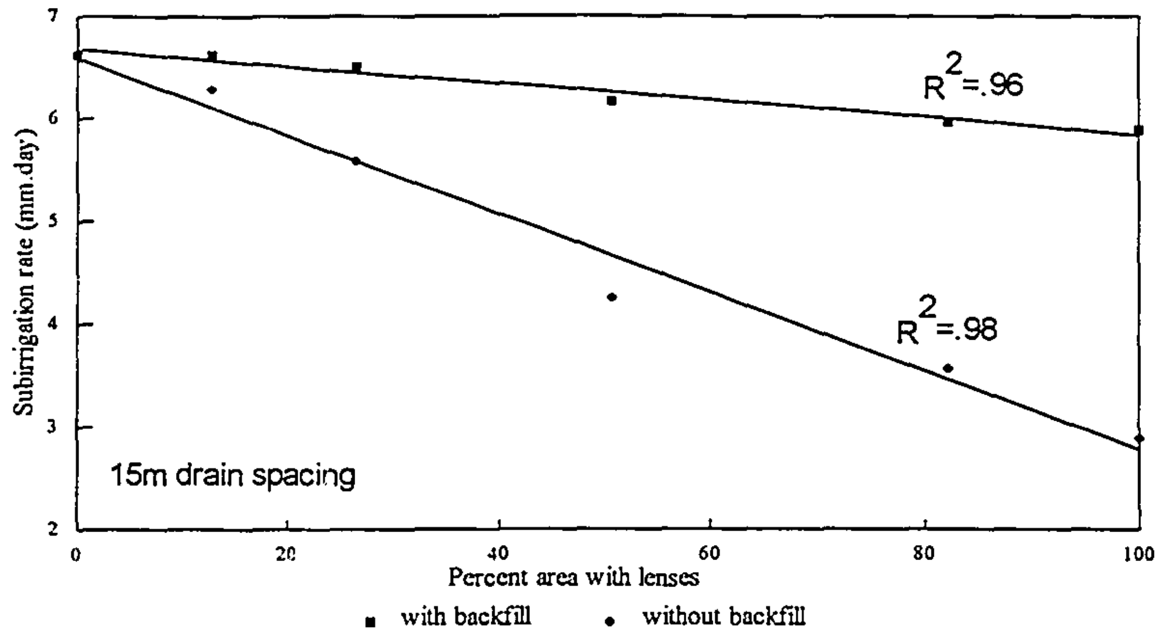

Figure 77. Rate of subirrigation after 7 days for different areas of low conductivity lenses. The spacing is 15m for the conditions of backfill and no backfill.

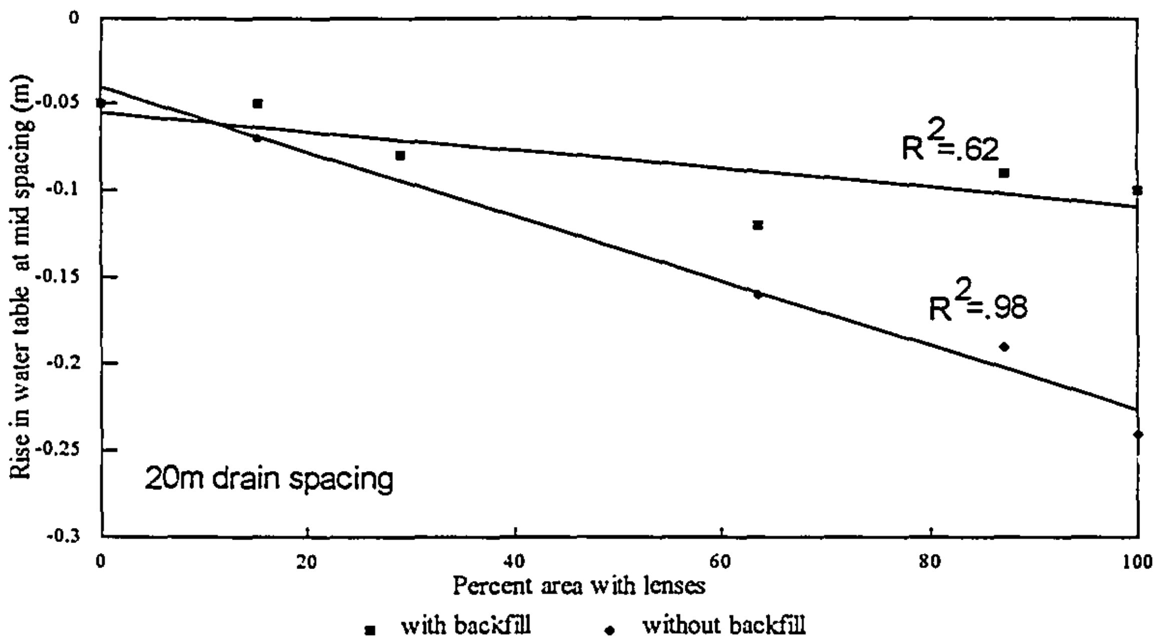

Figure 78. Rise in water table at mid spacing after 7 days of subirrigation for different areas of low conductivity lenses. The spacing is 20m for the conditions of backfill and no backfill.

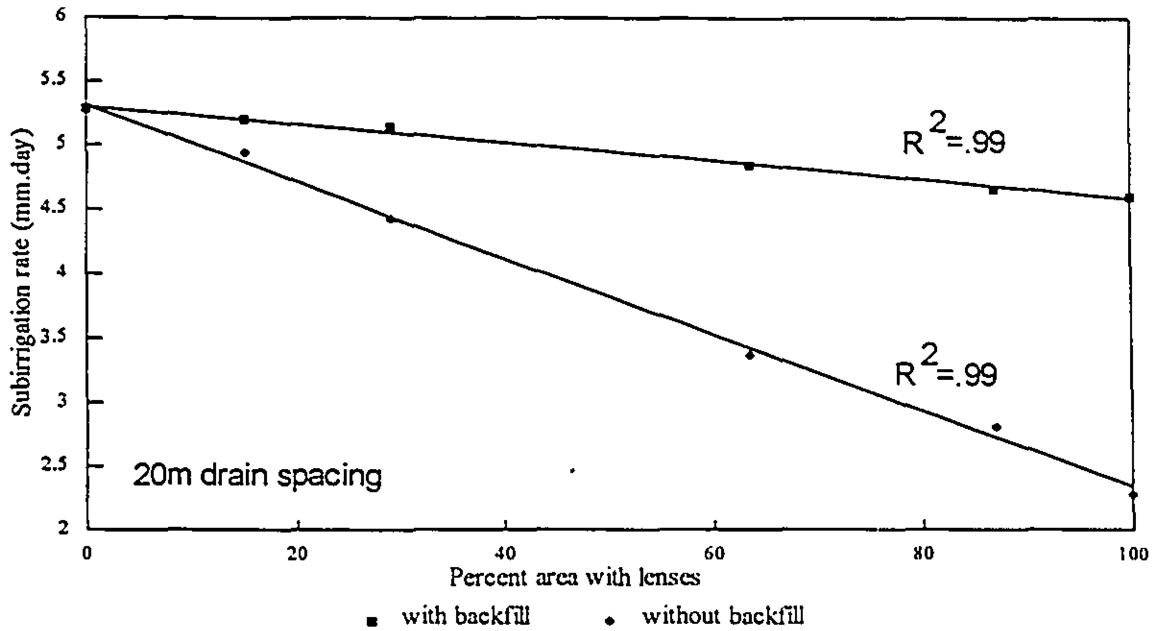

Figure 79. Rate of subirrigation after 7 days for different areas of low conductivity lenses. The spacing is 20m for the conditions of backfill and no backfill.

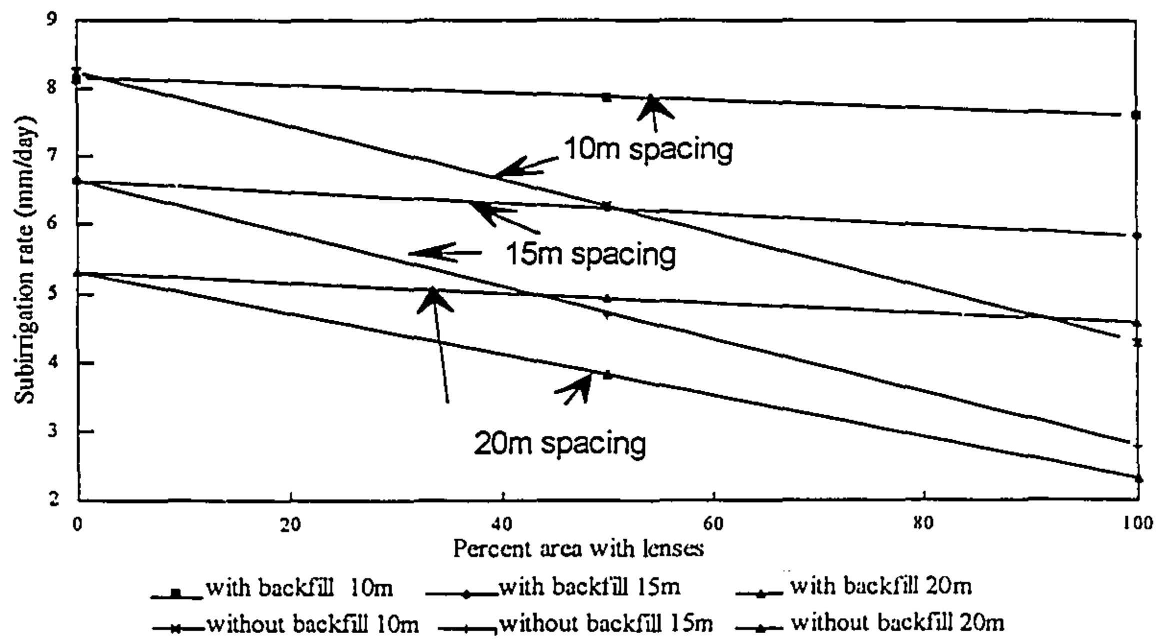

Figure 80. Summary for the rise in water table at mid spacing for different areas of low conductivity lenses and the three spacings with the conditions of backfill and no backfill.

6.3 Automated Control of Water Table Management Systems

Automated control in water table management systems ensure more timely and more frequent adjustments of the water heads in the system than is feasible with manual methods. Since high water tables are maintained in subirrigation systems, leaving relatively low water storage capacity in the soil, heavy rainfall events may result in excessively high moisture levels in the root zone. Timely interventions by the controls can reduce the impact of such occurrences.

LINKFLOW can simulate the effect of different water table control methods and can provide insight into what strategy may be used for a given field situation. Two methods are currently built into the model, and they will be demonstrated here. As new strategies are developed, they can be incorporated by updating the current routines .

When the model is run without selecting the automated control options, it simulates manual control, where the user sets the level in the control chamber for subirrigation and it is not changed in response to field conditions (like in DRAINMOD or SWATRE models). The model does account for periods of excess water by simulating a riser in the control chamber, so that when water levels in the chamber exceed 10cm over the set head, drainage occurs.

The first automated control routine in LINKFLOW follows a similar strategy as most automated controls for water table management systems in that it sets the control chamber water levels based on field water table heights

(MacKenzie, 1992). The location in the field for sensing is selected by the user (usually drain mid spacing). The control routine will raise the water level in the control chamber when the water table in the field is too low, the reverse if the water table is too high, and leaves the settings the same if the water table is within acceptable limits. The second automated control routine changes the water level in the control chamber in the same incremental steps but instead of using the water table height in the field as a control, the level of moisture stress in the root zone is used. Therefore, the water table is raised if the root zone is too dry, and is lowered if too wet for the crop. These routines will be explained further in the following sections when an example subirrigation simulation is done for each of these routines.

To demonstrate the first option in automated operation, a subirrigation simulation for 21 days was done with the following information: a PET equal to 5mm-day^{-1}, drain spacing of 15m and soil parameters as described for the example in Chapter 5. The sensing point for the water table level in this example was selected at one-third the distance between drains. This location was used to reduce the time of high water tables in the areas near the drains, while not being so close to the drains to poorly represent the field conditions. The control routine based on water table levels takes action once every 24 hours and uses the following logic: if the depth is less than 40cm from the soil surface then the control chamber head is reduced by 8cm; if the depth is between 40cm to 50cm then chamber head is reduced by 5cm; if the depth is 50 to 70cm then there is no change; and if depth is between 70cm to 80cm the chamber head is raised by 5cm; and if the depth is below 80cm then the chamber is set to its maximum head which, in this case, is the land surface elevation.

Figure 81 shows the results of the simulation compared to the fixed level control chamber case (manual control). The top line on the graph is the chamber elevation for the manually set control chamber of 19.75m. The next line shows water elevations in the control chamber for the automated control which had a constant level until the seventh day when it was reduced to 19.70m for the remainder of the simulation. The land surface elevation is at 20.0 m. From this, we can see that whereas the mid spacing water level was brought up to 19.44m elevation or 56cm from the surface over the 21 day period by the manual system, the automated system raised it to 19.38m elevation or 62cm from the surface. The automated control only changed the water level on day 7 but the mid spacing water level only began changing after day 10.

To see how well this met the moisture needs of the crop, the percent of field having no moisture stresses, as calculated from the WET factor, is shown in Figure 82. The WET factor is used to define the root zone moisture conditions into four categories: a) "aeration stress" which occurs when moisture levels are high in the root zone and limit aeration (WET is greater than 1.0); b) "no stress" when moisture conditions are in an optimum range for plant growth (WET equals 0.0); c) "low stress" when moisture levels are low enough to start slowing plant growth (WET is between 0.0 and -0.5); and d) "severe stress" when plant growth will be under very dry conditions (WET is between -1.0 and -0.5). LINKFLOW calculates the areas of the field which have each of these moisture categories and the automatic control routine uses the calculated areas to implement control. In Figure 82, the top two lines plotted are the fixed water level and water level for automated control in the control chamber. The third line is the resulting water table levels for the two types of control. Both had the same areas of no root zone water stress. The "no stress" level occurs in 65% of the field after 4 days with both types of control with the rest of the field having "aeration stress" caused by high water tables near the subirrigation drains. After day one, both types of control had 83% of the field under "no stress", and by day 4 a stable level had been reached.

It should be noted that manual and automated controls simulated are examples of the capabilities of LINKFLOW not the control strategy. Better performance could be obtained by both these systems now that their uniformity of irrigation has been determined and settings could be changed accordingly.

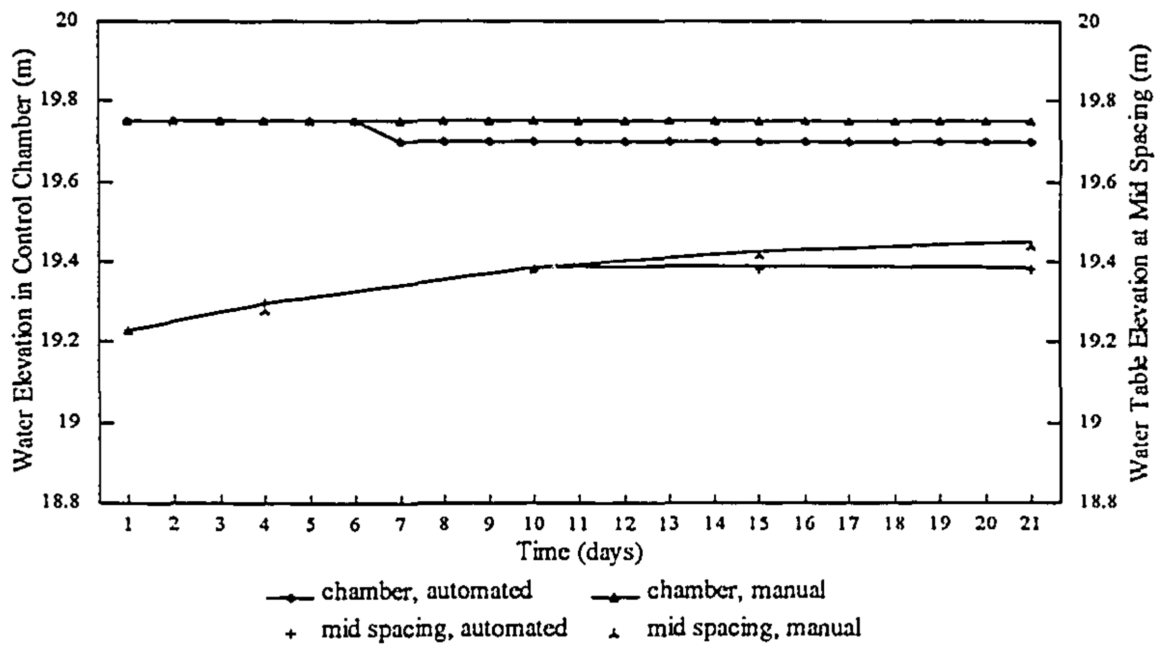

Figure 81. Water elevation in the control chamber and at mid spacing versus time for the case of constant control chamber head and the case of automatic head control based on field water table depth.

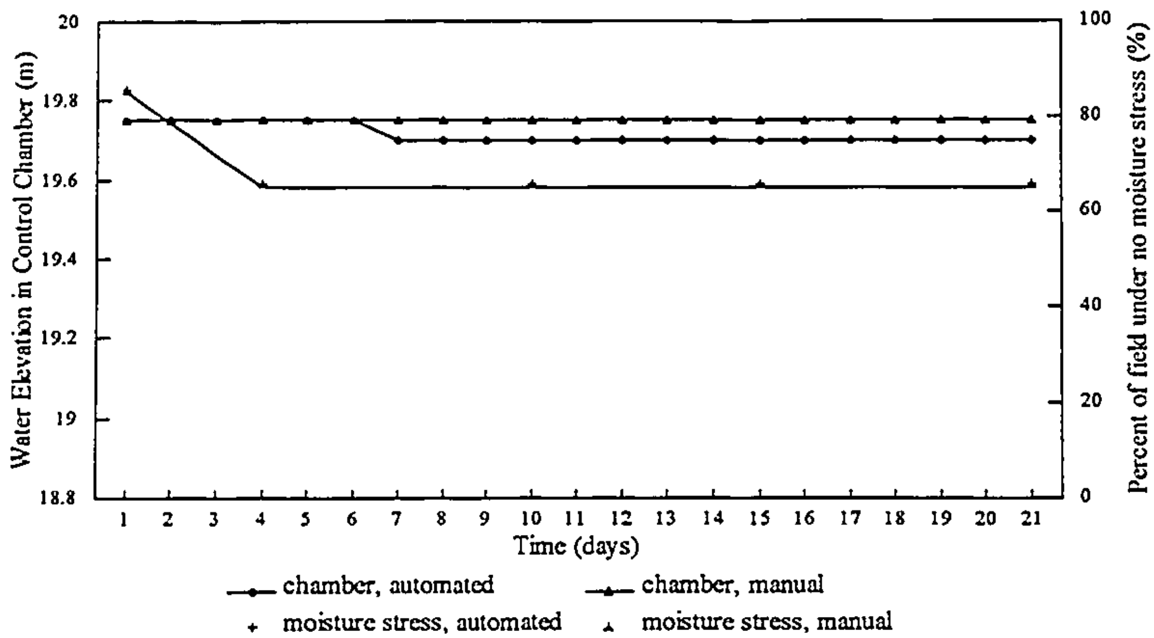

Figure 82. Water elevations in the control chamber and area with no moisture stress in root zone versus time for constant control chamber head and automatic head control by field water table depth.

Another approach for automated control is to have the control based on the moisture conditions in the root zone, such as using water potential as described by Johnson et al. (1993). This approach is not new for other types of irrigation systems but is new for control in subirrigation systems. The second automated control routine takes this approach.

The second automated control routine AMSUB in LINKFLOW directly uses the parameter WET which combines plant and soil factors to give a measure of moisture conditions in the root zone environment. The assumed control logic is as follows: if more than 20% of field has "severe stress", then bring the control chamber to its highest head; if the combined area of "severe stress" and "low stress" exceeds 30%, then raise the level in control chamber by

5cm; if the "no stress" area is greater than 80%, then leave settings the same; and if "aeration stress" exceeds 15%, then lower chamber head by 5cm; and if "aeration stress" exceeds 30%, then decrease chamber head by 30cm. These actions are prioritized with the last condition having the highest priority in the event of conflict in control logic statements.

Figure 83 graphs the water elevation in the control chamber and at mid spacing for the fixed and the automated control chamber level for this system. The fixed level system's control chamber level is the top line in Figure 83 and, as expected, is a horizontal line over the simulation time. The next line is the water level in the control chamber for the automated control, it decreases daily from an initial level of 19.75m to 19.55m and leaves it at that level for the rest of the period. The next two lines on the graph are the associated water table levels at mid drain spacing for the two control systems. The automated system resulted in almost no change in the mid spacing water levels while the fixed level brought the water table up. Figure 84 shows four lines across the graph, the second line down is the water level in the control chamber for manual control, the third line down is the water level for the automated control. The bottom line is the percent area with "no stress" in the root zone for the manual control. As discussed earlier, it decreased on day 4 to 65% and remained at that level for the rest of the simulation period. The top line is for the automated control which like the manual control started at 83% of the area under "no stress", but by day 4, had the "no stress" level at 100% and it remained that way for the rest of the simulation. Since water level control was based on the parameter by which the subirrigation performance was judged, this type of control if feasible to implement would have a major advantage over control by water levels. This was observed by the good root environment conditions that this form of control quickly brought to the field.

The amount of water each system applied to the field, averaged over the period, was 6.12 mm/day for the manual system, 5.92 mm/day for the automated by water table, and 5.05 mm/day for the automated by moisture stress. This suggests that a 17.5% savings in water could be achieved by the automated control system using moisture stress, as compared to the manual control. However, further simulations would be needed to make a fair comparison of these systems over a range of soil and climatic conditions, but now a tool exists (in the form of the LINKFLOW model) to fine tune these controls without the expense of field scale trial and error.

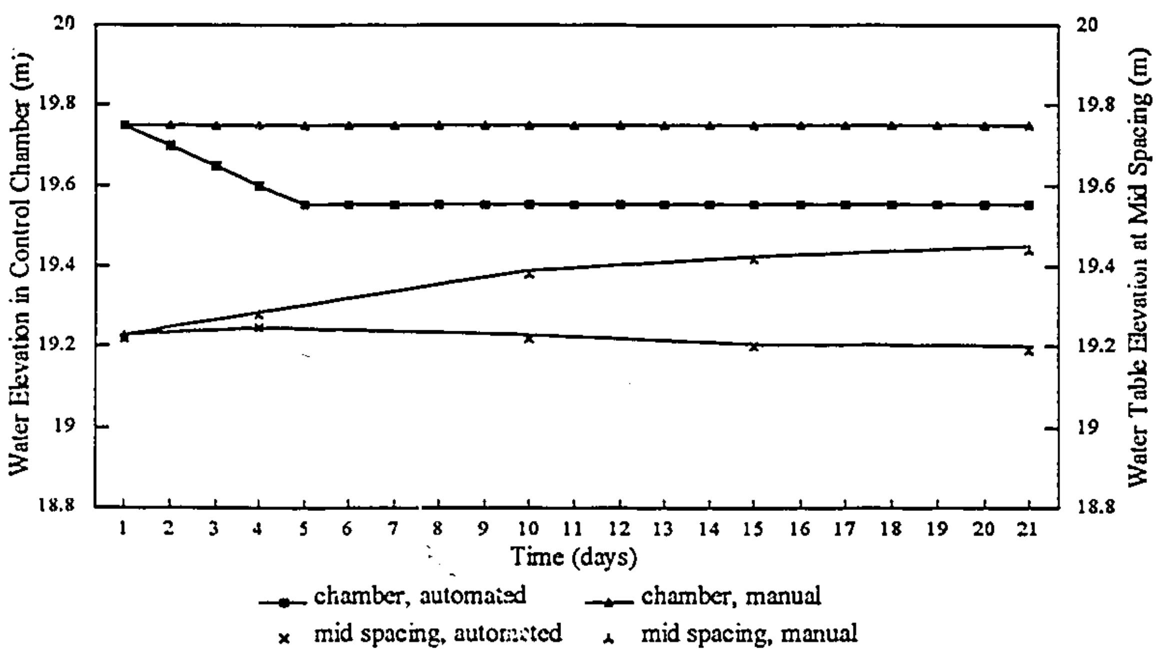

Figure 83. Water elevation in the control chamber and at mid spacing versus time for the case of constant control chamber head and the case of automatic head control based on moisture stress.

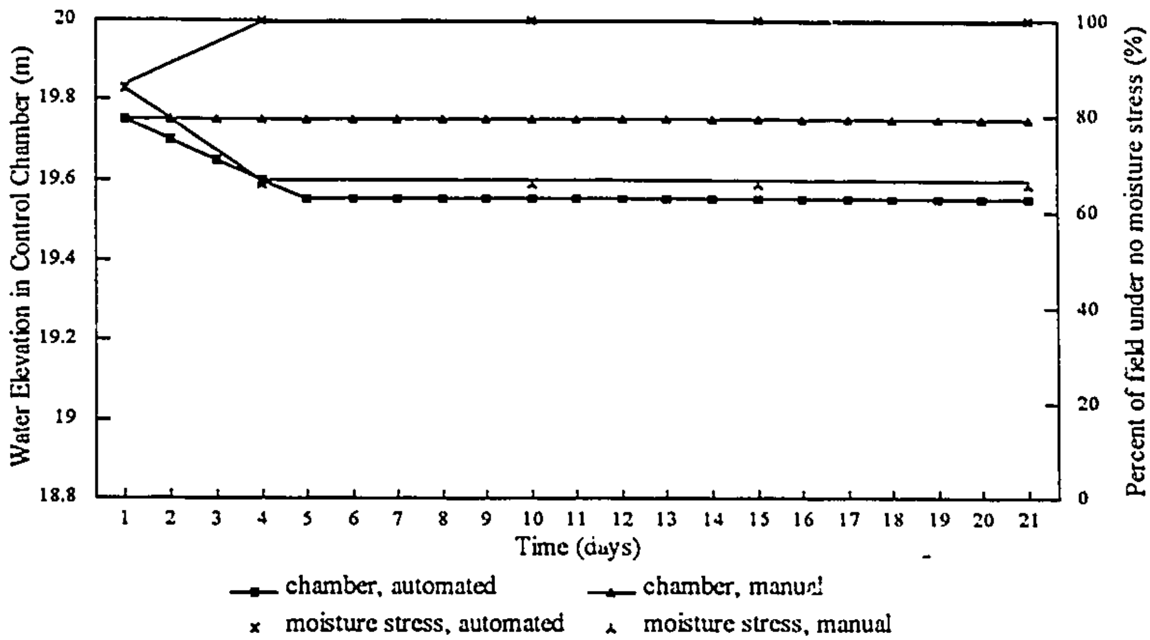

Figure 84. Water elevations in the control chamber and area with no moisture stress in root zone versus time for constant control chamber head and automatic head control by moisture stress.

Future controllers can use LINKFLOW to assist in developing the best algorithms for control in a wide range of situations that can be simulated. This could be done by upgrading the existing control algorithms and running simulations to access the performance of each type of system. In addition, LINKFLOW could be used as an irrigation scheduler to provide management decisions based on field, crop and weather constraints. It could simulate the water level changes required by a subirrigation system using current weather information. This would greatly improve the management of manually operated systems. In the future there are opportunities in computing, knowledge systems, telemetry, instrumentation and control engineering to bring water table management control systems to a much better level of control. Improved control systems can have environmental, energy, crop and management benefits.

As the use of water table management systems increase, the need for sophisticated controls will also grow as well. LINKFLOW can play a role in this aspect of development.

6.4 Conclusions

The LINKFLOW model was run to investigate two special soil conditions and to simulate automated water head controllers that existing water table management models can not adequately address.

The influence of anisotropy on the performance of both subirrigation and drainage was demonstrated through the results of a number of simulations. As the degree of anisotropy increases which means that the vertical conductivity is lower in respect to the horizontal when keeping the equivalent conductivity constant, the water removed or delivered by the water table management system is less compared to a system with an anisotropy of one.

The presence of lenses of low conductivity was simulated and they were found to have a detrimental effect on water table management systems. The effect was greater if the drains were located within the lenses. Allowing the lenses to surround the drain caused greater reductions in performance than if the drains were not surrounded by the lenses. The effect of lenses at the drain could be reduced by using backfilling techniques to ensure more permeable soils around and above the drains. This would also suggest that in shallow soils where tiles are often installed into a low permeable soil, the use of proper backfilling methods could enhance performance.

The use of automated controls for head levels in water table management systems could improve the performance of most systems. Quantifying this improvement and testing different control strategies can be done using LINKFLOW.

Chapter 7: Summary and Conclusions

7.0 Summary

A computer simulation model, LINKFLOW, was developed based on the numerical solution to the governing partial differential equations for saturated and unsaturated ground water flow. It is designed to perform quantitative calculations of water movement occurring in the soil with various water table management systems such as subsurface drainage, controlled drainage and subirrigation. The model can account for heterogeneous and anisotropic soil properties, topography, drain locations, and the interaction of plant roots. The model links a modified three-dimensional saturated ground water flow model, MODFLOW, developed by Harbaugh and MacDonald (1984), for saturated flow to a specially developed one-dimensional unsaturated water flow model. The programs are written in Fortran 77 and operate on IBM PC or compatible microcomputers. A program LINKINP was written in Visual Basic to aid in creating the data sets and in manipulating the output in a user-friendly WINDOWS 3.1 environment.

Under various water table management practices, LINKFLOW can simulate: (1) transient movement of water to and from drains; (2) moisture content and pressure head throughout the soil profile; (3) height and shape of the water table; and (4) amount of water extracted by plant roots for a region of the field. The results may be given in the form of tables, contour or surface plots. Also, a transient indicator of the spatial uniformity of irrigation or drainage (WET) is calculated for each system.

Soil properties required for the model include: (1) the pressure head relationship with hydraulic conductivity; (2) soil moisture retention curve; (3) anisotropy factor; (4) specific yield; (5) the soil-plant-water interactions in terms of the pressure heads at (a) permanent wilting point, (b) 50 percent available water content, and rooting depth. Descriptive data are needed, namely, the dimensions of the region, thickness of soil layers, topographic data, rainfall and evapotranspiration. LINKINP ensures the data sets are complete with the information that a user supplies or with the default values.

As part of model development, its various components were tested by comparing the simulated results with other published numerical solutions. They included problems of infiltration, drainage and evaporation to test the unsaturated flow component of the model. The unsaturated flow component was able to simulate these processes with good accuracy having relative errors less than 3%. Comparisons were then made with the numerical solution of a transient drainage problem to test the linked model. The model described this two-dimensional flow problem very well with a relative error of 7%.

To further validate the model with field data, measurements of moisture contents and water table heights were taken over a two-month period in the 1987 growing season. The site used for the water table management plots is located near Sorel, Quebec. Test plots at this site included replicated treatments for subirrigation, controlled drainage and conventional drainage. Soil and climatic data used in simulations were established from previous studies done at these plots. A topographic survey provided the ground elevations. The simulated values were close to the observed data with relative errors less than

5 percent for most situations. Therefore, it was concluded that the model can successfully simulate soil moisture conditions in a region with variable topography, heterogeneous soil conditions with varying climatic conditions for several water table management systems.

A sensitivity analysis was performed on the model inputs and it showed that errors in estimating hydraulic conductivity caused the most error in predictions of the midspan water table height. For example, an error of 100% in estimating the saturated hydraulic conductivity was observed to cause a 30% error in the simulated water table elevation.

The model was used to study the impact of anisotropy and the presence of clay lenses on the performance of a subirrigation system. Results from simulations of several of these cases showed that as the degree of anisotropy increases, the water table management system's performance decreases. In the case of clay lenses, as areas of lenses increase in the region, the water flow from a water table management system decreases. This effect is amplified if the drains are located in the lenses without precautions to ensure proper backfilling with more permeable soils around the drain.

The model was also used to simulate water movement from a subirrigation system with an automated controller for the water level in the control chamber. A simulation was run using the existing water level in the field as the controller's criteria to change the water level in the control chamber. The simulation showed that automated control would set the water level in the field, but adjustments would be needed to have it create the best moisture conditions for the crop. A second simulation used the moisture stress in the root zone, defined by the WET parameter, as the parameter to guide the automated controller. Better spatial distribution of moisture conditions in the crop root zone were found with the use of this strategy than would be expected from SEW_{30} or number of drys days (Skaggs, 1978). LINKFLOW was able to demonstrate the effectiveness of each controller type to operate the system and meet crop water requirements.

7.1 Conclusions

Based on the results of this investigation, the following conclusions were drawn:

1. LINKFLOW is the only water table management model that combines: a three-dimensional saturated ground water flow model for anisotropic, heterogeneous soils; a one-dimensional unsaturated flow model; and a root water extraction model to represent the soil water flow process occurring during water table management.

2. The model was verified with observations made in field experiments to simulate water movement for several types of water table management systems, including subirrigation, conventional drainage and controlled drainage. Moisture content profiles and water table depths of simulated and observed field measurements were in close agreement.

3. LINKFLOW was able to simulate the effect of soil anisotropy on the performance of water table management systems. Soils with degree of anisotropy values ($(k_h/k_v)^{0.5}$) greater than one were found to reduce the performance of drainage and subirrigation systems spanning a 21 day simulation. For an example drainage and subirrigation simulation, the rate water could be removed or supplied was reduced by 25% and 18%, respectively, for a degree of anisotropy of 5.

4. The model was also able to simulate the effect of clay lenses on the performance of water table management systems. The presence of lenses around the drainage was found to have the most detrimental effect to drainage and subirrigation system performance. This effect was shown to be reduced if drains were installed with more permeable soil around them to reduce the influence of the lens.

5. LINKFLOW can simulate the performance of automated and manual controls for subirrigation systems and indicate their success in providing suitable moisture conditions in the root zone on a field-scale. The model was able to demonstrate that controls based availability of water to the crop would have the best influence on crop yields.

6. A new parameter to provide a measure of uniformity of spatial irrigation/drainage, called WET, is proposed that simplifies describing the suitability of moisture conditions in the root zone for crop growth. This parameter can be used in the evaluation of water table management systems or as an operational parameter in a control system.

7. A water budget accounting for flows in the soil profile in the LINKFLOW program showed credible results, demonstrating a valid linkage between the unsaturated and saturated flow models.

8. The one-dimensional unsaturated model was found to give acceptable results using a 1 cm nodal spacing when solving the finite difference relations for the range of flow gradients encountered in this thesis.

9. Speed and accuracy of computations during a simulation varied with the number of unsaturated model profiles selected. As the number of unsaturated profiles used decreased, the program executed faster. Cases with heterogeneous soil conditions require a high number of unsaturated columns selected to reduce the error from averaging unsaturated flow results.

10. The layout of the finite difference grid will affect the performance of the linked model. Closer spacing in the grid is needed near drains where high flow gradients may occur.

Chapter 8: Suggestions for Future Research

LINKFLOW was developed in a modular format to allow updating model components as improved methods are developed or the capabilities of existing ones are expanded. Such changes would include improvements to the treatment of root water extraction, crop yields, infiltration, runoff, the soil-drain interface and automated control aspects.

The model requires considerable computation time and if convergence problems occur, the simulation may stop before all time steps are simulated. LINKFLOW could be rewritten to operate more efficiently, detect convergence problems and correct them without stopping the simulation. MODFLOW has a new release in which some of the problems have been addressed. Updating LINKFLOW with the new routines would improve its efficiency.

The unsaturated flow model performs simulation of unsaturated flow for points all over the area, but it assumes the same soil properties for all locations. The program could be improved to allow nonuniform heterogeneous soil properties in the unsaturated soil zone.

Research is needed into the incorporation of the model as the basis for a control strategy of a field water table management system. Such incorporation involves its use as a management tool and its eventual use as an automated controller in real time of the water table based on climate, soil, field, crop and time of the season. Improvements to the existing control routines will assist designers in better management recommendations.

The model can be applied to study the effect of the variability of hydraulic conductivity on drainage and subirrigation system's using Monte Carlo techniques by running a series of simulations with random combinations of conducuivities. The results can be used to analyze the effect of uncertain soil properties on the performance of a given system.

Future improvements to the model could incorporate chemical migration components into the model. LINKFLOW could simulate the impact of chemical migration in the soil profile for environmental studies.

The addition of open ditch and drip irrigation capabilities should be investigated to expand the range of problems that may be simulated.

Collection and preparation of data sets, especially ones with detailed drain systems, should be investigated. Future improvements might include the capability of scanning an existing drainage plan and from that scan obtain all the topographic and drain details required for the simulation.

Verification studies of field plots should be done for anisotropic soils and soils with clay lenses to compare with the results of the studies presented in this thesis.

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Appendices

Appendix A. Structure of Input data for LINKFLOW

Data Input Requirement for LINKFLOW and LINKINP

The following section explains the data sets required for LINKFLOW. LINKINP would be normally used to ensure all data requirements have a value in the proper format. However, the user may only wish to change one value in the data set and a text processor can do this quickly if the user has the information following to identify the values and their correct format.

Every simulation requires a data set which may have any name so the file START.PAN contains the name of the first file which in turn contains the names of the other data files.

<u>START.PAN</u> - file contains name of first data file (ie. a.pan)
A10

The data set name being used to illustrate the data sets required is "A" though any name may be used.

<u>A.PAN</u> - comment line, (**John Hunt's field 108**)for file only

- last date , and time of use (**06/06/92 10:05:00**)

- output files name (**a.out**) ,A12

- input file names (**a101.pm**) ,5A10
(**a111.pm**)
(**a117.pm**)
(**a120.pm**)
(**a121.pm**)

<u>A101.PRN</u> - HEADING to printed in simulation output
20A4

- HEADING

12A4

- nlay(1-40),nrow(1-40),ncol(1-40),nper(1-200)
- #layers,rows,columns,stress periods
  5I10

- itype,ithour,itable,igraph ,4I10

  itype - 1 column
  - 2 hcolumn
  - 3 all
  - 4 hall

  sthour - hour of day (1-24) for start

  itable - 1 full tables
  - 2 short tables

  igraph - 1 graph water tables
  - 2 graph moisture contents
  - 3 graph wetness factor
  - 4 no graphing

- IBOUND(NCOL,NROW) --- set 0,1 for each layer
  U2DINT - boundary array
  x NLAY
  (0 1) for each layer (all active)

- Shead(NCOL,NROW) - starting head
  U2DREL
  x NLAY
  (0 19.45)(m) for each layer

- PERLEN,NSTP,TSMULT - time length of Stress per.(d)
  F10,I10,F10.0 - number of time steps,multi.
  x NPER
  (1., 10 , 2) for each stress period

a111.pm

- TRPY(NLAY) --- soil anisotropy Kv/Kh
  U1DREL
  x NLAY
  (0 1.0) when all layers the same

- DELR(NCOL) - width of rows (m)
  U1DREL
  (11 1.0 (10G5.2) 0)
  (.5 1. 4. 5. 5. 5. 4.)

- DELC(NROW) - height of columns (m)
  U1DREL
  (11 1.0 (10G5.2) 0)
  (.5 1. 4. 5. 5. 5. 4.)

Each of the following inputs for the remainder of this data set are entered as a set for layer 1 then repeated for layer 2 and so on.

- HY(NCOL,NROW) - conductivity (.0001 - 10)
  U2DREL (m/day)
  (0 1.2)

- THICKNESS(NCOL,NROW) .01 - 2) (m)
  U1DREL
  (0 .6)

- SF2(NCOL,NROW) - specific yield (0.05 - .25)
  U2DREL
  (0 .09) - USE A CONSTANT

- TOP(NCOL,NROW) --- only recorded for layer 1
  U2DREL - surface elevation (m)
  (0 20.3)(m)

A117.PRN - MXBND,DK,NCCOL,NCROW ,I10,F10.4,2I10

MXBND - max number of const. head nodes(**0-80**)
DK - conductivity const. for drain(**.1-5**)
NCCOL,NCROW - column and row used for sensing during automated control mode(**1-NCOL,1-NROW**)

FOR EACH STRESS PERIOD

- ITMP, IMODE ,2I10

ITMP - max. number of nodes operating during stress period , -1 keeps previous values from last stress period so no further info needed in current stress period, only after first period.

IMODE - CODE FOR DRAIN OPERATION
1 ..... SUBIRRIGATION
2 ..... DRAINAGE
3 ..... AUTOMATED BY WATER STRESS
4 ..... AUTOMATED BY WATER LEVEL
(24, 2)

- LAYER,ROW,COL,HEAD,COND,DIR
(FOR FIRST STRESS PERIOD ONLY)
3I10,2F10.0 (FOLLOWING STRESS PERIODS)

node location by LAYER,ROW, COLUMN
HEAD water head in drain at node ,
COND conduction factor equal to DK times length of drain at node
DIR is direction of drain in cell R is along row
C is along column

(3 2 1 21.1 1.5),R

- STRESS PERIODS >1 , ONLY ENTER HEAD
F10.0 when ITMP is not equal -1

A120.PRN - IROW - row used for unsat model if single row
I10
(1 - NROW)

- DELTIM,PMAX - time step increment (days), max. press. change (m)
2F10.4
(0.01,0.01)

- PPWP,P50 - Permanent wilting point,Press. @ 50%AWC
2F10.4 - (m),(m)
(-2.5,-0.45)

- PTEMP(nodes) --- set to 99 (m)
U1DREL - if initial pressure heads 99 hydrostatic
(0 99)

- RTD,MAXR,MAXD,IRTDAY - root zone depth (m), ,mature root dep. (cm),days to mature, starting crop day
F10.4,3I10
(.1 - 1.5)

- TYPE - type of algorithm to calculate Properties
I5

IF TYPE = 1 Hoover's model
AK(2),AK(3),AK(4) - conductivity function
3D15.5

AMC(2),AMC(3),AMC(4) - moisture function
3D15.5

IF TYPE = 2 Van Genuchten's model
AK(2),AK(3),AK(4),AK(5) - conductivity function
4D15.5

AMC(2),AMC(3),AMC(4),AMC(5) - moisture function
4D15.5

- RAIN(NPER),EVAP(NPER),IP(NPER) - rainfall, potential evap.,PRINTOUT FLAG
  2F10.4,I5 - (m),(m)
  X NPER one for each stress period

a121.prn - MITER - max # of iteration in saturated flow model
I10
(50) - could be left at this value

- ACCEL,HCLOSE,IPRSOR
  F10.0,F10.0,I10

Appendix B. Output from LINKFLOW for the Case Study

```
 Date 29/ 8/ 92   Time 22:45

 OUTPUT FILE NAME a215.OUT


           LINKED SATURATED - UNSATURATED AGRICULTURAL SYSTEM GROUND-WATER MODEL
Case study data set                                          July 1992
   4 LAYERS       11 ROWS       13 COLUMNS
  6 STRESS PERIOD(S) IN SIMULATION
 MODEL TIME UNIT IS DAYS

STARTING HOUR in simulation   1.0

LINKAGE TYPE HALL

PRINTOUT TYPE IS FULL

GRAPH DATA SET IS WT


   LAYER  AQUIFER TYPE
   ------------------
     1       3
     2       3
     3       3
     4       3
 MAXIMUM OF   33 HEAD-DEPENDENT BOUNDARY NODES
DRAIN k VALUE USED FOR CONDUCTANCE CALC.  0.400

   50 ITERATIONS ALLOWED FOR SOR CLOSURE
Case study data set                                          July 1992
                                   BOUNDARY ARRAY =          1 FOR LAYER  1
                                   BOUNDARY ARRAY =          1 FOR LAYER  2
                                   BOUNDARY ARRAY =          1 FOR LAYER  3
                                   BOUNDARY ARRAY =          1 FOR LAYER  4
AQUIFER HEAD WILL BE SET TO  999.99    AT ALL NO-FLOW NODES (IBOUND=0).
                                   INITIAL HEAD =  19.25000    FOR LAYER  1
                                   INITIAL HEAD =  19.25000    FOR LAYER  2
                                   INITIAL HEAD =  19.25000    FOR LAYER  3
                                   INITIAL HEAD =  19.25000    FOR LAYER  4
DEFAULT OUTPUT CONTROL -- THE FOLLOWING OUTPUT COMES AT THE END OF EACH STRESS PERIOD:
 TOTAL VOLUMETRIC BUDGET
       HEAD
                                    H/V ANISOTROPY  OF HY. K =   1.000000


                                   DELR WILL BE READ UNFORMATTED ON UNIT  11

 0.20000    0.30000    0.60000     1.5000     2.0000     2.0000     2.0000     2.0000     2.0000     1.5000
0.60000    0.30000    0.20000


                                   DELC WILL BE READ UNFORMATTED ON UNIT  11

  50.000     75.000     50.000     10.000     5.0000     5.0000     2.5000     1.5000    0.60000    0.30000
0.20000
```

HOR.HYD.COND. (m/day) = 1.200000 FOR LAYER 1
THICKNESS (m) = 0.3000000 FOR LAYER 1
SECONDARY STORAGE COEF = 0.1400000 FOR LAYER 1
ELEVATION OF TOP (m) = 20.00000 FOR LAYER 1
HOR.HYD.COND. (m/day) = 0.9000000 FOR LAYER 2
THICKNESS (m) = 0.4000000 FOR LAYER 2
SECONDARY STORAGE COEF = 0.9000000E-01 FOR LAYER 2
HOR.HYD.COND. (m/day) = 0.6000000 FOR LAYER 3
THICKNESS (m) = 0.3000000 FOR LAYER 3
SECONDARY STORAGE COEF = 0.9000000E-01 FOR LAYER 3
HOR.HYD.COND. (m/day) = 0.1000000 FOR LAYER 4
THICKNESS (m) = 1.000000 FOR LAYER 4
SECONDARY STORAGE COEF = 0.9000000E-01 FOR LAYER 4

UNSATURATED COLUMN POSITION BY ROW = 1
MAXIMUM NUMBER OF VERTICAL NODES = 200
NODE SPACING LENGTH (m) = .01000
TIME INCREMENT LENGTH (day) = 0.0100
MAX. ALLOW. HEAD CHANGE (m) = 0.01000
PERMANENT WILTING POINT (m) = -2.5000
PRESSURE HEAD (m) AT 50% AWC = -0.8000

INIT. PRES. HEAD (m) = 99.00000
*** note if init. press. = 99 then steady state conditions in profiles ***
ROOT DEPTH (m) = 0.4000

Van Genuchtens COEFFICIENTS FOR CONDUCTIVITY RELATION Ksat,n,MCr,MCsat
0.11000E+01 0.36000E+01 0.78000E-01 0.43000E+00

Van Genuchtens COEFFICIENTS FOR MOISTURE CHARACTERISTIC ALPHA,n,MCr,MCsat
0.16780E-01 0.26740E+01 0.78000E-01 0.43000E+00

	RAINFALL AMOUNTS FOR EACH STRESS PERIOD (m)	POTENTIAL EVAPOTRANSPIRATION (m/day)	PRINTOUT FLAG
1	0.0000	0.0050	1
2	0.0000	0.0050	1
3	0.0000	0.0050	1
4	0.0000	0.0050	1
5	0.0000	0.0050	1
6	0.0000	0.0050	1

SOLUTION BY SLICE-SUCCESSIVE OVERRELAXATION

MAXIMUM ITERATIONS ALLOWED FOR CLOSURE = 50
ACCELERATION PARAMETER = 1.1000
HEAD CHANGE CRITERION FOR CLOSURE = 0.10000E-03
SOR HEAD CHANGE PRINTOUT INTERVAL = 1
STRESS PERIOD NO. 1, LENGTH = 0.5000000

NUMBER OF TIME STEPS = 250
MULTIPLIER FOR DELT = 1.050
INITIAL TIME STEP SIZE = 0.1260730E-06

DRAIN MODE OF OPERATION IS SUBIRRIGAT

33 HEAD-DEPENDENT BOUNDARY NODES

LAYER	ROW	COL	ELEVATION	CONDUCTANCE	BOUND NO.
3	1	1	19.75	10.00	1
3	2	1	19.75	30.00	2
3	3	1	19.75	20.00	3
3	4	1	19.75	4.000	4
3	5	1	19.75	2.000	5
3	6	1	19.75	2.000	6
3	7	1	19.75	1.000	7
3	8	1	19.75	0.6000	8
3	9	1	19.75	0.2400	9
3	10	1	19.75	0.1200	10
3	11	1	19.75	0.8000E-01	11
3	1	13	19.75	10.00	12
3	2	13	19.75	30.00	13
3	3	13	19.75	20.00	14
3	4	13	19.75	4.000	15
3	5	13	19.75	2.000	16
3	6	13	19.75	2.000	17
3	7	13	19.75	1.000	18
3	8	13	19.75	0.6000	19
3	9	13	19.75	0.2400	20
3	10	13	19.75	0.1200	21
3	11	13	19.75	0.8000E-01	22
3	11	2	19.75	0.1200	23
3	11	3	19.75	0.2400	24
3	11	4	19.75	0.6000	25
3	11	5	19.75	0.8000	26
3	11	6	19.75	0.8000	27
3	11	7	19.75	0.8000	28
3	11	8	19.75	0.8000	29
3	11	9	19.75	0.8000	30
3	11	10	19.75	0.6000	31
3	11	11	19.75	0.2400	32
3	11	12	19.75	0.1200	33

S O I L MOISTURE PROPERTIES

PRESS(m)	MOIST. CON.	HYDR. CON. m/day	CAPACITY 1/m
-0.03	0.430	1.0992	0.007
-0.08	0.429	1.0885	0.035
-0.13	0.426	1.0589	0.076
-0.18	0.421	1.0054	0.126
-0.23	0.414	0.9279	0.179
-0.28	0.404	0.8307	0.229
-0.33	0.391	0.7214	0.272
-0.38	0.377	0.6087	0.304
-0.43	0.361	0.5008	0.325
-0.48	0.344	0.4034	0.334
-0.53	0.328	0.3195	0.333
-0.58	0.311	0.2499	0.324
-0.63	0.295	0.1939	0.310
-0.68	0.280	0.1497	0.292
-0.73	0.266	0.1153	0.272
-0.78	0.253	0.0889	0.252
-0.83	0.241	0.0686	0.232
-0.88	0.230	0.0532	0.213
-0.93	0.220	0.0414	0.195
-0.98	0.210	0.0324	0.178
-1.03	0.202	0.0254	0.163

-1.08	0.194	0.0201	0.149
-1.13	0.187	0.0160	0.136
-1.18	0.180	0.0128	0.125
-1.23	0.174	0.0103	0.114

*** INITIAL UNSATURATED CONDITIONS ***

TOTAL ELAPSED TIME 0.0000
UNSAT. TIME INCREMENT 0.1261E-06 NODAL SPACING 0.1000E-01

D E P T H (m)	P R E S S U R E H E A D (m) DISTANCE (m)												
	0.000	0.250	0.700	1.75	3.50	5.50	7.50	9.50	11.5	13.3	14.3	14.8	15
0.0050	-0.745	0.000	-0.745	0.000	-0.745	0.000	-0.745	0.000	-0.745	0.000	-0.745	0.000	-0.7450
0.0350	-0.715	0.000	-0.715	0.000	-0.715	0.000	-0.715	0.000	-0.715	0.000	-0.715	0.000	-0.7150
0.0650	-0.685	0.000	-0.685	0.000	-0.685	0.000	-0.685	0.000	-0.685	0.000	-0.685	0.000	-0.6850
0.0950	-0.655	0.000	-0.655	0.000	-0.655	0.000	-0.655	0.000	-0.655	0.000	-0.655	0.000	-0.6550
0.1250	-0.625	0.000	-0.625	0.000	-0.625	0.000	-0.625	0.000	-0.625	0.000	-0.625	0.000	-0.6250
0.1550	-0.595	0.000	-0.595	0.000	-0.595	0.000	-0.595	0.000	-0.595	0.000	-0.595	0.000	-0.5950
0.1850	-0.565	0.000	-0.565	0.000	-0.565	0.000	-0.565	0.000	-0.565	0.000	-0.565	0.000	-0.5650
0.2150	-0.535	0.000	-0.535	0.000	-0.535	0.000	-0.535	0.000	-0.535	0.000	-0.535	0.000	-0.5350
0.2450	-0.505	0.000	-0.505	0.000	-0.505	0.000	-0.505	0.000	-0.505	0.000	-0.505	0.000	-0.5050
0.2750	-0.475	0.000	-0.475	0.000	-0.475	0.000	-0.475	0.000	-0.475	0.000	-0.475	0.000	-0.4750
0.3050	-0.445	0.000	-0.445	0.000	-0.445	0.000	-0.445	0.000	-0.445	0.000	-0.445	0.000	-0.4450
0.3350	-0.415	0.000	-0.415	0.000	-0.415	0.000	-0.415	0.000	-0.415	0.000	-0.415	0.000	-0.4150
0.3650	-0.385	0.000	-0.385	0.000	-0.385	0.000	-0.385	0.000	-0.385	0.000	-0.385	0.000	-0.3850
0.3950	-0.355	0.000	-0.355	0.000	-0.355	0.000	-0.355	0.000	-0.355	0.000	-0.355	0.000	-0.3550
0.4250	-0.325	0.000	-0.325	0.000	-0.325	0.000	-0.325	0.000	-0.325	0.000	-0.325	0.000	-0.3250
0.4550	-0.295	0.000	-0.295	0.000	-0.295	0.000	-0.295	0.000	-0.295	0.000	-0.295	0.000	-0.2950
0.4850	-0.265	0.000	-0.265	0.000	-0.265	0.000	-0.265	0.000	-0.265	0.000	-0.265	0.000	-0.2650
0.5150	-0.235	0.000	-0.235	0.000	-0.235	0.000	-0.235	0.000	-0.235	0.000	-0.235	0.000	-0.2350
0.5450	-0.205	0.000	-0.205	0.000	-0.205	0.000	-0.205	0.000	-0.205	0.000	-0.205	0.000	-0.2050
0.5750	-0.175	0.000	-0.175	0.000	-0.175	0.000	-0.175	0.000	-0.175	0.000	-0.175	0.000	-0.1750
0.6050	-0.145	0.000	-0.145	0.000	-0.145	0.000	-0.145	0.000	-0.145	0.000	-0.145	0.000	-0.1450
0.6350	-0.115	0.000	-0.115	0.000	-0.115	0.000	-0.115	0.000	-0.115	0.000	-0.115	0.000	-0.1150
0.6650	-0.085	0.000	-0.085	0.000	-0.085	0.000	-0.085	0.000	-0.085	0.000	-0.085	0.000	

-0.0850												
0.6950	-0.055	0.000	-0.055	0.000	-0.055	0.000	-0.055	0.000	-0.055	0.000	-0.055	0.000
-0.0550												
0.7250	-0.025	0.000	-0.025	0.000	-0.025	0.000	-0.025	0.000	-0.025	0.000	-0.025	0.000
-0.0250												
0.7550	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.0000												

DEPTH (m)	MOISTURE CONTENT											
	1	2	3	4	5	6	7	8	9	10	11	12 13
0.0050	0.262	0.000	0.262	0.000	0.262	0.000	0.262	0.000	0.262	0.000	0.262	0.000
0.2621												
0.0350	0.270	0.000	0.270	0.000	0.270	0.000	0.270	0.000	0.270	0.000	0.270	0.000
0.2703												
0.0650	0.279	0.000	0.279	0.000	0.279	0.000	0.279	0.000	0.279	0.000	0.279	0.000
0.2788												
0.0950	0.288	0.000	0.288	0.000	0.288	0.000	0.288	0.000	0.288	0.000	0.288	0.000
0.2877												
0.1250	0.297	0.000	0.297	0.000	0.297	0.000	0.297	0.000	0.297	0.000	0.297	0.000
0.2969												
0.1550	0.306	0.000	0.306	0.000	0.306	0.000	0.306	0.000	0.306	0.000	0.306	0.000
0.3064												
0.1850	0.316	0.000	0.316	0.000	0.316	0.000	0.316	0.000	0.316	0.000	0.316	0.000
0.3161												
0.2150	0.326	0.000	0.326	0.000	0.326	0.000	0.326	0.000	0.326	0.000	0.326	0.000
0.3260												
0.2450	0.336	0.000	0.336	0.000	0.336	0.000	0.336	0.000	0.336	0.000	0.336	0.000
0.3360												
0.2750	0.346	0.000	0.346	0.000	0.346	0.000	0.346	0.000	0.346	0.000	0.346	0.000
0.3461												
0.3050	0.356	0.000	0.356	0.000	0.356	0.000	0.356	0.000	0.356	0.000	0.356	0.000
0.3560												
0.3350	0.366	0.000	0.366	0.000	0.366	0.000	0.366	0.000	0.366	0.000	0.366	0.000
0.3657												
0.3650	0.375	0.000	0.375	0.000	0.375	0.000	0.375	0.000	0.375	0.000	0.375	0.000
0.3751												
0.3950	0.384	0.000	0.384	0.000	0.384	0.000	0.384	0.000	0.384	0.000	0.384	0.000
0.3841												
0.4250	0.392	0.000	0.392	0.000	0.392	0.000	0.392	0.000	0.392	0.000	0.392	0.000
0.3924												
0.4550	0.400	0.000	0.400	0.000	0.400	0.000	0.400	0.000	0.400	0.000	0.400	0.000
0.4001												
0.4850	0.407	0.000	0.407	0.000	0.407	0.000	0.407	0.000	0.407	0.000	0.407	0.000
0.4069												
0.5150	0.413	0.000	0.413	0.000	0.413	0.000	0.413	0.000	0.413	0.000	0.413	0.000
0.4128												
0.5450	0.418	0.000	0.418	0.000	0.418	0.000	0.418	0.000	0.418	0.000	0.418	0.000
0.4179												
0.5750	0.422	0.000	0.422	0.000	0.422	0.000	0.422	0.000	0.422	0.000	0.422	0.000
0.4219												
0.6050	0.425	0.000	0.425	0.000	0.425	0.000	0.425	0.000	0.425	0.000	0.425	0.000
0.4251												
0.6350	0.427	0.000	0.427	0.000	0.427	0.000	0.427	0.000	0.427	0.000	0.427	0.000
0.4273												
0.6650	0.429	0.000	0.429	0.000	0.429	0.000	0.429	0.000	0.429	0.000	0.429	0.000
0.4288												
0.6950	0.430	0.000	0.430	0.000	0.430	0.000	0.430	0.000	0.430	0.000	0.430	0.000
0.4296												
0.7250	0.430	0.000	0.430	0.000	0.430	0.000	0.430	0.000	0.430	0.000	0.430	0.000

```
0.4300
0.7550   0.430   0.000   0.430   0.000   0.430   0.000   0.430   0.000   0.430   0.000   0.430   0.000
0.4300

   4 ITERATIONS FOR TIME STEP 250 IN STRESS PERIOD  1
MAXIMUM HEAD CHANGE FOR EACH ITERATION:
   HEAD CHANGE  LAYER,ROW,COL
 ------------------------------------------------------------------------------
     0.6559E-02 (  2,  8,  4)    0.1457E-02 (  4, 10,  4)    0.3407E-03 (  4,  9,  4)    0.3338E-04 (  4, 10,  2)
              HEAD IN LAYER  1 AT END OF TIME STEP250 IN STRESS PERIOD  1
     -----------------------------------------------

      1        2        3        4        5        6        7        8        9       10
      11       12       13
 ...............................................................................
  1  1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30
1.0000E+30
     1.0000E+30 1.0000E+30 1.0000E+30
  2  1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30
1.0000E+30
     1.0000E+30 1.0000E+30 1.0000E+30
  3  1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30
1.0000E+30
     1.0000E+30 1.0000E+30 1.0000E+30
  4  1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30
1.0000E+30
     1.0000E+30 1.0000E+30 1.0000E+30
  5  1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30
1.0000E+30
     1.0000E+30 1.0000E+30 1.0000E+30
  6  1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30
1.0000E+30
     1.0000E+30 1.0000E+30 1.0000E+30
  7  1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30
1.0000E+30
     1.0000E+30 1.0000E+30 1.0000E+30
  8  1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30
1.0000E+30
     1.0000E+30 1.0000E+30 1.0000E+30
  9  1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30
1.0000E+30
     1.0000E+30 1.0000E+30 1.0000E+30
 10  1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30
1.0000E+30 1.0000E+30
     1.0000E+30 1.0000E+30 1.0000E+30
 11  1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30
1.0000E+30 1.0000E+30
     1.0000E+30 1.0000E+30 1.0000E+30
              HEAD IN LAYER  2 AT END OF TIME STEP250 IN STRESS PERIOD  1
     -----------------------------------------------

      1        2        3        4        5        6        7        8        9       10
      11       12       13
 ...............................................................................
  1  19.47      19.45      19.40      1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30
1.0000E+30
     19.40      19.45      19.47
  2  19.55      19.53      19.48      1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30
1.0000E+30
     19.48      19.53      19.55
  3  19.55      19.53      19.48      1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30
1.0000E+30
```

```
     19.48     19.53     19.55
 4   19.55     19.53     19.48     1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30
1.0000E+30
     19.48     19.53     19.55
 5   19.55     19.53     19.48     1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30
1.0000E+30
     19.48     19.53     19.55
 6   19.55     19.53     19.48     1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30
1.0000E+30
     19.48     19.53     19.55
 7   19.56     19.54     19.49     1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30
1.0000E+30
     19.49     19.54     19.56
 8   19.57     19.55     19.51     19.34   1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30  19.34
     19.51     19.55     19.57
 9   19.62     19.61     19.59     19.52     19.47     19.46     19.46     19.46     19.47     19.52
     19.59     19.61     19.62
10   19.65     19.64     19.63     19.58     19.55     19.55     19.55     19.55     19.55     19.58
     19.63     19.64     19.65
11   19.66     19.65     19.64     19.61     19.59     19.58     19.58     19.58     19.59     19.61
     19.64     19.65     19.66
               HEAD IN LAYER  3 AT END OF TIME STEP250 IN STRESS PERIOD  1
     ------------------------------------------------------------------

       1         2         3       4       5       6       7       8       9      10
      11        12        13
.......................................................................................
 1   19.50     19.45     19.40     19.28     19.25     19.24     19.24     19.24     19.25     19.28
     19.40     19.45     19.50
 2   19.59     19.54     19.48     19.30     19.25     19.24     19.24     19.24     19.25     19.30
     19.48     19.54     19.59
 3   19.59     19.54     19.48     19.30     19.25     19.24     19.24     19.24     19.25     19.30
     19.48     19.54     19.59
 4   19.59     19.54     19.48     19.30     19.25     19.24     19.24     19.24     19.25     19.30
     19.48     19.54     19.59
 5   19.59     19.54     19.48     19.30     19.25     19.24     19.24     19.24     19.25     19.30
     19.48     19.54     19.59
 6   19.59     19.54     19.48     19.30     19.25     19.24     19.24     19.24     19.25     19.30
     19.48     19.54     19.59
 7   19.60     19.54     19.48     19.31     19.25     19.24     19.24     19.24     19.25     19.31
     19.48     19.54     19.60
 8   19.61     19.56     19.51     19.35     19.28     19.27     19.27     19.27     19.28     19.35
     19.51     19.56     19.61
 9   19.65     19.62     19.59     19.52     19.47     19.46     13.46     19.46     19.47     19.52
     19.59     19.62     19.65
10   19.67     19.65     19.63     19.59     19.56     19.55     19.55     19.55     19.56     19.59
     19.63     19.65     19.67
11   19.69     19.68     19.67     19.65     19.63     19.62     19.62     19.62     19.63     19.65
     19.67     19.68     19.69
               HEAD IN LAYER  4 AT END OF TIME STEP250 IN STRESS PERIOD  1
     ------------------------------------------------------------------

       1         2         3       4       5       6       7       8       9      10
      11        12        13
.......................................................................................
 1   19.41     19.40     19.38     19.29     19.25     19.25     19.25     19.25     19.25     19.29
     19.38     19.40     19.41
 2   19.48     19.47     19.44     19.32     19.26     19.25     19.25     19.25     19.25     19.32
     19.44     19.47     19.48
 3   19.48     19.47     19.44     19.32     19.26     19.25     19.25     19.25     19.26     19.32
     19.44     19.47     19.48
 4   19.48     19.47     19.44     19.32     19.26     19.25     19.25     19.25     19.26     19.32
```

	19.44	19.47	19.48							
5	19.48	19.47	19.44	19.32	19.26	19.25	19.25	19.25	19.26	19.32
	19.44	19.47	19.48							
6	19.48	19.47	19.44	19.32	19.26	19.25	19.25	19.25	19.26	19.32
	19.44	19.47	19.48							
7	19.49	19.48	19.44	19.33	19.26	19.25	19.25	19.25	19.26	19.33
	19.44	19.48	19.49							
8	19.52	19.51	19.48	19.37	19.30	19.29	19.29	19.29	19.30	19.37
	19.48	19.51	19.52							
9	19.58	19.58	19.56	19.51	19.46	19.44	19.44	19.44	19.46	19.51
	19.56	19.58	19.58							
10	19.61	19.60	19.59	19.55	19.51	19.50	19.50	19.50	19.51	19.55
	19.59	19.60	19.61							
11	19.61	19.61	19.60	19.57	19.53	19.52	19.52	19.52	19.53	19.57
	19.60	19.61	19.61							

DEPTH TO W. TABLE IN LAYER 1 AT END OF TIME STEP 250 IN STRESS PERIOD 1

	1	2	3	4	5	6	7	8	9	10	11	12	13
1	0.53	0.55	0.60	0.72	0.75	0.76	0.76	0.76	0.75	0.72	0.60	0.55	0.53
2	0.45	0.47	0.52	0.70	0.75	0.76	0.76	0.76	0.75	0.70	0.52	0.47	0.45
3	0.45	0.47	0.52	0.70	0.75	0.76	0.76	0.76	0.75	0.70	0.52	0.47	0.45
4	0.45	0.47	0.52	0.70	0.75	0.76	0.76	0.76	0.75	0.70	0.52	0.47	0.45
5	0.45	0.47	0.52	0.70	0.75	0.76	0.76	0.76	0.75	0.70	0.52	0.47	0.45
6	0.45	0.47	0.52	0.70	0.75	0.76	0.76	0.76	0.75	0.70	0.52	0.47	0.45
7	0.44	0.46	0.51	0.69	0.75	0.76	0.76	0.76	0.75	0.69	0.51	0.46	0.44
8	0.43	0.45	0.49	0.66	0.72	0.73	0.73	0.73	0.72	0.66	0.49	0.45	0.43
9	0.38	0.39	0.41	0.48	0.53	0.54	0.54	0.54	0.53	0.48	0.41	0.39	0.38
10	0.35	0.36	0.37	0.42	0.45	0.45	0.45	0.45	0.45	0.42	0.37	0.36	0.35
11	0.34	0.35	0.36	0.39	0.41	0.42	0.42	0.42	0.41	0.39	0.36	0.35	0.34

VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 250 IN STRESS PERIOD 1

CUMULATIVE VOLUMES L**3		RATES FOR THIS TIME STEP L**3/T	
IN:		IN:	
STORAGE =	1.2323	STORAGE =	10.658
CONSTANT HEAD =	0.00000	CONSTANT HEAD =	0.00000
HEAD DEP BOUNDS =	16.020	HEAD DEP BOUNDS =	24.460
UNSAT. PAST W.T. =	0.00000	UNSAT. PAST W.T. =	0.00000
TOTAL IN =	17.252	TOTAL IN =	35.118
OUT:		OUT:	
STORAGE =	13.358	STORAGE =	4.3910
CONSTANT HEAD =	0.00000	CONSTANT HEAD =	0.00000

HEAD DEP BOUNDS = 0.00000
UNSAT. PAST W.T. = 3.4800
TOTAL OUT = 16.838
IN - OUT = 0.41398
PERCENT DISCREPANCY = 2.43

HEAD DEP BOUNDS = 0.00000
UNSAT. PAST W.T. = 26.266
TOTAL OUT = 30.657
IN - OUT = 4.4611
PERCENT DISCREPANCY = 13.56

TIME SUMMARY AT END OF TIME STEP 250 IN STRESS PERIOD 1

	SECONDS	MINUTES	HOURS	DAYS	YEARS
TIME STEP LENGTH	2057.15	34.2859	0.571431	0.238096E-01	0.651872E-04
STRESS PERIOD TIME	43200.0	720.000	12.0000	0.500000	0.136893E-02
TOTAL SIMULATION TIME	43200.0	720.000	12.0000	0.500000	0.136893E-02

TOTAL ELAPSED TIME 0.5000
UNSAT. TIME INCREMENT 0.1190E-01 NODAL SPACING 0.1000E-01

DEPTH (m) PRESSURE HEAD (m)
DISTANCE (m)

DEPTH (m)	0.000	0.250	0.700	1.75	3.50	5.50	7.50	9.50	11.5	13.3	14.3	14.8	15.0
0.0050	-0.534	0.000	-0.620	0.000	-0.760	0.000	-0.762	0.000	-0.760	0.000	-0.620	0.000	-0.5336
0.0350	-0.504	0.000	-0.590	0.000	-0.730	0.000	-0.731	0.000	-0.730	0.000	-0.590	0.000	-0.5036
0.0650	-0.473	0.000	-0.559	0.000	-0.700	0.000	-0.701	0.000	-0.700	0.000	-0.559	0.000	-0.4734
0.0950	-0.443	0.000	-0.528	0.000	-0.669	0.000	-0.670	0.000	-0.669	0.000	-0.528	0.000	-0.4431
0.1250	-0.413	0.000	-0.497	0.000	-0.638	0.000	-0.639	0.000	-0.638	0.000	-0.497	0.000	-0.4127
0.1550	-0.382	0.000	-0.466	0.000	-0.607	0.000	-0.608	0.000	-0.607	0.000	-0.466	0.000	-0.3823
0.1850	-0.352	0.000	-0.435	0.000	-0.576	0.000	-0.577	0.000	-0.576	0.000	-0.435	0.000	-0.3518
0.2150	-0.321	0.000	-0.404	0.000	-0.545	0.000	-0.547	0.000	-0.545	0.000	-0.404	0.000	-0.3213
0.2450	-0.291	0.000	-0.373	0.000	-0.514	0.000	-0.516	0.000	-0.514	0.000	-0.373	0.000	-0.2907
0.2750	-0.260	0.000	-0.341	0.000	-0.484	0.000	-0.485	0.000	-0.484	0.000	-0.341	0.000	-0.2601
0.3050	-0.229	0.000	-0.310	0.000	-0.453	0.000	-0.455	0.000	-0.453	0.000	-0.310	0.000	-0.2295
0.3350	-0.199	0.000	-0.279	0.000	-0.422	0.000	-0.424	0.000	-0.422	0.000	-0.279	0.000	-0.1989
0.3650	-0.169	0.000	-0.248	0.000	-0.392	0.000	-0.393	0.000	-0.392	0.000	-0.248	0.000	-0.1687
0.3950	-0.139	0.000	-0.217	0.000	-0.361	0.000	-0.363	0.000	-0.361	0.000	-0.217	0.000	-0.1389
0.4250	-0.110	0.000	-0.187	0.000	-0.331	0.000	-0.333	0.000	-0.331	0.000	-0.187	0.000	-0.1098
0.4550	-0.081	0.000	-0.157	0.000	-0.301	0.000	-0.302	0.000	-0.301	0.000	-0.157	0.000	-0.0815
0.4850	-0.054	0.000	-0.129	0.000	-0.270	0.000	-0.272	0.000	-0.270	0.000	-0.129	0.000	-0.0539
0.5150	-0.027	0.000	-0.103	0.000	-0.240	0.000	-0.242	0.000	-0.240	0.000	-0.103	0.000	-0.0268

0.5450	0.000	0.000	-0.078	0.000	-0.210	0.000	-0.211	0.000	-0.210	0.000	-0.078	0.000	0.0000
0.5750	0.000	0.000	-0.056	0.000	-0.179	0.000	-0.181	0.000	-0.179	0.000	-0.056	0.000	0.0000
0.6050	0.000	0.000	0.000	0.000	-0.149	0.000	-0.150	0.000	-0.149	0.000	0.000	0.000	0.0000
0.6350	0.000	0.000	0.000	0.000	-0.118	0.000	-0.120	0.000	-0.118	0.000	0.000	0.000	0.0000
0.6650	0.000	0.000	0.000	0.000	-0.087	0.000	-0.089	0.000	-0.087	0.000	0.000	0.000	0.0000
0.6950	0.000	0.000	0.000	0.000	-0.056	0.000	-0.058	0.000	-0.056	0.000	0.000	0.000	0.0000
0.7250	0.000	0.000	0.000	0.000	-0.025	0.000	-0.026	0.000	-0.025	0.000	0.000	0.000	0.0000
0.7550	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0000

DEPTH (m)	MOISTURE CONTENT												
	1	2	3	4	5	6	7	8	9	10	11	12	13
0.0050	0.326	0.000	0.298	0.000	0.258	0.000	0.258	0.000	0.258	0.000	0.298	0.000	0.3265
0.0350	0.336	0.000	0.308	0.000	0.266	0.000	0.266	0.000	0.266	0.000	0.308	0.000	0.3365
0.0650	0.347	0.000	0.318	0.000	0.275	0.000	0.274	0.000	0.275	0.000	0.318	0.000	0.3466
0.0950	0.357	0.000	0.328	0.000	0.284	0.000	0.283	0.000	0.284	0.000	0.328	0.000	0.3566
0.1250	0.366	0.000	0.339	0.000	0.293	0.000	0.292	0.000	0.293	0.000	0.339	0.000	0.3665
0.1550	0.376	0.000	0.349	0.000	0.303	0.000	0.302	0.000	0.303	0.000	0.349	0.000	0.3760
0.1850	0.385	0.000	0.359	0.000	0.312	0.000	0.312	0.000	0.312	0.000	0.359	0.000	0.3850
0.2150	0.393	0.000	0.369	0.000	0.323	0.000	0.322	0.000	0.323	0.000	0.369	0.000	0.3934
0.2450	0.401	0.000	0.379	0.000	0.333	0.000	0.332	0.000	0.333	0.000	0.379	0.000	0.4011
0.2750	0.408	0.000	0.388	0.000	0.343	0.000	0.343	0.000	0.343	0.000	0.388	0.000	0.4079
0.3050	0.414	0.000	0.396	0.000	0.353	0.000	0.353	0.000	0.353	0.000	0.396	0.000	0.4138
0.3350	0.419	0.000	0.404	0.000	0.363	0.000	0.363	0.000	0.363	0.000	0.404	0.000	0.4188
0.3650	0.423	0.000	0.410	0.000	0.373	0.000	0.373	0.000	0.373	0.000	0.410	0.000	0.4227
0.3950	0.426	0.000	0.416	0.000	0.382	0.000	0.382	0.000	0.382	0.000	0.416	0.000	0.4256
0.4250	0.428	0.000	0.420	0.000	0.391	0.000	0.390	0.000	0.391	0.000	0.420	0.000	0.4276
0.4550	0.429	0.000	0.424	0.000	0.399	0.000	0.398	0.000	0.399	0.000	0.424	0.000	0.4289
0.4850	0.430	0.000	0.426	0.000	0.406	0.000	0.405	0.000	0.406	0.000	0.426	0.000	0.4296
0.5150	0.430	0.000	0.428	0.000	0.412	0.000	0.412	0.000	0.412	0.000	0.428	0.000	0.4299
0.5450	0.430	0.000	0.429	0.000	0.417	0.000	0.417	0.000	0.417	0.000	0.429	0.000	0.4300
0.5750	0.430	0.000	0.430	0.000	0.421	0.000	0.421	0.000	0.421	0.000	0.430	0.000	0.4300
0.6050	0.430	0.000	0.430	0.000	0.425	0.000	0.425	0.000	0.425	0.000	0.430	0.000	0.4300

0.6350	0.430	0.000	0.430	0.000	0.427	0.000	0.427	0.000	0.427	0.000	0.430	0.000	0.4300
0.6650	0.430	0.000	0.430	0.000	0.429	0.000	0.429	0.000	0.429	0.000	0.430	0.000	0.4300
0.6950	0.430	0.000	0.430	0.000	0.430	0.000	0.430	0.000	0.430	0.000	0.430	0.000	0.4300
0.7250	0.430	0.000	0.430	0.000	0.430	0.000	0.430	0.000	0.430	0.000	0.430	0.000	0.4300
0.7550	0.430	0.000	0.430	0.000	0.430	0.000	0.430	0.000	0.430	0.000	0.430	0.000	0.4300

DEPTH (m) TOTAL HEAD IN UNSAT. ZONE (m)

DEPTH (m)	1	2	3	4	5	6	7	8	9	10	11		
0.0050	19.461	0.000	19.375	0.000	19.235	0.000	19.233	0.000	19.235	0.000	19.375	0.000	19.4614
0.0350	19.461	0.000	19.375	0.000	19.235	0.000	19.234	0.000	19.235	0.000	19.375	0.000	19.4614
0.0650	19.462	0.000	19.376	0.000	19.235	0.000	19.234	0.000	19.235	0.000	19.376	0.000	19.4616
0.0950	19.462	0.000	19.377	0.000	19.236	0.000	19.235	0.000	19.236	0.000	19.377	0.000	19.4619
0.1250	19.462	0.000	19.378	0.000	19.237	0.000	19.236	0.000	19.237	0.000	19.378	0.000	19.4623
0.1550	19.463	0.000	19.379	0.000	19.238	0.000	19.237	0.000	19.238	0.000	19.379	0.000	19.4627
0.1850	19.463	0.000	19.380	0.000	19.239	0.000	19.238	0.000	19.239	0.000	19.380	0.000	19.4632
0.2150	19.464	0.000	19.381	0.000	19.240	0.000	19.238	0.000	19.240	0.000	19.381	0.000	19.4637
0.2450	19.464	0.000	19.382	0.000	19.241	0.000	19.239	0.000	19.241	0.000	19.382	0.000	19.4643
0.2750	19.465	0.000	19.384	0.000	19.241	0.000	19.240	0.000	19.241	0.000	19.384	0.000	19.4649
0.3050	19.466	0.000	19.385	0.000	19.242	0.000	19.240	0.000	19.242	0.000	19.385	0.000	19.4655
0.3350	19.466	0.000	19.386	0.000	19.243	0.000	19.241	0.000	19.243	0.000	19.386	0.000	19.4661
0.3650	19.466	0.000	19.387	0.000	19.243	0.000	19.242	0.000	19.243	0.000	19.387	0.000	19.4663
0.3950	19.466	0.000	19.388	0.000	19.244	0.000	19.242	0.000	19.244	0.000	19.388	0.000	19.4661
0.4250	19.465	0.000	19.388	0.000	19.244	0.000	19.242	0.000	19.244	0.000	19.388	0.000	19.4652
0.4550	19.464	0.000	19.388	0.000	19.244	0.000	19.243	0.000	19.244	0.000	19.388	0.000	19.4635
0.4850	19.461	0.000	19.386	0.000	19.245	0.000	19.243	0.000	19.245	0.000	19.386	0.000	19.4611
0.5150	19.458	0.000	19.382	0.000	19.245	0.000	19.243	0.000	19.245	0.000	19.382	0.000	19.4582
0.5450	0.000	0.000	19.377	0.000	19.245	0.000	19.244	0.000	19.245	0.000	19.377	0.000	0.0000
0.5750	0.000	0.000	19.369	0.000	19.246	0.000	19.244	0.000	19.246	0.000	19.369	0.000	0.0000
0.6050	0.000	0.000	0.000	0.000	19.246	0.000	19.245	0.000	19.246	0.000	0.000	0.000	0.0000
0.6350	0.000	0.000	0.000	0.000	19.247	0.000	19.245	0.000	19.247	0.000	0.000	0.000	0.0000
0.6650	0.000	0.000	0.000	0.000	19.248	0.000	19.246	0.000	19.248	0.000	0.000	0.000	0.0000
0.6950	0.000	0.000	0.000	0.000	19.249	0.000	19.247	0.000	19.249	0.000	0.000	0.000	0.0000

0.7250	0.000	0.000	0.000	0.000	19.250	0.000	19.249	0.000	19.250	0.000	0.000	0.000	0.0000
0.7550	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0000

AVE. PRESSURE IN ROOT ZONE (m)

-0.3313	-0.3550	-0.4140	-0.5257	-0.5557	-0.5564	-0.5572	-0.5564	-0.5557	-0.5257	-0.4140	-0.3550	-0.3313
-0.2467	-0.2682	-0.3225	-0.5015	-0.5552	-0.5562	-0.5572	-0.5562	-0.5552	-0.5015	-0.3225	-0.2682	-0.2467
-0.2467	-0.2681	-0.3225	-0.5016	-0.5547	-0.5559	-0.5572	-0.5559	-0.5547	-0.5016	-0.3225	-0.2681	-0.2467
-0.2467	-0.2681	-0.3225	-0 5016	-0.5547	-0.5559	-0.5571	-0.5559	-0.5547	-0.5016	-0.3225	-0.2681	-0.2467
-0.2467	-0.2681	-0.3225	-0.5016	-0.5547	-0.5559	-0.5571	-0.5559	-0.5547	-0.5016	-0.3225	-0.2681	-0.2467
-0.2473	-0.2686	-0.3217	-0.5010	-0.5545	-0.5557	-0.5569	-0.5557	-0.5545	-0.5010	-0.3217	-0.2686	-0.2473
-0.2480	-0.2690	-0.3209	-0.5004	-0.5543	-0.5555	-0.5567	-0.5555	-0.5543	-0.5004	-0.3209	-0.2690	-0.2480
-0.2310	-0.2496	-0.2971	-0.4690	-0.5275	-0.5306	-0.5319	-0.5306	-0.5275	-0.4690	-0.2971	-0.2496	-0.2310
-0.1797	-0.1908	-0.2192	-0.2880	-0.3409	-0.3536	-0.3552	-0.3536	-0.3409	-0.2880	-0.2192	-0.1908	-0.1797
-0.1565	-0.1629	-0.1790	-0.2192	-0.2494	-0.2561	-0.2569	-0.2561	-0.2494	-0.2192	-0.1790	-0.1629	-0.1565
-0.1473	-0.1505	-0.1606	-0.1898	-0.2119	-0.2168	-0.2173	-0.2168	-0.2119	-0.1898	-0.1606	-0.1505	-0.1473

AVE. MOISTURE CONTENT IN ROOT ZONE

0.3855	0.3791	0.3632	0.3293	0.3202	0.3200	0.3197	0.3200	0.3202	0.3293	0.3632	0.3791	0.3855
0.4041	0.3994	0.3876	0.3359	0.3203	0.3200	0.3197	0.3200	0.3203	0.3359	0.3876	0.3994	0.4041
0.4041	0.3994	0.3876	0.3359	0.3205	0.3201	0.3197	0.3201	0.3205	0.3359	0.3876	0.3994	0.4041
0.4041	0.3994	0.3876	0.3359	0.3205	0.3201	0.3197	0.3201	0.3205	0.3359	0.3876	0.3994	0.4041
0.4041	0.3994	0.3876	0.3359	0.3205	0.3201	0.3197	0.3201	0.3205	0.3359	0.3876	0.3994	0.4041
0.4040	0.3993	0.3878	0.3360	0.3206	0.3202	0.3198	0.3202	0.3206	0.3360	0.3878	0.3993	0.4040
0.4038	0.3993	0.3880	0.3362	0.3206	0.3202	0.3199	0.3202	0.3206	0.3362	0.3880	0.3993	0.4038
0.4066	0.4028	0.3929	0.3448	0.3285	0.3276	0.3272	0.3276	0.3285	0.3448	0.3929	0.4028	0.4066
0.4150	0.4133	0.4091	0.3943	0.3829	0.3797	0.3793	0.3797	0.3829	0.3943	0.4091	0.4133	0.4150
0.4180	0.4171	0.4149	0.4076	0.4022	0.4007	0.4006	0.4007	0.4022	0.4076	0.4149	0.4171	0.4180
0.4192	0.4188	0.4176	0.4133	0.4101	0.4092	0.4091	0.4092	0.4101	0.4133	0.4176	0.4188	0.4192

RATE OF FLOW FROM WATER TABLE FOR TIME PERIOD (M/DAY)
NEGATIVE UPWARD, POSITIVE DRAINAGE

-0.00474	-0.00462	-0.00434	-0.00235	-0.00182	-0.00161	-0.00141	-0.00161	-0.00182	-0.00235	-0.00434

-0.00462
-0.00474
-0.00476 -0.00458 -0.00414 -0.00257 -0.00196 -0.00168 -0.00141 -0.00168 -0.00196 -0.00257 -0.00414
-0.00458
-0.00476
-0.00476 -0.00458 -0.00414 -0.00257 -0.00210 -0.00175 -0.00141 -0.00175 -0.00210 -0.00257 -0.00414
-0.00458
-0.00476
-0.00476 -0.00458 -0.00414 -0.00257 -0.00210 -0.00175 -0.00141 -0.00175 -0.00210 -0.00257 -0.00414
-0.00458
-0.00476
-0.00476 -0.00458 -0.00414 -0.00257 -0.00210 -0.00175 -0.00141 -0.00175 -0.00210 -0.00257 -0.00414
-0.00458
-0.00476
-0.00467 -0.00453 -0.00416 -0.00263 -0.00217 -0.00182 -0.00147 -0.00182 -0.00217 -0.00263 -0.00416
-0.00453
-0.00467
-0.00459 -0.00447 -0.00418 -0.00268 -0.00223 -0.00188 -0.00153 -0.00188 -0.00223 -0.00268 -0.00418
-0.00447
-0.00459
-0.00448 -0.00439 -0.00417 -0.00292 -0.00251 -0.00225 -0.00195 -0.00225 -0.00251 -0.00292 -0.00417
-0.00439
-0.00448
-0.00415 -0.00415 -0.00415 -0.00430 -0.00442 -0.00487 -0.00492 -0.00487 -0.00442 -0.00430 -0.00415
-0.00415
-0.00415
-0.00462 -0.00449 -0.00412 -0.00446 -0.00473 -0.00471 -0.00471 -0.00471 -0.00473 -0.00446 -0.00412
-0.00449
-0.00462
-0.00481 -0.00464 -0.00410 -0.00453 -0.00485 -0.00465 -0.00463 -0.00465 -0.00485 -0.00453 -0.00410
-0.00464
-0.00481

ROOT EXTRACTION RATE(m/DAY) FOR STRESS PERIOD

-0.0049 -0.0049 -0.0049 -0.0049 -0.0049 -0.0049 -0.0049 -0.0049 -0.0049 -0.0049 -0.0049 -0.0049
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TOTAL INFILTRATION OF RAIN (m)

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WETNESS FACTOR +1 SAT. -1 DRY

0.26591 0.23138 0.14533 0.04717 0.02071 0.02035 0.01998 0.02035 0.02071 0.04717 0.14533 0.23138
0.26591
0.43102 0.38883 0.28196 0.08099 0.02101 0.02049 0.01998 0.02049 0.02101 0.08099 0.28196 0.38883
0.43102
0.43103 0.38885 0.28198 0.08098 0.02130 0.02064 0.01998 0.02064 0.02130 0.08098 0.28198 0.38885
0.43103
0.43103 0.38884 0.28197 0.08097 0.02130 0.02064 0.01998 0.02064 0.02130 0.08097 0.28197 0.38884
0.43103
0.43102 0.38883 0.28197 0.08096 0.02131 0.02065 0.01999 0.02065 0.02131 0.08096 0.28197 0.38883
0.43102
0.42961 0.38784 0.28334 0.08165 0.02143 0.02076 0.02009 0.02076 0.02143 0.08165 0.28334 0.38784
0.42961
0.42819 0.38685 0.28471 0.08233 0.02156 0.02088 0.02019 0.02088 0.02156 0.08233 0.28471 0.38685
0.42819
0.46725 0.42965 0.33343 0.12299 0.05057 0.04684 0.04592 0.04684 0.05057 0.12299 0.33343 0.42965
0.46725
0.58472 0.55908 0.49353 0.35730 0.25241 0.23141 0.22876 0.23141 0.25241 0.35730 0.49353 0.55908
0.58472
0.63832 0.62350 0.58643 0.50034 0.43538 0.42206 0.42051 0.42206 0.43538 0.50034 0.58643 0.62350
0.63832
0.65959 0.65227 0.62900 0.56150 0.51026 0.49900 0.49779 0.49900 0.51026 0.56150 0.62900 0.65227
0.65959

S U M M A R Y OF SOIL CROP SITUATION

TOTAL AREA (m2) 3041.52
PERCENT SEVERE MOISTURE STRESS 0.00
PERCENT LIGHT MOISTURE STRESS 0.00
PERCENT NO STRESS 85.06
PERCENT AERATION STRESS <7% 14.94

CURRENT ROOT DEPTH (m) 0.400

STRESS PERIOD NO. 6, LENGTH = 6.000000

NUMBER OF TIME STEPS = 2100

MULTIPLIER FOR DELT = 1.000

INITIAL TIME STEP SIZE = 0.2857143E-02

DRAIN MODE OF OPERATION IS SUBIRRIGAT

0REUSING HEAD-DEPENDENT BOUNDS FROM LAST STRESS PERIOD
2 ITERATIONS FOR TIME STEP2100 IN STRESS PERIOD 6
MAXIMUM HEAD CHANGE FOR EACH ITERATION:
HEAD CHANGE LAYER,ROW,COL

0.3775E-03 (2, 1, 2) -0.3784E-04 (2, 1, 2)
HEAD IN LAYER 1 AT END OF TIME STEP*** IN STRESS PERIOD 6

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      1         2         3         4         5         6         7         8         9        10
     11        12        13
.....................................................................................................
 1 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30
1.0000E+30
   1.0000E+30 1.0000E+30 1.0000E+30
 2 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30
1.0000E+30
   1.0000E+30 1.0000E+30 1.0000E+30
 3 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30
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   1.0000E+30 1.0000E+30 1.0000E+30
 4 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30
1.0000E+30
   1.0000E+30 1.0000E+30 1.0000E+30
 5 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30
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   1.0000E+30 1.0000E+30 1.0000E+30
 6 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30
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   1.0000E+30 1.0000E+30 1.0000E+30
 7 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30 1.0000E+30
1.0000E+30
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     1.0000E+30  1.0000E+30  1.0000E+30
  8  1.0000E+30  1.0000E+30  1.0000E+30  1.0000E+30  1.0000E+30  1.0000E+30  1.0000E+30  1.0000E+30  1.0000E+30
1.0000E+30
     1.0000E+30  1.0000E+30  1.0000E+30
  9  19.72      19.71      19.71      1.0000E+30  1.0000E+30  1.0000E+30  1.0000E+30  1.0000E+30  1.0000E+30
1.0000E+30
     19.71      19.71      19.72
 10  19.72      19.72      19.72      19.71      1.0000E+30  1.0000E+30  1.0000E+30  1.0000E+30  1.0000E+30  19.71
     19.72      19.72      19.72
 11  19.73      19.72      19.72      19.71      1.0000E+30  1.0000E+30  1.0000E+30  1.0000E+30  1.0000E+30  19.71
     19.72      19.72      19.73
               HEAD IN LAYER  2 AT END OF TIME STEP*** IN STRESS PERIOD  6
     ---------------------------------------------------------

       1        2        3        4        5        6        7        8        9        10
      11       12       13
.............................................................................................
  1  19.55      19.54      19.51      19.43      1.0000E+30  1.0000E+30  1.0000E+30  1.0000E+30  1.0000E+30  19.43
     19.51      19.54      19.55
  2  19.63      19.62      19.59      19.51      19.39      1.0000E+30  1.0000E+30  1.0000E+30  19.39      19.51
     19.59      19.62      19.63
  3  19.63      19.62      19.59      19.51      19.39      1.0000E+30  1.0000E+30  1.0000E+30  19.39      19.51
     19.59      19.62      19.63
  4  19.63      19.62      19.59      19.51      19.39      1.0000E+30  1.0000E+30  1.0000E+30  19.39      19.51
     19.59      19.62      19.63
  5  19.64      19.62      19.60      19.52      19.41      19.31      1.0000E+30  19.31      19.41      19.52
     19.60      19.63      19.64
  6  19.65      19.64      19.61      19.55      19.45      19.38      19.35      19.38      19.45      19.55
     19.61      19.64      19.65
  7  19.67      19.67      19.65      19.60      19.54      19.50      19.48      19.50      19.54      19.60
     19.65      19.67      19.67
  8  19.70      19.69      19.68      19.66      19.62      19.59      19.59      19.59      19.62      19.66
     19.68      19.69      19.70
  9  19.72      19.71      19.71      19.69      19.67      19.66      19.65      19.66      19.67      19.69
     19.71      19.71      19.72
 10  19.72      19.72      19.72      19.71      19.69      19.68      19.68      19.68      19.69      19.71
     19.72      19.72      19.72
 11  19.73      19.72      19.72      19.71      19.70      19.69      19.69      19.69      19.70      19.71
     19.72      19.72      19.73
               HEAD IN LAYER  3 AT END OF TIME STEP*** IN STRESS PERIOD  6
     ---------------------------------------------------------

       1        2        3        4        5        6        7        8        9        10
      11       12       13
.............................................................................................
  1  19.58      19.55      19.51      19.43      19.29      19.18      19.14      19.18      19.29      19.43
     19.51      19.55      19.58
  2  19.66      19.63      19.59      19.51      19.39      19.28      19.24      19.28      19.39      19.51
     19.59      19.63      19.66
  3  19.66      19.63      19.59      19.51      19.39      19.28      19.24      19.28      19.39      19.51
     19.59      19.63      19.66
  4  19.66      19.63      19.59      19.51      19.39      19.28      19.24      19.28      19.39      19.51
     19.59      19.63      19.66
  5  19.66      19.63      19.60      19.52      19.41      19.31      19.27      19.31      19.41      19.52
     19.60      19.63      19.66
  6  19.67      19.64      19.61      19.55      19.45      19.38      19.36      19.38      19.45      19.55
     19.61      19.64      19.67
  7  19.69      19.67      19.65      19.60      19.54      19.50      19.48      19.50      19.54      19.60
     19.65      19.67      19.69
  8  19.71      19.70      19.68      19.66      19.62      19.59      19.59      19.59      19.62      19.66
     19.68      19.70      19.71
  9  19.72      19.72      19.71      19.69      19.67      19.66      19.65      19.66      19.67      19.69
```

	1	2	3	4	5	6	7	8	9	10	11	12	13
											19.71	19.72	19.72
10	19.73	19.72	19.72	19.71	19.69	19.68	19.68	19.68	19.69	19.71	19.72	19.72	19.73
11	19.73	19.73	19.73	19.72	19.71	19.71	19.71	19.71	19.71	19.72	19.73	19.73	19.73

HEAD IN LAYER 4 AT END OF TIME STEP*** IN STRESS PERIOD 6

	1	2	3	4	5	6	7	8	9	10	11	12	13
1	19.52	19.51	19.49	19.43	19.30	19.19	19.15	19.19	19.30	19.43	19.49	19.51	19.52
2	19.60	19.59	19.57	19.51	19.39	19.29	19.25	19.29	19.39	19.51	19.57	19.59	19.60
3	19.60	19.59	19.57	19.51	19.39	19.29	19.25	19.29	19.39	19.51	19.57	19.59	19.60
4	19.60	19.59	19.57	19.51	19.39	19.29	19.25	19.29	19.39	19.51	19.57	19.59	19.60
5	19.60	19.60	19.58	19.52	19.41	19.31	19.28	19.31	19.41	19.52	19.58	19.60	19.60
6	19.62	19.61	19.60	19.54	19.45	19.39	19.36	19.39	19.45	19.54	19.60	19.61	19.62
7	19.65	19.65	19.64	19.60	19.54	19.50	19.49	19.50	19.54	19.60	19.64	19.65	19.65
8	19.68	19.68	19.68	19.65	19.62	19.59	19.58	19.59	19.62	19.65	19.68	19.68	19.69
9	19.71	19.70	19.70	19.69	19.66	19.65	19.64	19.65	19.66	19.69	19.70	19.70	19.71
10	19.71	19.71	19.71	19.70	19.68	19.67	19.66	19.67	19.68	19.70	19.71	19.71	19.71
11	19.71	19.71	19.71	19.70	19.68	19.67	19.67	19.67	19.68	19.70	19.71	19.71	19.71

DEPTH TO W. TABLE IN LAYER 1 AT END OF TIME STEP*** IN STRESS PERIOD 6

	1	2	3	4	5	6	7	8	9	10	11	12	13
1	0.45	0.46	0.49	0.57	0.71	0.82	0.86	0.82	0.71	0.57	0.49	0.46	0.45
2	0.37	0.38	0.41	0.49	0.61	0.72	0.76	0.72	0.61	0.49	0.41	0.38	0.37
3	0.37	0.38	0.41	0.49	0.61	0.72	0.76	0.72	0.61	0.49	0.41	0.38	0.37
4	0.37	0.38	0.41	0.49	0.61	0.72	0.76	0.72	0.61	0.49	0.41	0.38	0.37
5	0.36	0.38	0.40	0.48	0.59	0.69	0.73	0.69	0.59	0.48	0.40	0.37	0.36
6	0.35	0.36	0.39	0.45	0.55	0.62	0.65	0.62	0.55	0.45	0.39	0.36	0.35
7	0.33	0.33	0.35	0.40	0.46	0.50	0.52	0.50	0.46	0.40	0.35	0.33	0.33
8	0.30	0.31	0.32	0.34	0.38	0.41	0.41	0.41	0.38	0.34	0.32	0.31	0.30
9	0.28	0.29	0.29	0.31	0.33	0.34	0.35	0.34	0.33	0.31	0.29	0.29	0.28
10	0.28	0.28	0.28	0.29	0.31	0.32	0.32	0.32	0.31	0.29	0.28	0.28	0.28
11	0.27	0.28	0.28	0.29	0.30	0.31	0.31	0.31	0.30	0.29	0.28	0.28	0.27

VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP*** IN STRESS PERIOD 6

CUMULATIVE VOLUMES L**3

IN:

STORAGE = 102.66
CONSTANT HEAD = 0.00000
HEAD DEP BOUNDS = 338.09

RATES FOR THIS TIME STEP L**3/T

IN:

STORAGE = 0.79559E-02
CONSTANT HEAD = 0.00000
HEAD DEP BOUNDS = 14.489

UNSAT. PAST W.T. = 0.76997E-01	UNSAT. PAST W.T. = 0.00000
TOTAL IN = 440.83	TOTAL IN = 14.497
OUT:	OUT:
—	—
STORAGE = 134.61	STORAGE = 7.1775
CONSTANT HEAD = 0.00000	CONSTANT HEAD = 0.00000
HEAD DEP BOUNDS = 0.00000	HEAD DEP BOUNDS = 0.00000
UNSAT. PAST W.T. = 303.98	UNSAT. PAST W.T. = 7.2521
TOTAL OUT = 438.59	TOTAL OUT = 14.430
IN - OUT = 2.2391	IN - OUT = 0.67059E-01
PERCENT DISCREPANCY = 0.51	PERCENT DISCREPANCY = 0.46

TIME SUMMARY AT END OF TIME STEP*** IN STRESS PERIOD 6

	SECONDS	MINUTES	HOURS	DAYS	YEARS
TIME STEP LENGTH	246.857	4.11429	0.685714E-01	0.285714E-02	0.782243E-05
STRESS PERIOD TIME	518406.	8640.11	144.002	6.00008	0.164273E-01
TOTAL SIMULATION TIME	0.181447E+07	30241.1	504.019	21.0008	0.574970E-01

TOTAL ELAPSED TIME 21.0008
UNSAT. TIME INCREMENT 0.2857E-02 NODAL SPACING 0.1000E-01

D E P T H (m) P R E S S U R E H E A D (m)

DEPTH (m) \ DISTANCE (m)	0.000	0.250	0.700	1.75	3.50	5.50	7.50	9.50	11.5	13.3	14.3	14.8	15.0
0.0050	-0.441	0.000	-0.484	0.000	-0.706	0.000	-0.859	0.000	-0.706	0.000	-0.484	0.000	-0.4408
0.0450	-0.401	0.000	-0.444	0.000	-0.666	0.000	-0.819	0.000	-0.666	0.000	-0.444	0.000	-0.4008
0.0850	-0.361	0.000	-0.404	0.000	-0.625	0.000	-0.778	0.000	-0.625	0.000	-0.404	0.000	-0.3608
0.1250	-0.321	0.000	-0.364	0.000	-0.585	0.000	-0.738	0.000	-0.585	0.000	-0.364	0.000	-0.3207
0.1650	-0.281	0.000	-0.324	0.000	-0.545	0.000	-0.698	0.000	-0.545	0.000	-0.324	0.000	-0.2807
0.2050	-0.241	0.000	-0.284	0.000	-0.505	0.000	-0.658	0.000	-0.505	0.000	-0.284	0.000	-0.2406
0.2450	-0.201	0.000	-0.244	0.000	-0.465	0.000	-0.618	0.000	-0.465	0.000	-0.244	0.000	-0.2006
0.2850	-0.160	0.000	-0.204	0.000	-0.425	0.000	-0.578	0.000	-0.425	0.000	-0.204	0.000	-0.1605
0.3250	-0.120	0.000	-0.163	0.000	-0.385	0.000	-0.537	0.000	-0.385	0.000	-0.163	0.000	-0.1205
0.3650	-0.080	0.000	-0.123	0.000	-0.345	0.000	-0.497	0.000	-0.345	0.000	-0.123	0.000	-0.0801
0.4050	-0.063	0.000	-0.083	0.000	-0.305	0.000	-0.457	0.000	-0.305	0.000	-0.083	0.000	-0.0633
0.4450	0.000	0.000	-0.045	0.000	-0.264	0.000	-0.417	0.000	-0.264	0.000	-0.045	0.000	0.0000
0.4850	0.000	0.000	0.000	0.000	-0.224	0.000	-0.377	0.000	-0.224	0.000	0.000	0.000	0.0000
0.5250	0.000	0.000	0.000	0.000	-0.184	0.000	-0.337	0.000	-0.184	0.000	0.000	0.000	0.0000
0.5650	0.000	0.000	0.000	0.000	-0.144	0.000	-0.297	0.000	-0.144	0.000	0.000	0.000	0.0000

0.6050	0.000	0.000	0.000	0.000	-0.104	0.000	-0.257	0.000	-0.104	0.000	0.000	0.000	0.0000
0.6450	0.000	0.000	0.000	0.000	-0.064	0.000	-0.216	0.000	-0.064	0.000	0.000	0.000	0.0000
0.6850	0.000	0.000	0.000	0.000	-0.024	0.000	-0.176	0.000	-0.024	0.000	0.000	0.000	0.0000
0.7250	0.000	0.000	0.000	0.000	0.000	0.000	-0.136	0.000	0.000	0.000	0.000	0.000	0.0000
0.7650	0.000	0.000	0.000	0.000	0.000	0.000	-0.096	0.000	0.000	0.000	0.000	0.000	0.0000
0.8050	0.000	0.000	0.000	0.000	0.000	0.000	-0.056	0.000	0.000	0.000	0.000	0.000	0.0000
0.8450	0.000	0.000	0.000	0.000	0.000	0.000	-0.016	0.000	0.000	0.000	0.000	0.000	0.0000

DEPTH (m)	MOISTURE CONTENT 1	2	3	4	5	6	7	8	9	10	11	12	13
0.0050	0.357	0.000	0.343	0.000	0.273	0.000	0.234	0.000	0.273	0.000	0.343	0.000	0.3574
0.0450	0.370	0.000	0.356	0.000	0.285	0.000	0.244	0.000	0.285	0.000	0.356	0.000	0.3702
0.0850	0.382	0.000	0.369	0.000	0.297	0.000	0.253	0.000	0.297	0.000	0.369	0.000	0.3824
0.1250	0.394	0.000	0.381	0.000	0.309	0.000	0.264	0.000	0.309	0.000	0.381	0.000	0.3936
0.1650	0.403	0.000	0.393	0.000	0.323	0.000	0.275	0.000	0.323	0.000	0.393	0.000	0.4034
0.2050	0.412	0.000	0.403	0.000	0.336	0.000	0.287	0.000	0.336	0.000	0.403	0.000	0.4118
0.2450	0.419	0.000	0.411	0.000	0.349	0.000	0.299	0.000	0.349	0.000	0.411	0.000	0.4185
0.2850	0.424	0.000	0.418	0.000	0.363	0.000	0.312	0.000	0.363	0.000	0.418	0.000	0.4236
0.3250	0.427	0.000	0.423	0.000	0.375	0.000	0.325	0.000	0.375	0.000	0.423	0.000	0.4270
0.3650	0.429	0.000	0.427	0.000	0.387	0.000	0.339	0.000	0.387	0.000	0.427	0.000	0.4290
0.4050	0.429	0.000	0.429	0.000	0.398	0.000	0.352	0.000	0.398	0.000	0.429	0.000	0.4295
0.4450	0.430	0.000	0.430	0.000	0.407	0.000	0.365	0.000	0.407	0.000	0.430	0.000	0.4300
0.4850	0.430	0.000	0.430	0.000	0.415	0.000	0.378	0.000	0.415	0.000	0.430	0.000	0.4300
0.5250	0.430	0.000	0.430	0.000	0.421	0.000	0.389	0.000	0.421	0.000	0.430	0.000	0.4300
0.5650	0.430	0.000	0.430	0.000	0.425	0.000	0.400	0.000	0.425	0.000	0.430	0.000	0.4300
0.6050	0.430	0.000	0.430	0.000	0.428	0.000	0.409	0.000	0.428	0.000	0.430	0.000	0.4300
0.6450	0.430	0.000	0.430	0.000	0.429	0.000	0.416	0.000	0.429	0.000	0.430	0.000	0.4300
0.6850	0.430	0.000	0.430	0.000	0.430	0.000	0.422	0.000	0.430	0.000	0.430	0.000	0.4300
0.7250	0.430	0.000	0.430	0.000	0.430	0.000	0.426	0.000	0.430	0.000	0.430	0.000	0.4300
0.7650	0.430	0.000	0.430	0.000	0.430	0.000	0.428	0.000	0.430	0.000	0.430	0.000	0.4300
0.8050	0.430	0.000	0.430	0.000	0.430	0.000	0.430	0.000	0.430	0.000	0.430	0.000	0.4300
0.8450	0.430	0.000	0.430	0.000	0.430	0.000	0.430	0.000	0.430	0.000	0.430	0.000	0.4300

DEPTH (m) TOTAL HEAD IN UNSAT. ZONE (m)

DEPTH (m)	1	2	3	4	5	6	7	8	9	10	11	12	13
0.0050	19.554	0.000	19.511	0.000	19.289	0.000	19.136	0.000	19.289	0.000	19.511	0.000	19.5542
0.0450	19.554	0.000	19.511	0.000	19.289	0.000	19.136	0.000	19.289	0.000	19.511	0.000	19.5542
0.0850	19.554	0.000	19.511	0.000	19.290	0.000	19.137	0.000	19.290	0.000	19.511	0.000	19.5542
0.1250	19.554	0.000	19.511	0.000	19.290	0.000	19.137	0.000	19.290	0.000	19.511	0.000	19.5543
0.1650	19.554	0.000	19.511	0.000	19.290	0.000	19.137	0.000	19.290	0.000	19.511	0.000	19.5543
0.2050	19.554	0.000	19.511	0.000	19.290	0.000	19.137	0.000	19.290	0.000	19.511	0.000	19.5544
0.2450	19.554	0.000	19.511	0.000	19.290	0.000	19.137	0.000	19.290	0.000	19.511	0.000	19.5544
0.2850	19.555	0.000	19.511	0.000	19.290	0.000	19.137	0.000	19.290	0.000	19.511	0.000	19.5545
0.3250	19.555	0.000	19.512	0.000	19.290	0.000	19.138	0.000	19.290	0.000	19.512	0.000	19.5545
0.3650	19.555	0.000	19.512	0.000	19.290	0.000	19.138	0.000	19.290	0.000	19.512	0.000	19.5549
0.4050	19.532	0.000	19.512	0.000	19.290	0.000	19.138	0.000	19.290	0.000	19.512	0.000	19.5317
0.4450	0.000	0.000	19.510	0.000	19.291	0.000	19.138	0.000	19.291	0.000	19.510	0.000	0.0000
0.4850	0.000	0.000	0.000	0.000	19.291	0.000	19.138	0.000	19.291	0.000	0.000	0.000	0.0000
0.5250	0.000	0.000	0.000	0.000	19.291	0.000	19.138	0.000	19.291	0.000	0.000	0.000	0.0000
0.5650	0.000	0.000	0.000	0.000	19.291	0.000	19.138	0.000	19.291	0.000	0.000	0.000	0.0000
0.6050	0.000	0.000	0.000	0.000	19.291	0.000	19.138	0.000	19.291	0.000	0.000	0.000	0.0000
0.6450	0.000	0.000	0.000	0.000	19.291	0.000	19.139	0.000	19.291	0.000	0.000	0.000	0.0000
0.6850	0.000	0.000	0.000	0.000	19.291	0.000	19.139	0.000	19.291	0.000	0.000	0.000	0.0000
0.7250	0.000	0.000	0.000	0.000	0.000	0.000	19.139	0.000	0.000	0.000	0.000	0.000	0.0000
0.7650	0.000	0.000	0.000	0.000	0.000	0.000	19.139	0.000	0.000	0.000	0.000	0.000	0.0000
0.8050	0.000	0.000	0.000	0.000	0.000	0.000	19.139	0.000	0.000	0.000	0.000	0.000	0.0000
0.8450	0.000	0.000	0.000	0.000	0.000	0.000	19.137	0.000	0.000	0.000	0.000	0.000	0.0000

AVE. PRESSURE IN ROOT ZONE (m)

-0.2416	-0.2534	-0.2837	-0.3631	-0.5051	-0.6144	-0.6580	-0.6144	-0.5051	-0.3631	-0.2837	-0.2534	-0.2416
-0.1678	-0.1779	-0.2053	-0.2840	-0.4051	-0.5189	-0.5602	-0.5189	-0.4051	-0.2840	-0.2053	-0.1779	-0.1678
-0.1678	-0.1779	-0.2053	-0.2839	-0.4050	-0.5188	-0.5601	-0.5188	-0.4050	-0.2839	-0.2053	-0.1779	-0.1678
-0.1656	-0.1754	-0.2048	-0.2831	-0.4036	-0.5168	-0.5578	-0.5168	-0.4036	-0.2831	-0.2048	-0.1775	-0.1655
-0.1634	-0.1729	-0.1984	-0.2729	-0.3870	-0.4909	-0.5264	-0.4909	-0.3870	-0.2729	-0.1984	-0.1728	-0.1633
-0.1539	-0.1620	-0.1841	-0.2486	-0.3456	-0.4159	-0.4419	-0.4158	-0.3455	-0.2486	-0.1843	-0.1624	

-0.1543												
-0.1309	-0.1362	-0.1507	-0.1947	-0.2603	-0.3003	-0.3128	-0.3000	-0.2597	-0.1949	-0.1515	-0.1377	-0.1326
-0.1116	-0.1147	-0.1231	-0.1469	-0.1813	-0.2044	-0.2118	-0.2043	-0.1813	-0.1471	-0.1235	-0.1154	-0.1124
-0.0989	-0.1005	-0.1050	-0.1164	-0.1327	-0.1437	-0.1473	-0.1437	-0.1325	-0.1165	-0.1051	-0.1008	-0.0992
-0.0933	-0.0951	-0.0977	-0.1052	-0.1159	-0.1242	-0.1269	-0.1242	-0.1159	-0.1052	-0.0977	-0.0954	-0.0939
-0.0913	-0.0930	-0.0948	-0.1007	-0.1091	-0.1162	-0.1185	-0.1162	-0.1090	-0.1006	-0.0947	-0.0933	-0.0920

AVE. MOISTURE CONTENT IN ROOT ZONE

0.4051	0.4027	0.3966	0.3748	0.3359	0.3024	0.2891	0.3024	0.3359	0.3748	0.3966	0.4027	0.4051
0.4166	0.4151	0.4111	0.3933	0.3659	0.3313	0.3188	0.3313	0.3659	0.3933	0.4111	0.4151	0.4166
0.4166	0.4151	0.4111	0.3933	0.3660	0.3313	0.3188	0.3313	0.3660	0.3933	0.4111	0.4151	0.4166
0.4169	0.4154	0.4112	0.3935	0.3664	0.3320	0.3195	0.3320	0.3664	0.3935	0.4112	0.4152	0.4169
0.4171	0.4158	0.4121	0.3959	0.3710	0.3399	0.3293	0.3399	0.3710	0.3959	0.4121	0.4158	0.4171
0.4183	0.4171	0.4141	0.4008	0.3809	0.3607	0.3533	0.3607	0.3810	0.4008	0.4141	0.4172	0.4183
0.4210	0.4204	0.4186	0.4117	0.4014	0.3928	0.3901	0.3928	0.4015	0.4118	0.4187	0.4204	0.4210
0.4232	0.4228	0.4219	0.4184	0.4135	0.4092	0.4078	0.4092	0.4135	0.4185	0.4219	0.4228	0.4232
0.4246	0.4244	0.4240	0.4227	0.4210	0.4196	0.4191	0.4196	0.4210	0.4227	0.4240	0.4244	0.4246
0.4250	0.4249	0.4247	0.4239	0.4227	0.4219	0.4216	0.4219	0.4228	0.4239	0.4247	0.4249	0.4250
0.4252	0.4251	0.4249	0.4243	0.4235	0.4228	0.4226	0.4228	0.4235	0.4243	0.4250	0.4251	0.4252

RATE OF FLOW FROM WATER TABLE FOR TIME PERIOD (M/DAY)
NEGATIVE UPWARD, POSITIVE DRAINAGE

-0.00508	-0.00502	-0.00486	-0.00480	-0.00469	-0.00455	-0.00450	-0.00455	-0.00469	-0.00480	-0.00486	-0.00502	-0.00508
-0.00513	-0.00513	-0.00512	-0.00503	-0.00488	-0.00496	-0.00499	-0.00496	-0.00488	-0.00503	-0.00512	-0.00513	-0.00513
-0.00513	-0.00513	-0.00512	-0.00503	-0.00488	-0.00496	-0.00499	-0.00496	-0.00488	-0.00503	-0.00512	-0.00513	-0.00513
-0.00513	-0.00513	-0.00512	-0.00503	-0.00488	-0.00497	-0.00500	-0.00497	-0.00488	-0.00503	-0.00512	-0.00513	-0.00513
-0.00513	-0.00513	-0.00513	-0.00506	-0.00495	-0.00499	-0.00501	-0.00499	-0.00495	-0.00506	-0.00513	-0.00513	-0.00513
-0.00514	-0.00513	-0.00513	-0.00505	-0.00494	-0.00491	-0.00491	-0.00491	-0.00494	-0.00505	-0.00513	-0.00513	-0.00514
-0.00514	-0.00514	-0.00513	-0.00505	-0.00492	-0.00479	-0.00475	-0.00479	-0.00491	-0.00504	-0.00513	-0.00514	

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ROOT EXTRACTION RATE(m/DAY) FOR STRESS PERIOD

-0.0051 -0.0051 -0.0051 -0.0051 -0.0051 -0.0051 -0.0051 -0.0051 -0.0051 -0.0051 -0.0051 -0.0051
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TOTAL INFILTRATION OF RAIN (m)

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WETNESS FACTOR +1 SAT. -1 DRY

0.44215	0.41730	0.35337	0.24444	0.04985	0.01213	-0.00289	0.01213	0.04985	0.24444	0.35337	0.41730	0.44215
0.61230	0.58888	0.52551	0.37878	0.15289	0.05332	0.01722	0.05332	0.15289	0.37878	0.52551	0.58888	0.61230
0.61235	0.58894	0.52558	0.37886	0.15296	0.05335	0.01723	0.05335	0.15296	0.37886	0.52558	0.58894	0.61235
0.61734	0.59472	0.52680	0.38030	0.15488	0.05467	0.01847	0.05468	0.15490	0.38030	0.52682	0.58986	0.61750
0.62233	0.60050	0.54150	0.39771	0.17747	0.07146	0.03524	0.07145	0.17748	0.39767	0.54158	0.60078	0.62266
0.64446	0.62559	0.57457	0.44556	0.25065	0.17026	0.13903	0.17044	0.25105	0.44537	0.57410	0.62481	0.64355
0.69749	0.68516	0.65167	0.55142	0.40165	0.32242	0.29770	0.32303	0.40285	0.55083	0.64987	0.68185	0.69361
0.74214	0.73496	0.71556	0.66103	0.58215	0.53392	0.51853	0.53416	0.58224	0.66060	0.71473	0.73330	0.74018
0.77144	0.76778	0.75735	0.73110	0.69451	0.66804	0.65960	0.66800	0.69388	0.73072	0.75711	0.76717	0.77071
0.78441	0.78022	0.77426	0.75687	0.73224	0.71295	0.70680	0.71301	0.73220	0.75689	0.77429	0.77955	0.78309
0.78900	0.78502	0.78104	0.76731	0.74782	0.73145	0.72625	0.73157	0.74802	0.76748	0.78118	0.78432	0.78747

S U M M A R Y OF SOIL CROP SITUATION

TOTAL AREA (m2) 3041.52
PERCENT SEVERE MOISTURE STRESS 0.00
PERCENT LIGHT MOISTURE STRESS 0.00
PERCENT NO STRESS 44.39
PERCENT AERATION STRESS <7% 55.61

CURRENT ROOT DEPTH (m) 0.400

Appendix C. Field Observations

Subirrigation Plots 5&6

		Observed water table depths					Observed moisture contents @15cm		
		distance from drain					distance from drain		
		0.15	7.5	15	22.5	30	0.15	15	30
July 2	6N	0.714	0.621	0.554	0.687	0.625			
	6S	0.672	0.705	0.563	0.646	0.595			
	5N	0.667	0.659	0.663	0.64	0.672			
	5S	0.755	0.77	0.765	0.706	0.684			
July 9	6N	0.75	0.865	0.584	0.716	0.643	35.5	35.3	34.3
	6S	0.708	0.731	0.581	0.665	0.606	35.5	40.4	37.6
	5N	0.718	0.707	0.705	0.67	0.658	35	35.2	38.4
	5S	0.826	0.84	0.823	0.746	[illegible]33	33.9	33.2	34.8
July 13	6N		0.81	0.74	0.83		29	33.3	29.7
	6S	1.01	1.02	0.67	0.67	0.55	28.4	36	
	5N	0.85	0.86	0.85	0.83	0.76	26.2	27.6	32
	5S	0.95	0.99	0.98	0.92	0.87	18.4	29.4	30
July 15	6N	0.33	0.73	0.637	0.71	0.413	28.9	30.4	29.7
	6S	0.805	0.843	0.62	0.664	0.668		33.9	29.5
	5N	0.889	0.895	0.868	0.82	0.716	26.6	26.2	31.7
	5S	0.99	1.035	1.025	0.93	0.849	18.5	29.7	28.9
July 20	6N	1.14	0.96	0.98	1.17	1.05			
	6S	1.44	0.97	1.04	0.96	1.17			
	5N	0.95	1.02	0.93	1.14	1.21			
	5S	1.06	1.13	1.18	1.11	1.24			
July 23	6N	0.535	0.815	0.713	0.795	0.598	27	31.1	28.5
	6S	0.885	0.885	0.69	0.805	0.708	21.1	33.2	29.7
	5N	0.984	0.977	0.88	0.89	0.792	22.8	24	31.8
	5S	1.028	1.125	1.115	1.002	0.866	17.5	24.6	27.5
July 27	6N	0.65	0.895	0.797	0.872	0.66	26.2	30.8	26.2
	6S	0.95	0.885	0.7	0.877	0.785	26.2	33.2	28.8
	5N	1.03	1.021	0.86	0.95	0.85	22.7	23.9	30
	5S	0.87	1.168	1.16	1.058	0.95	17.5	28.2	26
July 29	6N	0.708	0.943	0.845	0.92	0.83	25.7		25
	6S	0.99	0.89	0.66	0.928	0.835			26.9
	5N	1.062	1.026	0.862	0.991	0.894			
	5S	1.069	1.197	1.186	1.08	0.975			
Aug 4	6N	0.85	0.89	0.79	0.87	0.63	25.1		27.2
	6S	0.97	0.88	0.7	0.87	0.75			26.9
	5N	1.08	1.03	0.86	0.97	0.82			
	5S	1.08	1.19	1.22	1.09	0.96			
Aug 6	6N	0.85	0.91	0.81	0.9	0.73	26.3	30.9	27.9
	6S	0.98	0.88	0.71	0.89	0.79	24.3	33.3	26.4
	5N	1.07	1.03	0.87	0.97	0.86	20.5	23.5	29
	5S	1.08	1.19	1.22	1.09	0.97	16.8	28.7	27.2
Aug 10	6N	0.59	1.03	0.93	1.01	0.7	24.7	28	24.3
	6S	1.07	0.88	0.7	0.98	0.9	23.3	31.2	24.1
	5N	1.11	1.03	0.89	1.06	0.95	17.8	19.8	24.1
	5S	1.08	1.2	1.22	1.13	1.02	12.7	26.5	24.9
Aug 12	6N	0.73	1.05	0.96	1.03	0.73	23.3	27.8	22.7
	6S	1.08	0.89	0.7	0.96	0.93	24.3	31.5	23.5
	5N	1.13	1.03	0.9	1.08	0.97	17.8	20.7	25.2
	5S	1.07	1.2	1.23	1.16	1.05	13.2	26.8	24
Aug 14	6N	0.8	1.07	0.98	1.05	0.75			
	6S	1.1	0.9	0.71	0.97	0.93			
	5N	1.15	1.04	1.19	1.12	0.98			
	5S	1.14	1.2	1.23	1.18	1.05			

Aug 17	6N	1.08	1.08	0.98	1.06	0.94	23.7	27.9	23.3
	6S	1.11	0.89	0.69	0.98	0.97	22.4	31.2	24
	5N	1.17	1.04	1.19	1.11	1.01	16.8	19.9	25
	5S	1.08	1.18	1.23	1.18	1.09	12.6	26.8	25.7
Aug 19	6N	0.85	1.08	1	1.07	0.76	21.8	28.1	22.8
	6S	1.11	0.9	0.7	0.96	0.97	21.2	31.5	22
	5N	1.17	1.04	0.9	1.12	1.01	15.7	20.6	24.8
	5S	1.08	1.2	1.23	1.19	1.06	12.3	26.5	23.5
Aug 21	6N	0.98	1.09	1	1.07	0.9			
	6S	1.14	0.92	0.93	0.99	0.96			
	5N	1.19	1.06	0.86	1.11	1			
	5S	1.08	1.2	1.23	1.25	1.09			
Aug 24	6N	0.96	1.08	0.99	1.06	0.89	22.2	28.7	22.9
	6S	1.11	0.92	0.93	0.97	0.95	20.8	30.6	24.3
	5N	1.2	1.07	0.9	1.11	0.99	0.1	21.4	25.4
	5S	1.14	1.2	1.23	1.21	1.09	12.9	26.5	23.6
Aug 26	6N	0.95	1.09	1.03	1.09	0.81	21.2	27.1	22.5
	6S	1.11	0.92	0.89	0.98	0.97	19.9	29.8	22.3
	5N	1.2	1.07	0.9	1.14	1.01	14	20.8	24.9
	5S	1.06	1.2	1.23	1.21	1.08	12.6	24.6	23.7
Aug 28	6N	1	1.1	1.03	1.11	0.93			
	6S	1.09	0.93	0.88	0.97	1			
	5N	1.21	1.12	1.19	1.15	1.03			
	5S	1.14	1.2	1.24	1.22	1.09			

Drainage Plots 1 & 2

		Observed water table depths					Observed moisture contents		
		distance from drain					distance from drain @15cm		
		0.15	7.5	15	22.5	30	0.15	15	30
July 2	2N	0.734	0.743	0.68	0.752	0.818	31.9	35.1	
	2S	0.793	0.759	0.991	0.694	0.828		34	30.2
	1N	0.984	0.826	0.806	0.81	0.96	27.8		
	1S	1.223	0.952	0.939	1.02	1.189	24.7		22.2
July 9	2N	1.04	0.8	0.728	0.815	0.88	34.3	36.3	31.5
	2S	0.83	0.81	1.04	0.735	0.937	34.3	36.6	29.8
	1N	1.015	0.88	0.86	0.876	1.021	26.2	32.5	27.5
	1S	1.215	0.985	0.993	1.102	1.241	22.2	25.4	19.5
July 13	2N	0.95	0.95	0.96		1	31.1	33.9	26.2
	2S	1	0.97	1.19	0.87	0.99	31.4	33.6	26.2
	1N	1.15	1.02	1	1.01	1.12	22	29.7	22.7
	1S	1.22	1.06	1.1	1.12	1.28	17.8	22.9	15.6
July 15	2N	1.012	0.999	0.928	0.983	1.042	27.7	33.1	26.6
	2S	1.064	1.022	1.242	0.924	1.031	29.4	32.3	25.5
	1N	1.198	1.075	1.055	1.055	1.17	20.9	27.5	22.2
	1S	1.255	1.04	1.1	1.115	1.28	15.6	23.8	13.5
July 20	2N	0.74	0.95	1.01	1.03	0.41			
	2S	1	0.82	1.18	0.86	1.09			
	1N	0.75	0.93	0.88	1.02	0.58			
	1S	0.76	0.87	0.86	0.88	0.65			
July 23	2N	1.038	1.118	1.33	1.09	1.119	25.2	36	24.9
	2S	1.185	1.136	1.352	1.028	1.116	27.8	31	22.3
	1N	1.218	1.179	1.159	1.147	1.249	19.3	27.2	18.2
	1S	0.953	1.084	1.114	1.127	1.281	14.5	22.2	10.7
July 27	2N	1.189	1.177	0.866	1.135	1.165	24.1	30.8	23.4
	2S	1.22	1.145	1.398	1.072	1.152	25.3	32	20.2
	1N	1.216	1.208	1.195	1.176	1.28	18.3	27.1	16.5
	1S	1.254	1.089	1.115	1.143	1.288	13.5	20.4	11.1
July 29	2N	1.194	1.198	0.87	1.168	1.19	22.7	31.2	21
	2S	1.235	1.145	1.425	1.097	1.17	25.4	29.7	18.1
	1N	1.216	1.228	1.216	1.195	1.287	15.4	26.2	14.4
	1S	1.252	1.088	1.118	1.147	1.285	12.6	20.3	11.5
Aug 4	2N	1.2	1.23	0.87	1.19	1.21	24	31.6	23.2
	2S	1.23	1.14	1.45	1.13	1.2	26	31.7	18
	1N	1.22	1.1	1.23	1.34	1.29	17.4	27.5	16.2
	1S	1.24	1.09	1.12	1.15	1.28	11.8	21	13.9
Aug 6	2N	1.19	1.23	0.87	1.18	1.21	22.9	31.3	21.4
	2S	1.24	1.14	1.46	1.13	1.21	24.3	27.2	18
	1N	1.22	1.24	1.23	1.25	1.29	16.4	25.6	14.2
	1S	1.24	1.09	1.12	1.16	1.28	12.8	20	12.8
Aug 10	2N	1.19	1.23	0.87	1.22	1.25	19.5	31.2	18.6
	2S	1.23	1.15	1.49	1.15	1.22	23.4	21.6	15.4
	1N	1.22	1.23	1.23	1.25	1.28	11.5	25.2	14.1
	1S	1.24	1.11	1.12	1.16	1.28	11	16	11.2
Aug 12	2N	1.19	1.27	0.88	1.23	1.26	19.9	29.8	18.3
	2S	1.23	1.15	1.5	1.17	1.23	23.7	28.6	13.7
	1N	1.23	1.23	1.23	1.25	1.29	12.2	25.4	19.9
	1S	1.24	1.09	1.13	1.17	1.3	11.7	15.3	10.6
Aug 14	2N	1.2	1.26	1.05	1.23	1.26			
	2S	1.24	1.15	1.52	1.18	1.25			
	1N	1.22	1.24	1.23	1.26	1.29			
	1S	1.24	1.09	1.12	1.17	1.31			
Aug 17	2N	1.19	1.27	1.01	1.23	1.26	17.4	29.2	15.9
	2S	1.23	1.15	1.53	1.19	1.26	20.7	26.9	13.9
	1N	1.23	1.24	1.23	1.27	1.29	11.3	24.1	12.4
	1S	1.24	1.11	1.13	1.2	1.36	10.5	13.7	10.4

Aug 19	2N	1.19	1.26	1.03	1.23	1.26	15	28.1	15.1
	2S	1.24	1.15	1.53	1.2	1.27	20.4	26.9	13.4
	1N	1.23	1.23	1.23	1.2	1.29	10.1	24.9	12.5
	1S	1.24	1.1	1.13	1.17	1.35	9.3	14.7	9.8
Aug 21	2N	1.2	1.28	1.02	1.23	1.26			
	2S	1.23	1.15	1.53	1.2	1.28			
	1N	1.24	1.23	1.23	1.28	1.29			
	1S	1.24	1.11	1.13	1.15	1.33			
Aug 24	2N	1.19	1.26	1.03	1.23	1.26	14.9	29.9	15.1
	2S	1.23	1.15	1.54	1.2	1.28	18.9	26	13.8
	1N	1.24	1.23	1.23	1.29	1.29	11.7	23.9	13.6
	1S	1.24	1.15	1.19	1.2	1.35	10.7	14.6	11
Aug 26	2N	1.19	1.26	1.03	1.23	1.26	14.8	29.3	14.4
	2S	1.23	1.16	1.54	1.2	1.28	18.7	23.7	12.5
	1N	1.25	1.23	0.9	1.29	1.29	11.4	24	14
	1S	1.24	1.15	1.14	1.17	1.35	11.3	14.5	11
Aug 28	2N	1.19	1.26	1.02	1.23	1.31			
	2S	1.23	1.16	1.53	1.21	1.28			
	1N	1.25	1.23	1.23	1.3	1.29			
	1S	1.24	1.11	1.14	1.17	1.35			

Subirrigation Plots 12

		Observed water table depths					Observed moisture contents @15cm		
		distance from drain					distance from drain		
		0.15	7.5	15	22.5	30	0.15	15	30
July 2	12N	0.691	0.716	0.581	0.667	0.687		33.7	
	12S	0.741	0.685	0.615	0.645	0.519	28.4	27.6	
July 9	12N	0.742	0.757	0.625	0.721	0.723	36.3	39.3	33.6
	12S	0.794	0.745	0.679	0.707	0.581	34.3	37	42
July 13	12N	0.78	0.91	0.79	0.88	0.86	32.9	33.4	23.2
	12S	0.83	0.88	0.82	0.86	0.73	27.4	28.8	42.1
July 15	12N	0.643	0.808	0.767	0.882	0.864	33.7	31.9	22.8
	12S	0.694	0.802	0.792	0.835	0.7	29.8	28.1	40.5
July 20	12N	0.5	0.64	0.72	0.65	0.31			
	12S	0.48	0.55	0.63	0.69	0.41			
July 23	12N	0.806	0.943	0.854	0.97	0.869	33.1	30.7	20.6
	12S	0.905	0.929	0.878	0.917	0.788	28.9	24.9	41
July 27	12N	0.93	1.018	0.933	1.055	0.896	31.3	28.1	18.3
	12S	0.901	1.001	0.96	1.001	0.854	26.8	28.9	40.1
July 29	12N	0.675	0.918	0.933	1.076	0.897			
	12S	0.73	0.9	0.964	1.033	0.852			
Aug 4	12N	0.59	0.79	0.81	1	0.91			
	12S	0.69	0.8	0.85	0.92	0.78			
Aug 6	12N	0.73	0.85	0.83	1	0.92	35.3	28.2	20.1
	12S	0.79	0.85	0.87	0.93	0.8	30.6	18.3	42.6
Aug 10	12N	0.63	0.85	0.88	1.05	0.9	36	26.4	18.2
	12S	0.7	0.84	0.92	1.01	0.85	23.3	24.7	31.4
Aug 12	12N	0.84	0.97	0.96	1.11	0.91	34.5	27.3	18.2
	12S	0.9	0.97	1	1.07	0.86	27.6	26.1	41.7
Aug 14	12N	0.83	1	0.99	1.14	0.94			
	12S	0.9	1	1.03	1.1	0.86			
Aug 17	12N	0.75	0.94	0.95	1.11	0.97	33.7	27.5	15.4
	12S	0.82	0.94	0.99	1.08	0.84	30.1	23.6	20.1
Aug 19	12N	0.82	0.98	0.99	1.14	0.97	35	26.8	15.1
	12S	0.86	0.98	1.03	1.11	0.86	29.2	24	39.3
Aug 21	12N	0.8	0.99	0.99	1.15	0.94			
	12S	0.87	1	1.04	1.11	0.86			
Aug 24	12N	0.74	0.93	0.95	1.12	0.94	35	27.7	16.7
	12S	0.81	0.94	1	1.08	0.85	28.3	24.5	40.9
Aug 26	12N	0.74	0.94	0.96	1.12	0.97	34.4	26.1	16.1
	12S	0.81	0.93	1	1.09	0.87	28.2	24.3	38.1
Aug 28	12N	0.91	1.03	1	1.15	0.94			
	12S	0.91	1.03	1.05	1.12	0.87			

Control drainage Plots 13&14

		Observed water table depths			Observed moisture content @15cm
		7.5	15	22.5	15
July 2	14N	0.755	0.695	0.705	
	14S	0.757	0.733	0.744	
	13N	0.83	0.727	0.782	
	13S	0.832	0.837	0.807	
July 9	14N	0.765	0.706	0.741	38.4
	14S	0.563	0.733	0.741	36.2
	13N	0.845	0.748	0.793	38.3
	13S	0.851	0.855	1.089	35.4
July 13	14N	0.94	0.88	0.89	33.1
	14S	0.93	0.91	0.92	29.9
	13N	1.01	0.92	0.96	34.6
	13S	1.01	1.01	0.97	26
July 15	14N	0.983	0.912	0.938	30.9
	14S	0.995	0.964	0.97	30.4
	13N	1.073	0.955	1.023	32.9
	13S	1.07	1.074	1.038	21.2
July 20	14N	0.94	0.83	0.74	
	14S	1.02	0.72	0.99	
	13N	1.13	0.88	0.86	
	13S	1.15	1.07	1.12	
July 23	14N	1.06	1.045	1.073	39.4
	14S	1.128	0.99	1.098	30.7
	13N	1.163	0.96	1.1	31.9
	13S	1.19	1.15	1.15	25.1
July 27	14N	1.065	1.105	1.103	27
	14S	1.174	1.107	1.143	31
	13N	1.16	0.98	1.108	29.4
	13S	1.22	1.175	1.182	20.7
July 29	14N	1.073	1.133	1.124	31.2
	14S	1.192	1.115	1.166	
	13N	1.17	0.928	1.119	
	13S	1.22	1.18	1.205	
Aug 4	14N	1.07	1.14	1.14	
	14S	1.23	1.12	1.16	
	13N	1.16	0.95	1.14	
	13S	1.21	1.17	1.22	
Aug 6	14N	1.08	1.15	1.14	24.9
	14S	1.24	1.11	1.17	29.4
	13N	1.21	0.96	1.14	24.9
	13S	1.23	1.18	1.23	20.9
Aug 10	14N	1.08	1.16	1.14	23.6
	14S	1.26	1.13	1.16	24.2
	13N	1.21	0.95	1.13	19.5
	13S	1.22	1.19	1.22	16.1
Aug 12	14N	1.08	1.16	1.15	22.5
	14S	1.28	0.95	1.16	23.5
	13N	1.16	0.93	1.13	17.4
	13S	1.23	1.19	1.22	14.4
Aug 14	14N	1.09	1.17	1.15	
	14S	1.29	1.16	1.17	
	13N	1.25	0.95	1.14	
	13S	1.23	1.2	1.24	
Aug 17	14N	1.08	1.18	1.12	18.2
	14S	1.3	1.15	1.17	16.7
	13N	1.12	0.93	1.14	15.2
	13S	1.23	1.3	1.25	12

Aug 19	14N	1.08	1.18	1.15	17.1
	14S	1.3	1.1	1.17	16.9
	13N	1.15	0.94	1.14	13.6
	13S	1.22	1.2	1.26	11.2
Aug 21	14N	1.1	1.19	1.15	
	14S	1.3	1.1	1.16	
	13N	1.25	1.02	1.14	
	13S	1.23	1.19	1.26	
Aug 24	14N	1.1	1.19	1.15	17.7
	14S	1.3	1.16	1.17	16.9
	13N	1.2	0.95	1.23	14.1
	13S	1.22	1.2	1.22	12.1
Aug 26	14N	1.08	1.33	1.15	17.7
	14S	1.3	1.3	1.17	16.8
	13N	1.21	0.97	1.14	13.1
	13S	1.23	1.21	1.26	11.1
Aug 28	14N	1.1	1.2	1.16	
	14S	1.3	1.11	1.17	
	13N	1.16	0.99	1.23	
	13S	1.23	1.21	1.24	

Appendix D. Information for Simulation Stress Periods

Date	Stress No.	Time Length days	Rainfall m	Evaporation m/day	Print results
July 2	1	2	0	.0041	yes
5	2	3	.0363	.0043	no
9	3	4	0	.0052	yes
13	4	4	0	.0058	yes
14	5	1	0	.0058	no
15	6	1	.0051	.0047	yes
18	7	3	0	.0038	no
20	8	2	.0203	.004	yes
21	9	1	.0064	.0044	no
23	10	2	0	.0048	yes
25	11	2	0	.0055	no
26	12	1	.0101	.005	no
27	13	1	0	.004	yes
28	14	1	0	.003	no
29	15	1	.005	.003	yes
Aug 2	16	4	0	.004	no
4	17	2	.0231	.0044	yes
6	18	2	0	.0032	yes
7	19	1	0	.004	no
8	20	1	.0132	.004	no
10	21	2	0	.004	yes
12	22	2	0	.0034	yes
14	23	2	0	.004	yes
15	24	1	0	.004	no
17	25	2	.0107	.0047	yes
19	26	2	0	.0042	yes
21	27	2	.0043	.0038	yes
22	28	1	0	.0034	no
24	29	2	.00204	.0025	yes
26	30	2	0	.0026	yes
28	31	3	0	.0023	yes