DESIGN OF SUB SURFACE DRAINS

A DISSERTATION

submitted in partial fulfillment of the
requirements for the award of the degree
of
MASTER OF ENGINEERING
in
WATER RESOURCES DEVELOPMENT

By
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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the dissertation entitled "DESIGN OF SUB SURFACE DRAINS" in partial fulfillment of the requirement for the award of the Degree of MASTER OF ENGINEERING IN WATER RESOURCES DEVELOPMENT submitted in Water Resources Development Training Centre, University of Roorkee, is an authentic record of my own work carried out during the period July, 2000 to December, 2000 under supervision of Dr. G.C. MISHRA, Professor of WRDTC, University of Roorkee, India.

The matter embodied in this dissertation has not been submitted by me for the award of any other degree.

Dated : 02 December 2000
Place : Roorkee

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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ABSTRACT

The basic purpose of sub surface drainage system in irrigated areas is to provide a soil moisture regime conducive to better plant growth. Where the deep percolation from irrigation is common, the water table may rise very rapidly into the root zone and even to the soil surface. In such case, the function of a sub surface drainage system would be to lower the water table within the root zone fast enough after irrigation to avoid damage to the crop.

The design criteria of sub surface drains accounting falling water table are based on the unsteady state formula. One of the unsteady state formulae for determining depth and spacing of parallel drainage system has been derived by Glover (1954), which popularly known as U.S. Bureau of Reclamation formula. The formula has been derived on the basis of the Dupuit-Forchheimer assumption.

The cost of drains increases with depth of placement of drains because of increase in excavation cost. On the other hand the shallow drain will require closer drain spacing and the drainage system would require more number of drain pipes leading to increase cost of material.

In this study, the economical depth and spacing of parallel drains have been determined. The economical design is based on the Glover's formula. Two cases have been dealt. In the first case, the recharge originates only from local irrigation application and in the second case the recharge originates from local as well as external source.

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LIST OF SYMBOLS

A	area to be drained (m2)
B_e	width of excavation (m)
B_f	diameter of pipe (m)
C	canal or watercourse seepage losses as decimal of percent of the flow
C_E	total cost of excavation (Rs)
C_e	cost per unit volume of earth work at ground level (Rs/m^3)
C_r	the additional cost per unit volume of excavation per unit depth (Rs/m^4)
C_p	cost of pipe (Rs/m)
D	depth from drain level to impermeable layer (m)
D_C	drainage coefficient (mm/day)
D_n	natural drainage which is equal to groundwater flow out of the area to be drained (mm/day)
d	thickness of the "equivalent layer" (m)
d_m	inside pipe diameter (cm)
d_p	depth of drain below ground surface (m)
d_r	depth of root zone below ground surface (m)
F	interval between irrigation (days)
H	water table height above drain level at $t > 0$ (m)
h	water table height above drain level at $t = 0$ (m)
Δh	water table rise above drain level (m)
i	irrigation application (mm)
K(N)	unit step response function
k	hydraulic conductivity (m/day)
L	drain spacing (m)
L_t	total length of pipe (m)

P	deep percolation from irrigation including the leaching requirement as decimal of percent of the flow
Q_s	water to be removed by the onfarm drainage system which is the design drainage rate or drainage coefficient (mm/day)
q	drainage discharge rate (m/day)
R	recharge rate (m/day)
R_f	onfarm recharge to the groundwater i.e. leaching water, rainfall and deep percolation resulting from excessive water application (mm/day)
r	radius of drain (m)
S	slope of field drain (m/m)
S_c	seepage from canals (mm/day)
S_l	groundwater flow into the area including artesian inflow (mm/day)
T	transmissivity (m^2/day)
t	time (days)
Δt	time interval (days)
x	horizontal distance from a reference point (m)
α	kD/ϕ
ϕ	specific yield
γ	an integer index
$\delta(N)$	unit pulse response function or discrete kernel

Chapter 1

INTRODUCTION

1.1. GENERAL

The drainage systems can be classified into surface and sub surface drainage system. Although the basic objective of surface and sub surface drains is to provide a soil moisture regime conducive to better plant growth, the way this is achieved is different. Surface drainage system removes water before it has entered the soil. Provision of surface drainage results in an increase in the surface run off by an amount of water which does not get an opportunity time to enter into soil storage. Sub surface drainage system removes water after it has entered the soil. Sub surface drains aims to increasing the rate at which water can be drained from the soil so as to lower the water table for increasing the depth of unsaturated soil above the water table.

Sub surface drains is accomplished by a system of open ditches or buried tube drains into which water seeps by gravity. In buried type, the drains, usually pipes, are laid in trenches below ground surface, then backfilled with sand and excavated material. The required depth at which the drains should be placed, is mainly governed by the type of crops, soil, climatic and rainfall characteristics.

The drain depth is derived in relation to spacing with an economic view point. The cost of drains increases with depth because of increase in excavation cost. The shallow drains require closer spacing.

Depth and spacing of pipe drains are still largely determined by experience and judgement for given drainage conditions. In recent years many investigators have proposed depth and spacing formulae which are more systematic and scientific in approach. Most of the formulae used for finding the spacing of drains to contain the water table below root zone depth are based on the Dupuit-Forchheimer assumption. The theoretical solutions are based either on the assumptions of a stationary water table (steady state) or on a falling water table (unsteady state) in the root zone.

The spacing formulae based on a static water table have been developed by several investigators, such as Donnan (1946), Hooghoudt (1940) and Kirkham (1958), etc. who have presented different solutions for each of several boundary conditions. Spacing formulae based on a falling water table have been reported by several investigators, such as Neal (1934), Walker (1952), Dumm, Tapp, Moody (1954), Kraijenhoff van de Leur (1958) and Maasland (1959). The spacing formula developed by Glover (1954) is popularly known as U.S. Bureau of Reclamation formula.

In design of sub surface drains, the various essential parameters required are soil permeability, soil thickness underlain by impermeable layer, depth to water table, drainage coefficient, percolation rate and drainable porosity or specific yield. These parameters govern the depth and spacing of drains.

In relation to irrigation and drainage, the main objective of ensuring effective drains in irrigated areas is to increase crop production and to sustain high yields by providing a conducive root environment. Drainage is one of the important aspects of irrigation management, which is often neglected. Irrigated agriculture cannot survive indefinitely without drainage. In most irrigated areas the ground water table rises. When it gets close to the soil surface, the area is said to be water logged. Plant growth is retarded by lack of oxygen and/or by toxicity from salts.

1.2. Scope of the Study

The scope of the present study is to find the economical spacing of sub surface field drains for containing the water table below root zone. The spacing is computed considering the fluctuating water table resulting from discontinous irrigation application. The water level evolution is computed using Glover solution. Considering the amount, number and interval of irrigation, discontinous deep percolation or recharge rate during different time are ascertained and resulting evolution of water table height is predicted.

For each depth and spacing of drain pipes and irrigation schedule of a particular crop, the maximum water table height is computed. That spacing and depth for which water table does not stay more than one day, is an acceptable depth and spacing of drain pipes. For a set of acceptable depth and spacing, the corresponding costs are computed, the minimum of which is the most economical one.

The water logging may be caused due to external source or due to local irrigation application. In this dissertation, the computation of drain spacings has been made both for local and external irrigation application.

Chapter 2

REVIEW OF LITERATURE

2.1. GENERAL

Any drain or well which is installed to control or lower the high water table in an area is considered to be an element of sub surface drainage system. The high water table may be caused due to percolation from precipitation, seepage from canals and surface water bodies located at higher elevation, irrigation water, leaching water and leakage from artesian aquifer. In arid and semi arid areas a minor portion of excess water comes from precipitation. The major sources of excess water in irrigated areas are application losses and seepage from irrigation canals. If the total quantity of water introduced into the sub surface in an area from the various sources exceeds the total quantity disposed of through natural drainage processes, the water table will rise. It is then necessary to install artificial drains to remove the surplus water to maintain the water table at some predetermined level which is not harmful to crops.

2.2. CLASSIFICATION OF SUB SURFACE DRAINS

From a functional point of view, sub surface drains can be classified into two categories: relief and interception drains. The designer must evaluate the various site conditions while planning a sub surface drainage system and decide to use which type of them.

i). Relief Drains

In a relief drainage system one can distinguish three categories of drains : field laterals, collectors and main drains. These may be either open ditches which may carry surface and sub surface water or buried pipe drains that are buried conduits with open joints or perforations which collect and/or convey drainage water.

Relief drainage systems are classified into four general types :

a. Parallel system
b. Herringbone system
c. Double-main system
d. Random system

ii). Intercepting Drains

Intercepting drainage system is used to intercept flows, reduce the flows, and lower the flow lines in the problem area. These drains may be either open ditches which can serve to collect both surface and ground water flows or buried pipe drains. Proper location of intercepting drains is very important. Intercepting drains are required where the slope of the barrier converges with the ground surface slope. These should normally be located above the wet area to intercept the greatest flows.

2.3. DESIGN CONSIDERATION OF SUB SURFACE DRAINS

Sub surface drainage is defined as the removal of excess ground water below the ground surface. This system lowers the high water table caused by rainfall, irrigation leaching water, seepage from higher lands or irrigation canals, etc. There are various essential parameters for design of sub surface drainage system. These parameters are mentioned here;

i). Soil Permeability

If there is more than one layer, the permeability of each layer must be found. For most drain-spacing equations, details of soil permeability and depth to the impermeable layer are required. The insitu permeability should be obtained from field test.

ii). Permissible Depth to Impermeable Layer

The depth to the impermeable layer below the drain depth has a major effect on the spacing. In fact the drain spacing can be doubled if the impermeable layer is 1 meter below the drain level and still further increases as the depth to the impermeable layer increase.

iii). Depth to Water Table

The aim of land drainage installation is the removal of excess water from the soil for providing a favourable root zone for plant growth. In any irrigation planning, it is essential requirement that the water table should be controlled so that it does not enter the root zone to cause water logging. The water table positions that a drainage system is required to maintain are primarily related to soil type, climate, crops, cropping intensity and water management.

The water table depths suggested by FAO (1980) for steady and unsteady state drainage design are given in Table 2.1.

Table 2.1. Suggested Irrigated Season Water Table Depths For Drain Spacing Design Using Steady and Unsteady State Formula

Crops	Steady State		Unsteady State	
	WT Depth in m below Ground Surface		WT Depth in m below Ground Surface	
	Fine textured soil	Light textured soil	Fine textured soil	Light textured soil
Field Crops	1.2	1.0	0.5	0.9
Vegetables	1.1	1.0	0.9	0.9
Tree Crops	1.6	1.2	1.4	1.1

Source : FAO No. 28/1980

iv). Deep Percolation

Bureau of Reclamation makes use of deep percolation in estimating drain spacing. When drainage problem exists on an operating project and drains are being planned, the build up in the water table due to irrigation application can best be determined by field measurement. In the planning stage of new projects or on the operating projects where the measured build up is not available, the amount of deep percolation must be estimated from each irrigation application.

v). Drainage Coefficient

Drainage coefficient is defined as the depth of water to be removed from the drained area in 24 hours or one day. The design drainage coefficient for pipe drains is based on entirely different criteria for humid and for irrigated conditions.

In humid areas the drainage coefficient depends largely on rainfall. It is difficult to correlate rainfall with the drainage coefficient since the distribution of rainfall during the growing season and its intensity must be considered along with evaporation and other losses. The selection of a drainage coefficient for humid conditions is based primarily on experience and judgment. Where the annual rainfall varies from 750 to 1500 mm, the drainage coefficient ranges from 10 to 13 mm/day for mineral soils. For organic soils or for high value crops this rate is normally increased by 30 to 50 percent. Where surface runoff is removed by pipe drains, the rate is about doubled, that is 19 to 25 mm/day.

In irrigated areas the discharge from drains may be expected to vary from 10 to 50 percent of the water applied. The drainage coefficient will generally decrease as the size of the area contributing to the flow increases. The drainage coefficient depends on the depth of irrigation, method of irrigation, leaching requirement and soil characteristics.

There are few methods to determine drainage coefficient :

- US SCS Method (1973)

  US SCS method recommends the following equation, which is based on irrigation practices,

$$D_C = \frac{(P+C)i}{F} \tag{2.1}$$

where :

D_C = drainage coefficient (mm/day)

P = deep percolation from irrigation including the leaching requirement as decimal of percent of the flow (mm)

C = canal or watercourse seepage losses as a decimal of percent of the flow (mm)

i = irrigation application (mm)

F = interval between irrigation (days)

- FAO Method (1980)

This method recommends the following equation, which is based on a groundwater balance,

$$Q_s = R_f + S_c + S_i - D_n \tag{2.2}$$

where :

Q_s = water to be removed by the onfarm drainage system which is the design drainage rate or drainage coefficient (mm/day)

R_f = onfarm recharge to the groundwater i.e. leaching water, rainfall and deep percolation resulting from excessive water application (mm/day)

S_c = seepage from canals (mm/day)

S_I = groundwater flow into the area including artesian inflow (mm/day)

D_n = natural drainage which is equal to groundwater flow out of the area to be drained (mm/day)

- USBR Method

Before finding drainage coefficient, it is required to determine the flow rate based on the highest position of water table above the drain. The following equation provides a reasonable design capacity for most drains,

$$q = 0.0727.C.K.H.D/L \tag{2.3}$$

where :

q = discharge (l/s per meter length of drain)
K = hydraulic conductivity (m/day)
H = maximum height of water table above drain level (m)
C = correction factors for drainage design flow rate (Table 2.2)
D = d+H/2 = average flow depth (m)
d = depth from drain level to impermeable layer (m)
L = drain spacing (m)

Drainage coefficient is expressed as,

$$D_C = 86400\frac{q}{A} \tag{2.4}$$

where :

D_C = drainage coefficient (mm/day)
q = discharge (l/s per meter length of drain)
A = area (m^2) for 1 m length of drain, which is equal to the spacing, L, (m)

The above formula accounts only for the flow from the soil into the drain, which serves an area that can be irrigated in about two days. Canal or seepage from other sources, if any, must be added to obtain the design flow rate.

Table 2.2. . Correction factors for drainage design flow rate

Area Drained in ha	Factor, C
0 – 30	1.0 – 0.92
30 – 50	0.92 – 0.87
50 – 80	0.87 – 0.79
80 – 130	0.79 – 0,72
130 – 200	0.72 – 0.65
200 – 260	0.65 – 0.60
260 – 400	0.66 – 0.54
400 – 2000	0.54 – 0.50

Source : USBR (1978)

vi). <u>Drainable Porosity or Specific Yield</u>

- Representative drainable porosity values for use in unsteady or transient state equations are difficult to be measured accurately. Whenever possible and practical, the drainable porosity should be determined from measurement of drain discharge and drawdown of existing drains or pilot drains.

The values of these parameters will help in determining depth and spacing of drains.

2.3.1. Size of Pipe

After determining the drainage coefficient and the area to be drained, the pipe of adequate size is selected to carry the flow. Based on tests and trials Yarnell and Woodward, have suggested the following formula for determining drain pipe diameter;

$$d_m = 51.7(Q.A.n)^{0.375}.S^{-0.1875} \qquad (2.5)$$

where :

d_m = inside drain diameter (mm)

Q = drainage coefficient (mm/day)

A = area to be drained (ha) for 1 drain line

S = slope of the drain (m/m)

n = Manning roughness coefficient for the drain pipe

2.3.2. Length of Pipe

Total length of pipe can be known after finding the spacing of drains considering the area to be drained. In the case of parallel relief drains the area served by the drain is equal to the spacing times the length of the drain, as shown in the Figure 2.1,

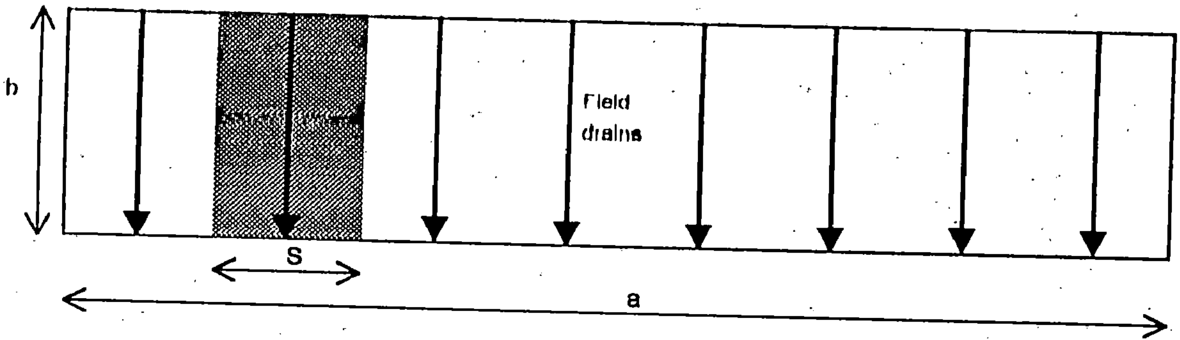


Figure 2.1. Parallel Drainage System

Refer to the figure, showing a parallel drain system, which contains several field drains. The shaded area indicates the area drained by one of the field drains.

The number of pipe length (n) depends on the spacing, or simply can be expressed as follows :

$$n = \frac{a}{s} \tag{2.6}$$

where :

n = number of pipe length

a = total length of the area to be drained (m)

s = spacing of drain (m)

Total length of pipe is,

$$Lt = n.L \tag{2.7}$$

where :

Lt = total length of pipe (m)

L = length of pipe for one field lateral drain (m)

n = number of pipe

2.3.3. Excavation Cost

The cost of excavation depends on the volume and depth of cut and fill. It also depends on the strata to be excavated (Nichols 1959; Singh 1976). The cross section of excavation is shown in Figure 2.2,

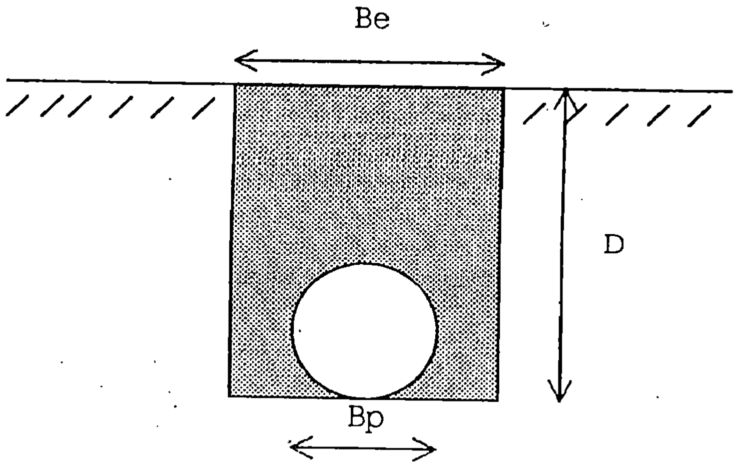


Figure 2.2. Cross Section of Excavation

The cost of excavation can be expressed as,

$$C_E = C_e.A + C_r.A.(D/2) \tag{2.8}$$

where :

C_E = total cost of excavation (Rs)

C_e = cost per unit volume of earth work at ground level (Rs/m^3)

C_r = the additional cost per unit volume of excavation per unit depth (Rs/m^4)

A = area to be excavated = B_e x D (m^2)

D = depth of excavation (m)

B_e = width of excavation = 2 to 3 B_p (m)

B_p = diameter of pipe (m)

2.4. STEADY STATE DRAINAGE EQUATION

In parallel drainage systems, spacings are usually equal for a given soil and depend largely on the total amount of water to be removed in a given unit of time. Spacing equations based on a static water table have been developed by several investigators, such as Donnan (1946) and Hooghoudt (1940).

2.4.1. Donnan's Formula

This formula is based on the assumption that a barrier or practically an impervious stratum exists in the soil at a finite distance below the normal root zone of crops. The flow to vertically walled ditches reaching an impermeable layer can be described by the so-called Donnan's equation :

$$R = q = \frac{4k(H^2 - D^2)}{L^2} \tag{2.9}$$

Or the drain spacing will be :

$$L = 2\sqrt{(k/q).(H^2 - D^2)} \tag{2.10}$$

where :

L = drain spacing (m)
R = recharge rate (m/day)
q = drainage discharge rate (m/day)
k = hydraulic conductivity of the soil (m/day)
H = height above the impermeable layer of the ground water table midway between two drains (m)
D = depth from drain level to impermeable layer (m)

2.4.2. Hooghoudt's Formula

Hooghoudt (1940), in his drain-spacing formula, took into account not only the horizontal flow but also the radial flow caused by the convergence of flow lines near the drains. This was accomplished by reducing the depth of the flow layer *D* below the drains to a hypothetical depth *d* of an "equivalent layer", where *d* depends on *D*, *L* and the radius *r* of the drain.

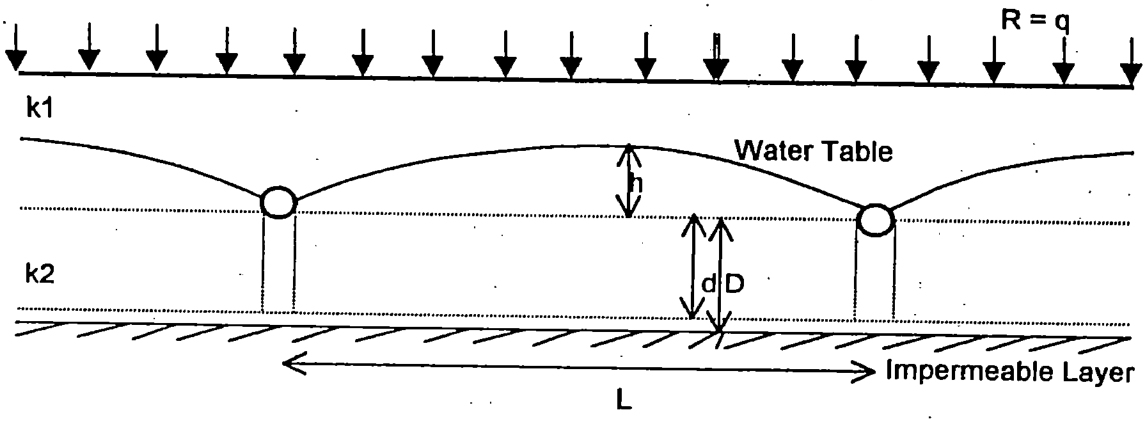


Figure 2.3. Hooghoudt's Drain Spacing Formula

Hooghoudt equation reads :

$$L^2 = \frac{8k_2dh}{q} + \frac{4k_1h^2}{q} \qquad (2.11)$$

where :

L = drain spacing (m)

q = drainage discharge rate (m/day)

k_1 = hydraulic conductivity above the level of the drains (m/day)

k_2 = hydraulic conductivity below the level of the drains (m/day)

d = thickness of the "equivalent layer" (m)

h = height of the ground water table above the plane through the drains midway between two drains (m)

Since the drain spacing *L* depends on the equivalent depth *d*, which in turn is a function of *L*, the formula cannot be given explicitly in *L*. Its use therefore as a drain-spacing formula involves a trial and error procedure.

2.4.3. Kirkham's Formula

Kirkham (1958) has analyzed the problem by using exact mathematical procedure. His result are, therefore, more accurate than Hooghoudt's. However the computations are complicated. Wesseling (1964) indicates that the two equations differ by less than 5 %. Kirkham formula is :

$$h = \frac{qL}{k} F(L, D, r) \qquad (2.12)$$

where :

$$F(L,D,r) = \frac{1}{\pi}\left[\ln\frac{L}{\pi r} + \sum_{n=1}^{\infty}\frac{1}{n}\left(\cos\frac{2n\pi r}{L} - \cos(n\pi)\coth\left(\frac{2n\pi D}{L} - 1\right)\right)\right] \quad ..(2.13)$$

where :

h = maximum height of the water table above the drains (m)
q = drainage discharge rate (m/day)
k = hydraulic conductivity (m/day)
L = drain spacing (m)
r = radius of drain (m)

2.5. UNSTEADY STATE DRAINAGE EQUATIONS

In areas with periodic irrigations or high intensity rainfall, the assumption of a steady recharge is not justified. Under these conditions, unsteady state solutions of the flow problem must be applied. Unsteady state solutions are indispensable when actual, unsteady water table elevation due to drain discharge, as obtained from field data, must be evaluated.

The first approximation of the differential equation for unsteady state flow derived on the basis of the Dupuit-Forchheimer assumption can be written as :

$$kD\frac{\partial^2 h}{\partial x^2} = \phi\frac{\partial h}{\partial t} \tag{2.14}$$

or :

$$\alpha\frac{\partial^2 h}{\partial x^2} = \frac{\partial h}{\partial t} \tag{2.15}$$

where :

$kD = T$ = transmissivity of the aquifer (m^2/day)
k = hydraulic conductivity (m/day)
D = depth from drain level to impermeable layer (m)
h = hydraulic head as a function of x and t (m)
x = horizontal distance from a reference point (m)
t = time (day)
ϕ = specific yield
α = KD/ϕ = hydraulic diffusivity (m^2/day)

For the required initial and boundary conditions, this equation must be solved for predicting the moving of water table.

2.5.1. Glover's Formula

Glover (1954) assumed that the water table was initially flat and parallel with the soil surface. The initial and boundary conditions are :

$h = H$ for $0<x<L$ at $t = 0$ (initial horizontal ground water table)

$h = 0$ for $x = 0,L$ at $t > 0$ (water level in drains remains at zero level = drain level)

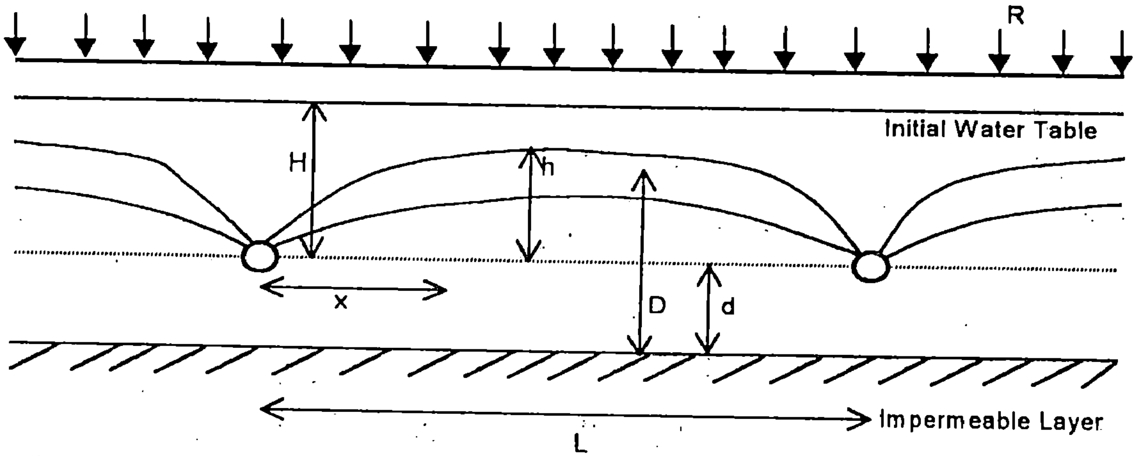


Figure 2.4. Glover's Drain Spacing Formula

Glover has taken the value of D as the average thickness of the soil transmitting the water to the drains because, for the unsteady case, the falling water table D is not constant. It varies with the slope and position of the water table.

For an analogous heat condition problem, the solution to the drainage problem is found in Carslaw and Jaeger (1959),

$$h(x,t) = \frac{4H}{\pi} \sum_{n=1,3,5...}^{\infty} \left[\frac{1}{n} \exp(-n^2\pi^2 \frac{\alpha t}{L^2}) \sin(\frac{n\pi x}{L}) \right] \qquad (2.16)$$

where :

h = water table height above drain level at $t > 0$ (cm)

H = water table height above drain level at $t = 0$ (cm)

α = kD/ϕ

k = hydraulic conductivity (cm/day)
D = d+0.5/ϕ = average depth of flow region (cm)
d = depth from drain level to impermeable layer (cm)
x = horizontal distance from a reference point (cm)
t = time (day)
ϕ = specific yield
L = drain spacing (cm)

when x = L/2, this expression takes the form :

$$h_{\max} = \frac{4H}{\pi} \sum_{n=1,3,5...}^{\infty} \left[\frac{1}{n} \exp\left(-n^2\pi^2 \frac{\alpha t}{L^2}\right) \sin\left(\frac{n\pi}{2}\right) \right] \tag{2.17}$$

For all but the smallest time periods, all terms but the first may be neglected, resulting the simple expression at the midpoint (x = L/2),

$$L^2 = \frac{\pi^2 kDt}{\phi \ln(4H/\pi h)} \tag{2.18}$$

to which we shall refer as the Glover equation.

2.5.2. Dumm, Tapp and Moody Formula

This formula was developed at U.S. Bureau of Reclamation to provide an orderly approach to the problem of determining drain spacings. Dumm (1964), Tapp and Moody observed that the initial water table shape encountered in the field has a shape that corresponds with a fourth degree parabola. At time t = 0 the water table has a shape given by the equation,

$$h = \frac{8H}{L^4}(L^3 x - 3L^2 x^2 + 4L x^3 - 2x) \qquad (2.19)$$

At the two drains the water table is taken to be at the same elevation as the drains or,

h = 0 for x = 0,L at t = 0

The solution to the flow equation for these conditions is,

$$h = \frac{192H}{\pi}\sum_{m=0}^{\infty}\left[\frac{(2m+1)^2\pi^2 - 8}{(2m+1)}\exp\left(\frac{(2m+1)^2\pi\alpha t}{L^2}\right)\sin\left(\frac{2m+1)\pi x}{L}\right)\right]$$

....(2.20)

An approximate solution can be obtained by taking only the first term of the series. The Bureau of Reclamation indicates that the spacing obtained with this formula (by Donnan, Tapp and Moody) is very little different from the spacing obtained with the formula based on an initially flat water table (by Glover).

2.5.3. Kraijenhoff van de Leur and Maasland Formula

Both Kraijenhoff van de Leur (1958) and Maasland (1959) derived solution for unsteady state groundwater flow to drains. The solution is based on a steady recharge over any time period t instead of an instantaneous recharge as assumed by Glover and Dumm.

Starting with a flat water table at drain level at $t = 0$ and assuming a recharge intensity R (m/day) from the moment $t = 0$ onwards, yields the following initial and boundary conditions,

$h = 0$ for $0<x<L$ at $t = 0$ (initial horizontal ground water table at drain level at $t = 0$)

$h = 0$ for $x = 0,L$ at $t > 0$ (water in drains remains at zero level = drain level)

R = constant for $t > 0$ (constant recharge R starts at $t = 0$)

For the above initial and boundary conditions, the height of the water table midway between parallel drains ($x = L/2$) at any time t is,

$$h_{max} = \frac{4R}{\pi\phi} \sum_{n=1,3,5...}^{\infty} \frac{1}{n^3}\left(1 - \exp(-n^2\pi^2 \frac{\alpha t}{L^2})\right)\sin\left(\frac{n\pi}{2}\right) \qquad (2.21)$$

This equation is not used for routine drain spacing computations, which are usually based on an assumed steady or instantaneous recharge.

Chapter 3

OPTIMAL SPACING OF SUB SURFACE FIELD DRAINS

3.1. GENERAL

Depth and spacing of pipe drains are still largely determined by experience and judgement for given drainage conditions. Many formulae have been developed for finding depth and spacing of pipe drains. Most of these formulae have been derived on the assumption of steady state flow condition. Design based on steady state flow condition would lead to uneconomical design. If the parameters of design are precisely known, an unsteady state formula can be used which would lead to economical design of field drain. One of the unsteady state formulae for determining depth and spacing of field or parallel drainage system has been derived by Glover, which is popularly known as U.S. Bureau of Reclamation formula.

In this study, the maximum water table height at the middle of the drains during irrigation application is computed using unit pulse response function coefficients (discrete kernel coefficient) and Duhamel's convolution technique for time varying recharge. The discrete kernel coefficients are obtained using Glover's basic solution. There will be several combinations of depth and spacing which would contain the water table below root zone depth, one of which would be economical. The economical spacing and depth have been determined in the present study.

3.2. DERIVATION OF DISCRETE KERNEL FOR WATER TABLE RISE ABOVE DRAINS

Glover's solution has been used in deriving the discrete kernel coefficients. Glover's solution is valid where the initial water level in the soil before irrigation application coincides with drain level and water level changes due to an impulse recharge causing a rise H in the level between two drains.

For an initial condition :

$h(x,0) = H \quad \text{for } 0 < x < L$

and the boundary conditions :

$h(0,t) = 0 \quad \text{for } t > 0$

$h(L,t) = 0 \quad \text{for } t > 0$

the solution derived by Glover to the one dimensional Boussinesq equation governing the flow is,

$$h(x,t) = \frac{4H}{\pi} \sum_{n=1,3,5\ldots}^{\infty} \left[\frac{1}{n} \exp\left(-n^2\pi^2 \frac{\alpha t}{L^2}\right) \sin\left(\frac{n\pi x}{L}\right) \right] \tag{3.1}$$

where :

h = water table height above drain level at t > 0 (cm)

H = water table height above drain level at t = 0 (cm)

α = kD/ϕ = hydraulic diffusivity (cm^2/day)

k = hydraulic conductivity (cm/day)

D = $d+0.5/\phi$ = average depth of flow region (cm)

d = depth from drain level to impermeable layer (cm)

x = horizontal distance from a reference point (cm)

t = time since instantaneous application of the impulse recharge causing the rise H in water level (day)

ϕ = specific yield

L = drain spacing (cm)

For x = L/2, the expression takes the form,

$$h_{\max} = \frac{4H}{\pi} \sum_{n=1,3,5\ldots}^{\infty} \left[\frac{1}{n} \exp(-n^2\pi^2 \frac{\alpha t}{L^2}) \sin(\frac{n\pi}{2}) \right] \tag{3.2}$$

For unit impulse recharge at t = 0, the solution is,

$$h(x,t) = \frac{4}{\pi\phi} \sum_{n=1,3,5\ldots}^{\infty} \left[\frac{1}{n} \exp(-n^2\pi^2 \frac{\alpha t}{L^2}) \sin(\frac{n\pi x}{L}) \right] \tag{3.3}$$

This expression is the response of the aquifer drain system to a unit impulse perturbation. The response to a unit step perturbation is given by,

$$h(x,t) = \frac{4}{\pi\phi} \int_0^t \left\{ \sum_{n=1,3,5\ldots}^{\infty} \left[\frac{1}{n} \exp(-n^2\pi^2 \frac{\alpha(t-\tau)}{L^2}) \sin(\frac{n\pi x}{L}) \right] \right\} d\tau \tag{3.4}$$

$$= \frac{4L^2}{T\pi^3} \sum_{n=1,3,5\ldots}^{\infty} \left[\frac{1}{n^3} \sin(\frac{n\pi x}{L}) \right] - \frac{4L^2}{T\pi^3} \sum_{n=1,3,5\ldots}^{\infty} \left[\frac{1}{n^3} \exp(-n^2\pi^2 \frac{\alpha t}{L^2}) \sin(\frac{n\pi x}{L}) \right] \tag{3.5}$$

For x = L/2,

$$h(L/2,t) = \frac{L^2}{8T} - \frac{4L^2}{T\pi^3} \sum_{n=1,3,5\ldots}^{\infty} \left[\frac{1}{n^3} \exp(-n^2\pi^2 \frac{\alpha t}{L^2}) \sin(\frac{n\pi}{2}) \right] \tag{3.6}$$

Let the time parameter be discretized by uniform time steps of size Δt that may be 1 minute, 1 hour, half day, 1 day, etc. Let the drawdown, h(x,NΔt) corresponding to a continous constant recharge per unit time be designated as K(N). K(N) is known as unit step response function. If unit recharge takes place during the first unit time period and no recharge afterwards, the drawdown at the end of Nth unit time step corresponding to this unit pulse recharge is known as unit pulse response function or discrete kernel δ(N). For a linear system δ(N) = K(N) – K(N-1).

The perturbation can be assumed to be comprised of a train of pulses, each being constant within a time step, but varying from step to step. For such discretization of the pertubation, the maximum water table height at the end of Nth unit time step is,

$$h(L/2,N)=\sum_{\gamma=1}^{N}Q(\gamma).\delta(N-\gamma+1) \tag{3.7}$$

where :

Q(γ) is drainage coefficient such as percolation losses from the irrigation and leaching water applied as a variable recharge rate at time γ, and

$$\delta(N)=K(N)-K(N-1)$$

$$=\frac{4L^2}{T\pi^3}\Bigg[\sum_{n=1,3,5...}^{\infty}\{\ \frac{1}{n^3}\exp(-n^2\pi^2\frac{\alpha(N-1)\Delta t}{L^2})\sin(\frac{n\pi}{2})\ \}$$

$$-\sum_{n=1,3,5...}^{\infty}\{\ \frac{1}{n^3}\exp(-n^2\pi^2\frac{\alpha N\Delta t}{L^2})\sin(\frac{n\pi}{2})\ \}\Bigg] \tag{3.8}$$

3.3. CASE 1: DRAINAGE COEFFICIENT ORIGINATING FROM LOCAL IRRIGATION APPLICATION

3.3.1. Statement of the Problem

A schematic cross section of parallel drains is shown in figure 3.1. The function of the drainage system in an irrigated area is to keep the water table below the root zone during the irrigation period. The drains are perforated pipe drain and are located above an impermeable layer. The drainage coefficient (Q) originates as recharge from local irrigation application (Q=R). It is assumed that the same recharge goes to groundwater on each irrigation. It is required to determine the height of the water table which is governed by depth and spacing of the drains. The water table is permitted to stay only for one day in the root zone. It is possible to achieve this goal, placing the drains at different depth and placing. It is aimed to find the optimal depth and spacing for which the provision of drainage is economical. Cost of pipe and cost of excavation in relation to the depth of placement of the drain are known.

The minimization of problem can be stated as,

$$\min_{L,\, dp} \{ C = C_P + C_E \}$$

$$\text{Subject to} \quad h(L/2, N_i) > (d_p - d_r)$$

$$h(L/2, N_i + 1) < d_p - d_r)$$

where :

$$h(L/2, N_i) = \sum_{\gamma\ 1}^{Ni} Q(\gamma).\delta(Ni - \gamma + 1)$$

N_i = time step during which the water table enters the root zone depth

$N_i + 1$ = time step during which the water table is below the root zone

C = total cost of sub surface field drainage system

C_P = cost of pipe

C_E = cost of excavation

L = spacing of drains

d_p = depth of drain below ground surfce

d_r = depth of root zone below ground surface

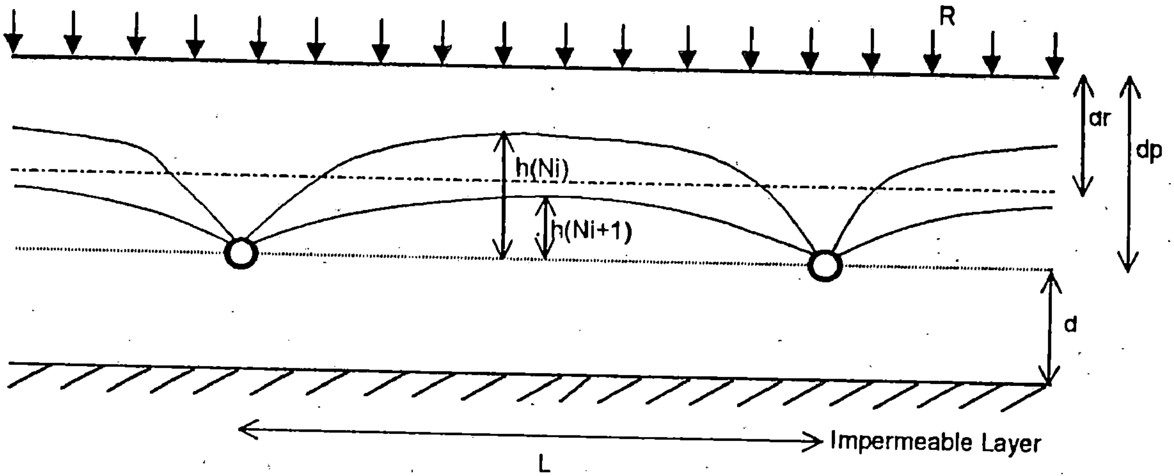


Figure 3.1. Cross Section of Parallel Drains

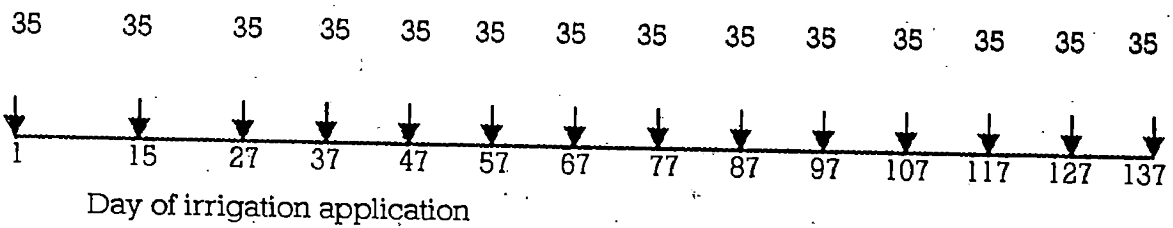
3.3.2. Data Used in the Study

To determine the drain spacing and placement which keep the height of water table below the root zone during the irrigation period and to find the optimal depth and spacing of drains, the data in this study were taken from the experiment of Dumm and Winger (1963).

- Irrigation Application

1. Type of crop is safflower, a total cropped area 60 ha is assumed.

2. The maximum allowable water table height (root zone) is 1.20 m below the ground surface.
3. Total growing season is 138 days
4. Number of irrigation is 14 times.
5. Interval between two irrigations was taken as :
    - for the first irrigation = 14 days
    - for the second irrigation = 12 days
    - for the third to fourteenth irrigation = 10 days
6. Deep percolation as a recharge rate (Q) = 35 mm for each irrigation.



- <u>Soil Parameters</u>

1. Type of soil is sandy loam with value of hydraulic conductivity (k) = 11.4 m/day.
2. The value of specific yield (ϕ) = 0.23.
3. Depth to impermeable layer from ground surface = 5.5 m

3.3.3. Result and Discussion

For the prescribed transmissivity (T), specific yield (ϕ) and assumed values of soil depth below drain level (d) and spacing of drains (L), the discrete kernel coefficients were generated.

For the known percolation loss and irrigation schedule, the maximum water table height above drain level was predicted during the cropping period.

Adopting a systematic search the spacing L for the assumed value of d was found for which the water table remains maximum for one day continously within the root zone. The water table may enter several times during the cropping period.

The depth and spacing for which the constraint is satisfied are presented in Table 3.1. For placement of the drain 1.40 m below ground surface, the maximum spacing for which the water logging condition is not violated is 120 m. For L = 120 m and d = 1.40 m, the water level enters root zone depth on the days of irrigation application but leaves the root zone within 1 day. This could be seen from Table 3.1.

The fluctuation in maximum water table height during cropping period is presented in Figure 3.2. It is seen that by increasing the depth to drain level from ground surface, the entry of maximum water table height to root zone is delayed. The results presented in Figure 3.2. are for possible depth of placement and spacing of drains.

The relation of depth and maximum spacing for which the water logging constraint is satisfied (ie. violated only for a maximum of one day continously) is shown in Figure 3.3. From the figure it is seen that as the depth of placement increases the spacing increases. As the drain depth approaches the impermeable boundary, the spacing increases significantly. The graph has flatter slope for small as well has high values of depth of placement indicating rapid variation in spacing.

The evolution of water table between two drains are shown in Figure 3.4. for certain depth of placement of drain below ground surface and spacing of drain.

The costs of material and excavation for the feasible depth and spacing are given in Table 3.2. (Example for economical cost calculation is enclosed in Appendix 1). The variation of excavation cost, material cost and total cost with spacing are presented in Figure in 3.5. The graph does not exhibit a sharp stationary point. From this graph, the optimal spacing can be taken as 267 m.

Table 3.1. Water Table Height during Time Step for Various Depth and Spacing (Root Zone Depth = 1.20 m below Ground Surface)

Depth below G.S. (m)	Spacing (m)	Ni (days)	Ni+1 (days)	h{Ni} (m)	h {Ni+1} (m)
1.40	118.00	37	38	0.20284	0.19051
Critical height 0.20 m		47	48	0.20635	0.19355
		57	58	0.20717	0.19426
		67	68	0.20736	0.19443
		77	78	0.20741	0.19447
		87	88	0.20742	0.19448
		97	98	0.20742	0.19448
		107	108	0.20742	0.19448
		117	118	0.20742	0.19448
		127	128	0.20742	0.19448
		137	138	0.20742	0.19448
	119.00	37	38	0.20445	0.19229
		47	48	0.20813	0.19548
		57	58	0.20902	0.19625
		67	68	0.20923	0.19643
		77	78	0.20928	0.19647
		87	88	0.20929	0.19649
		97	98	0.20930	0.19649
		107	108	0.20930	0.19649
		117	118	0.20930	0.19649
		127	128	0.20930	0.19649
		137	138	0.20930	0.19649
	120.00	37	38	0.20608	0.19407
		47	48	0.20994	0.19742
		57	58	0.21088	0.19825
		67	68	0.21112	0.19845
		77	78	0.21119	0.19850
		87	88	0.21119	0.19851
		97	98	0.21120	0.19851
		107	108	0.21120	0.19852
		117	118	0.21120	0.19852
		127	128	0.21120	0.19852
		137	138	0.21120	0.19852
	121.00	37	38	0.20773	0.19586
		47	48	0.21176	0.19937
		57	58	0.21278	0.20026
		67	68	0.21303	0.20048
		77	78	0.21310	0.20054
		87	88	0.21312	0.20055
		97	98	0.21312	0.20056
		107	108	0.21312	0.20056
		117	118	0.21312	0.20056
		127	128	0.21312	0.20056
		137	138	0.21312	0.20056

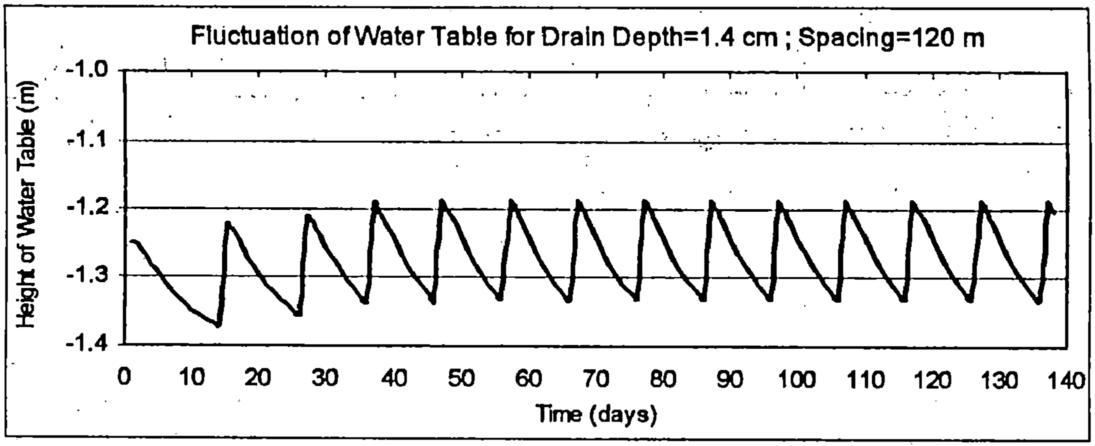
1.50 Critical height 0.30 m	157.00	67	68	0.30223	0.29018
		77	78	0.30353	0.29139
		87	88	0.30412	0.29193
		97	98	0.30438	0.29217
		107	108	0.30450	0.29228
		117	118	0.30455	0.29233
		127	128	0.30458	0.29235
		137	138	0.30459	0.29236
	158.00	57	58	0.30195	0.2901
		67	68	0.30498	0.2929
		77	78	0.30635	0.29417
		87	88	0.30698	0.29475
		97	98	0.30726	0.29501
		107	108	0.30739	0.29513
		117	118	0.30745	0.29518
		127	128	0.30748	0.29521
		137	138	0.30749	0.29522
	159.00	57	58	0.30458	0.2927
		67	68	0.30774	0.29563
		77	78	0.30919	0.29697
		87	88	0.30986	0.29759
		97	98	0.31017	0.29787
		107	108	0.31031	0.298
		117	118	0.31037	0.29806
		127	128	0.31040	0.29809
		137	138	0.31042	0.2981
	160.00	47	48	0.30009	0.28871
		57	58	0.30721	0.29531
		67	68	0.31052	0.29837
		77	78	0.31205	0.29979
		87	88	0.31276	0.30045
		97	98	0.31309	0.30075
		107	108	0.31324	0.30090
		117	118	0.31332	0.30096
		127	128	0.31335	0.30099
		137	138	0.31336	0.30101

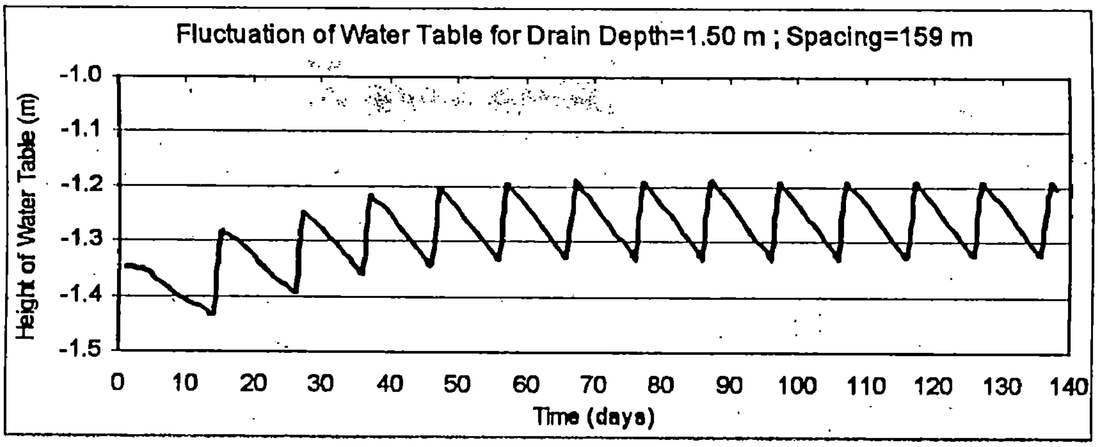
1.60 Critical height 0.40 m	186.00	87	88	0.40029	0.38866
		97	98	0.40381	0.39029
		107	108	0.40480	0.39123
		117	118	0.40537	0.39176
		127	128	0.40570	0.39207
		137	138	0.40589	0.39225
	187.00	77	78	0.40236	0.38907
		87	88	0.40549	0.39203
		97	98	0.40729	0.39374
		107	108	0.40834	0.39472
		117	118	0.40894	0.3953
		127	128	0.40929	0.39563
		137	138	0.40949	0.39582
	188.00	67	68	0.40004	0.38701
		77	78	0.40564	0.39232
		87	88	0.40890	0.39541
		97	98	0.41079	0.3972
		107	108	0.41189	0.39824
		117	118	0.41253	0.39885
		127	128	0.41290	0.3992
		137	138	0.41312	0.3994
	189.00	67	68	0.40313	0.39009
		77	78	0.40893	0.39559
		87	88	0.41232	0.39880
		97	98	0.41430	0.40068
		107	108	0.41546	0.40117
		117	118	0.41614	0.40242
		127	128	0.41653	0.40279
		137	138	0.41676	0.40301
1.70 Critical height 0.50 m	209.00	107	108	0.50023	0.48596
		117	118	0.50226	0.48791
		127	128	0.50358	0.48918
		137	138	0.50445	0.49000
	210.00	97	98	0.50091	0.48676
		107	108	0.50415	0.48986
		117	118	0.50626	0.49189
		127	128	0.50765	0.49322
		137	138	0.50856	0.49409
	211.00	97	98	0.50471	0.49055
		107	108	0.50807	0.49377
		117	118	0.51028	0.49589
		127	128	0.51173	0.49728
		137	138	0.51269	0.4982

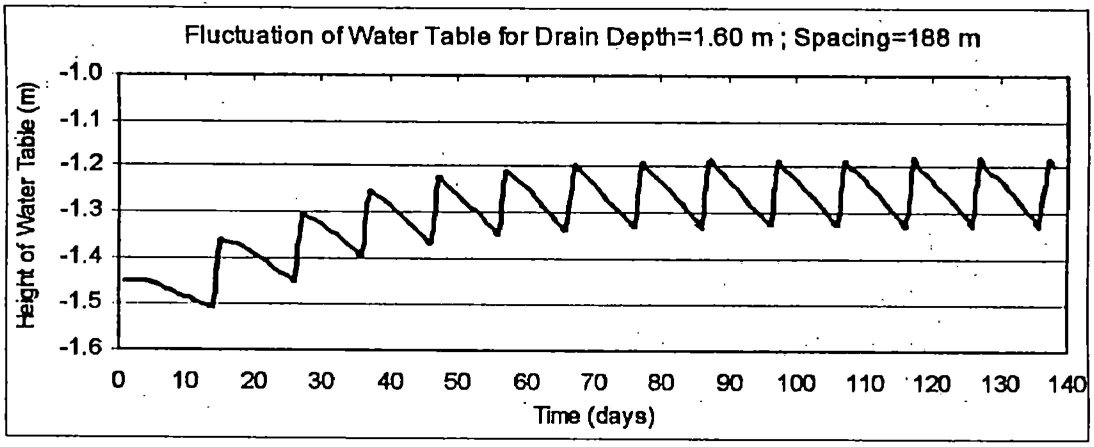
	212.00	87	88	0.50324	0.48929
		97	98	0.50853	0.49435
		107	108	0.51201	0.49770
		117	118	0.51431	0.49990
		127	**128**	**0.51583**	**0.50136**
		137	**138**	**0.51683**	**0.50232**
1.80	229.00	127	128	0.60047	0.58376
		137	138	0.60280	0.58802
Critical height	230.00	117	118	0.60143	0.58684
0.60 m		127	128	0.60485	0.59014
		137	138	0.60727	0.59248
	231.00	107	108	0.60074	0.58631
		117	118	0.60571	0.59111
		127	128	0.60924	0.59453
		137	138	0.61175	0.59696
	232.00	107	108	0.60486	0.59044
		117	118	0.60999	0.59540
		127	128	0.61364	0.59893
		137	**138**	**0.61625**	**0.60145**
1.90	248.00	127	128	0.70024	0.68559
		137	138	0.70511	0.69032
Critical height	249.00	127	128	0.70481	0.69017
0.70 m		137	138	0.70982	0.69504
	250.00	117	118	0.70254	0.68810
		127	128	0.70938	0.69475
		137	138	0.71454	0.69976
	251.00	117	118	0.70694	0.69251
		127	128	0.71396	0.69934
		137	**138**	**0.71926**	**0.70449**
2.00	265.00	137	138	0.80354	0.78897
Critical height 0.80 m	266.00	137	138	0.80837	0.79382
	267.00	127	128	0.80449	0.79016
		137	138	0.81321	0.79867
	268.00	127	128	0.80912	0.79482
		137	**138**	**0.81804**	**0.80352**

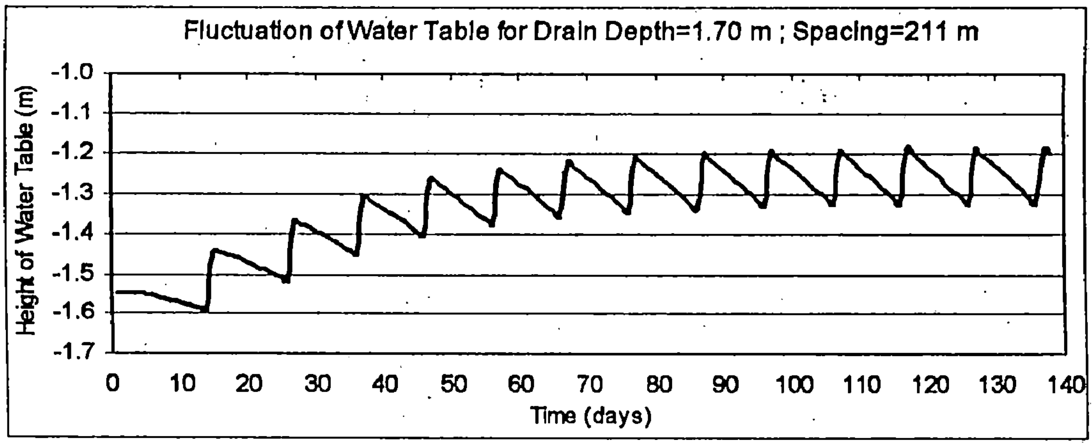
2.10 Critical height 0.90 m	281.00	137	138	0.90029	0.88610
	282.00	137	138	0.90515	0.89098
	283.00	137	138	0.91000	0.89586
	284.00	127 137	128 138	0.90144 0.91485	0.89760 0.90073
2.20 Critical height 1.00 m	298.00	137	138	1.00323	0.98959
	299.00	137	138	1.00802	0.99441
	300.00	137	138	1.01280	0.99922
	301.00	137	138	1.01758	1.00402
2.30 Critical height 1.10 m	314.00	137	138	1.10108	1.08806
	315.00	137	138	1.10574	1.09275
	316.00	137	138	1.11038	1.09742
	317.00	137	138	1.11501	1.10208
2.40 Critical height 1.20 m	331.00	137	138	1.20179	1.18950
	332.00	137	138	1.20623	1.19348
	333.00	137	138	1.21066	1.19844
	334.00	137	138	1.21508	1.20290
2.50 Critical height 1.30 m	348.00	137	138	1.29925	1.28774
	349.00	137	138	1.30344	1.29197
	350.00	137	138	1.30760	1.29618
	351.00	137	138	1.31176	1.30037

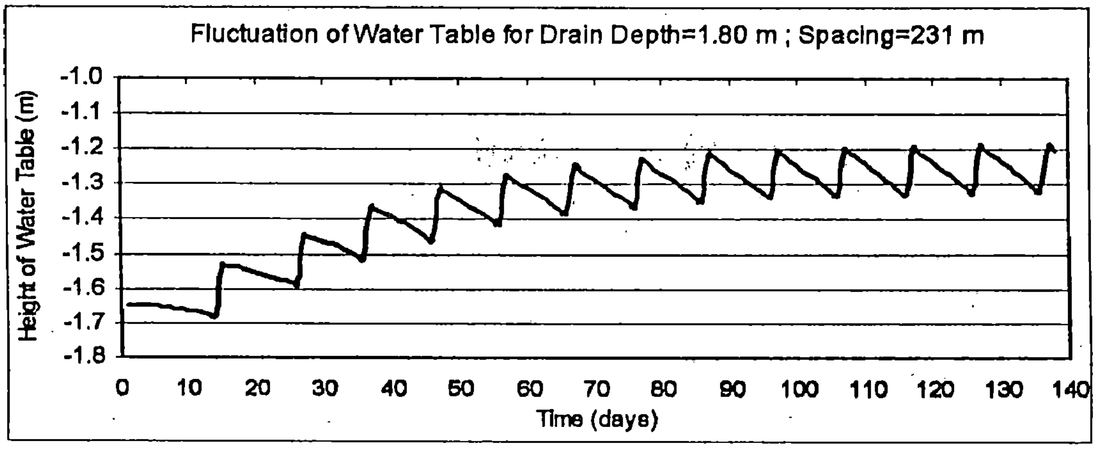
Figure 3.2. Fluctuation of Water Table for Different Depth and Spacing (Root Zone Depth = 1.20 m below Ground Surface)

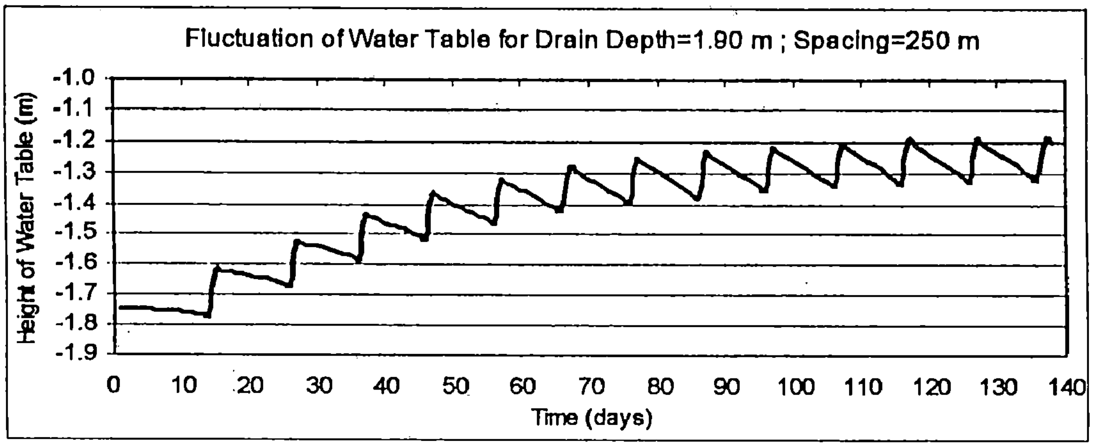


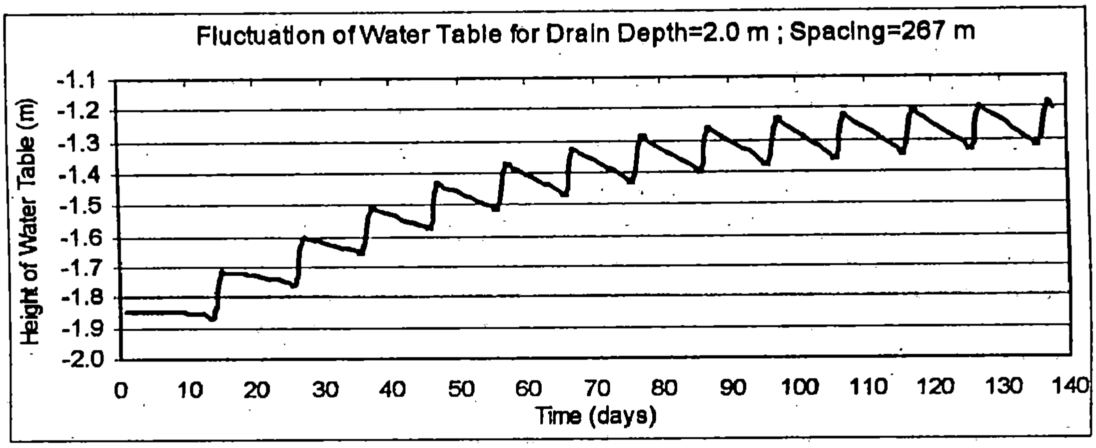


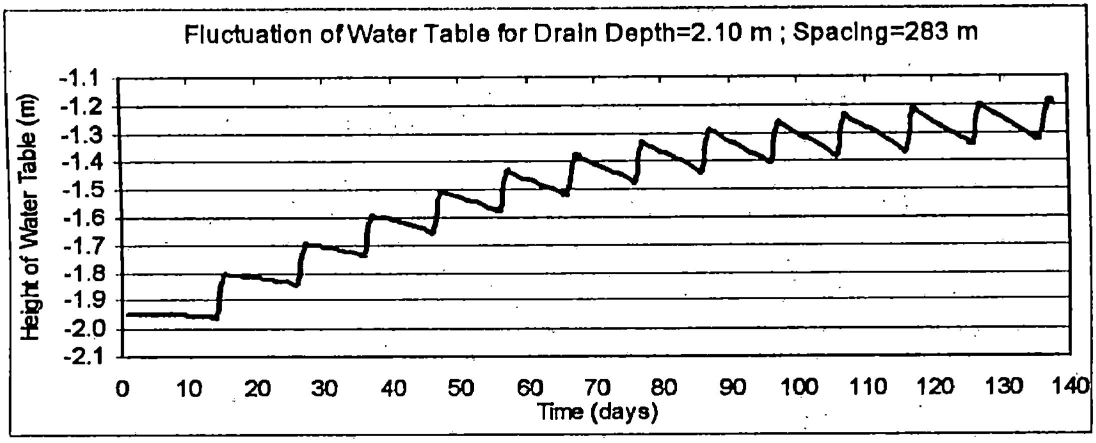


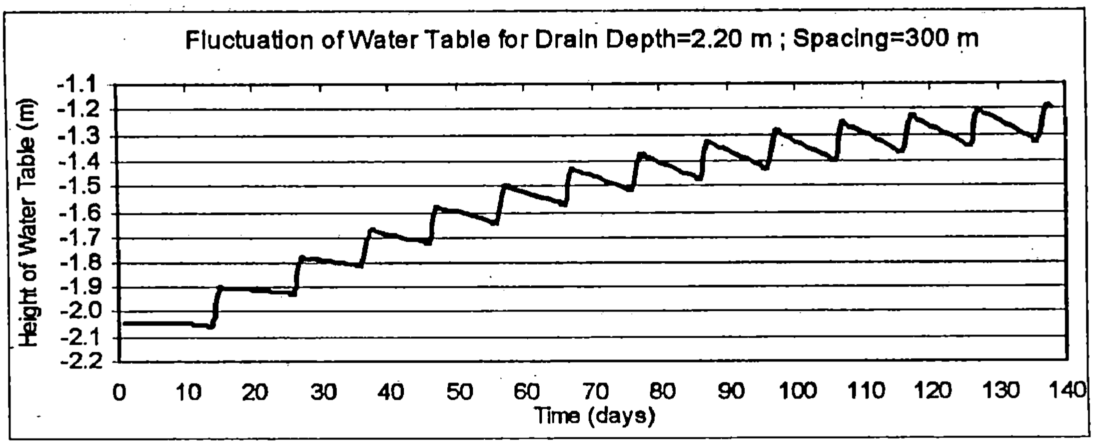

Fluctuation of Water Table for Drain Depth=1.70 m ; Spacing=211 m
Height of Water Table (m)
-1.0
-1.1
-1.2
-1.3
-1.4
-1.5
-1.6
-1.7
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Time (days)

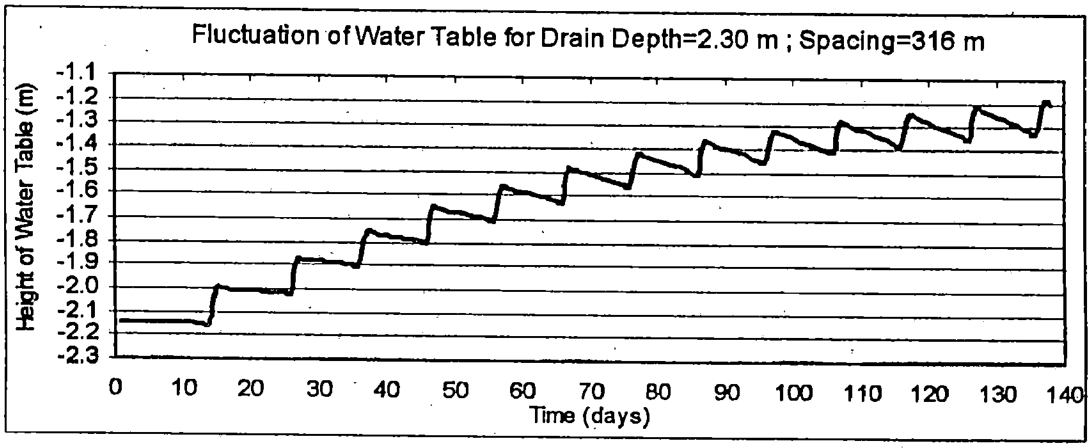

Fluctuation of Water Table for Drain Depth=1.80 m ; Spacing=231 m
Height of Water Table (m)
-1.0
-1.1
-1.2
-1.3
-1.4
-1.5
-1.6
-1.7
-1.8
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Time (days)

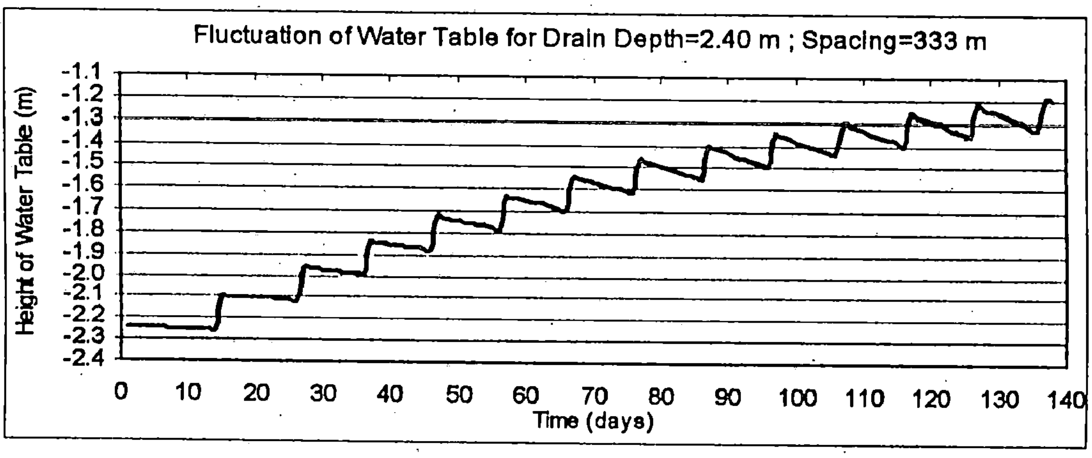

Fluctuation of Water Table for Drain Depth=1.90 m ; Spacing=250 m
Height of Water Table (m)
-1.0
-1.1
-1.2
-1.3
-1.4
-1.5
-1.6
-1.7
-1.8
-1.9
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Time (days)

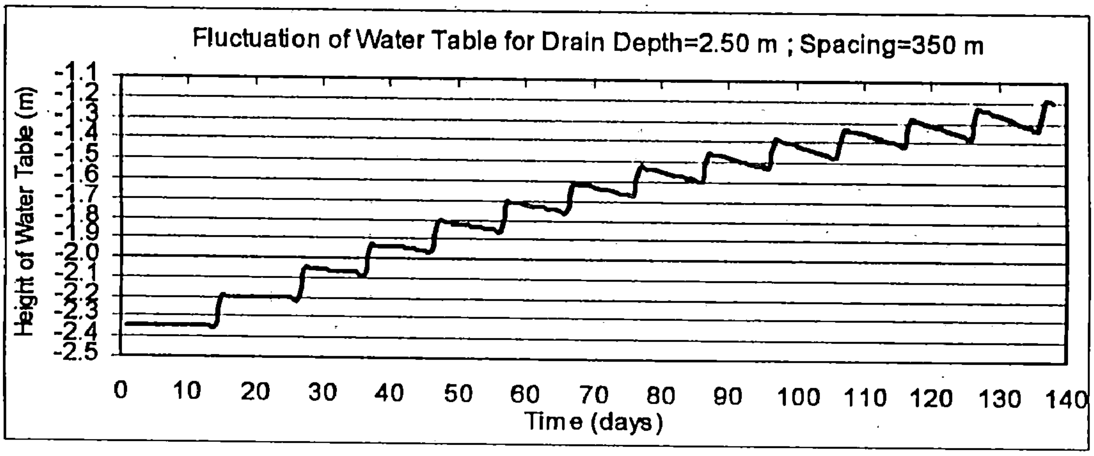

Fluctuation of Water Table for Drain Depth=2.0 m ; Spacing=267 m
Height of Water Table (m)
-1.1
-1.2
-1.3
-1.4
-1.5
-1.6
-1.7
-1.8
-1.9
-2.0
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Time (days)

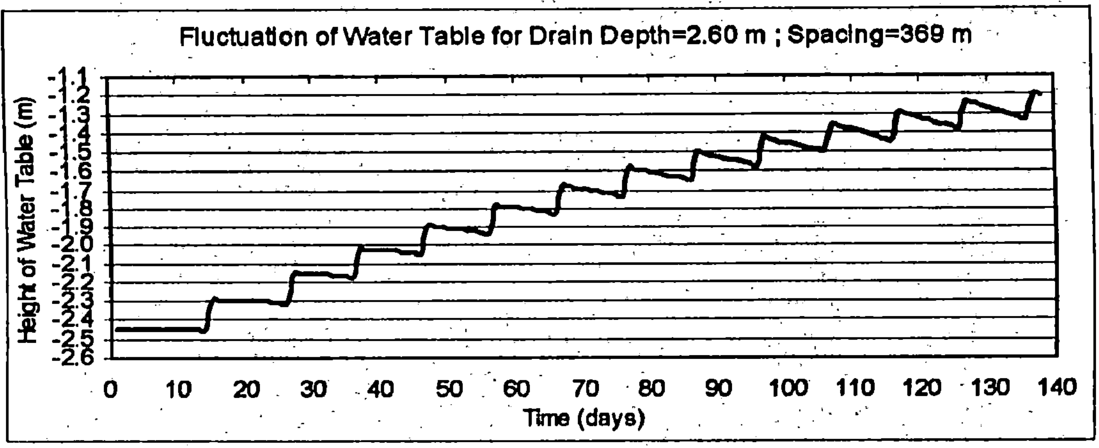

Fluctuation of Water Table for Drain Depth=2.10 m ; Spacing=283 m
Height of Water Table (m)
-1.1
-1.2
-1.3
-1.4
-1.5
-1.6
-1.7
-1.8
-1.9
-2.0
-2.1
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Time (days)

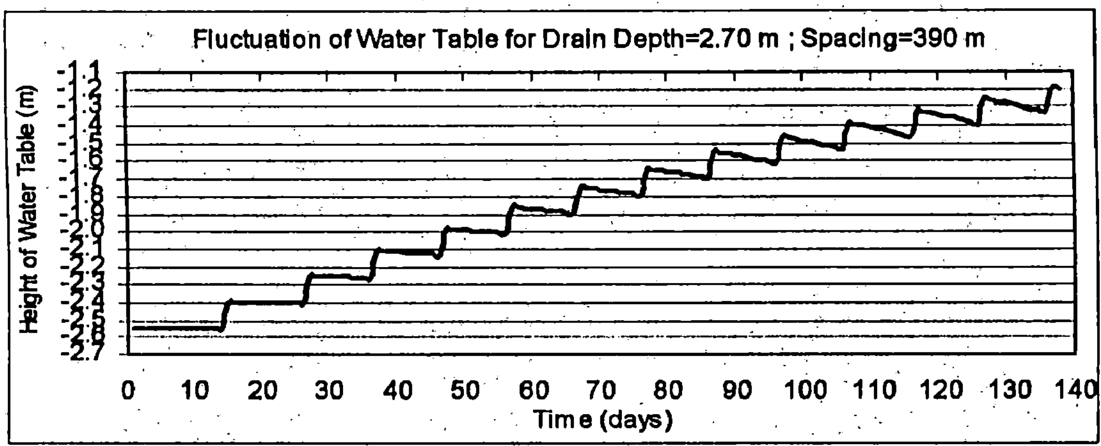

Fluctuation of Water Table for Drain Depth=2.20 m ; Spacing=300 m
Height of Water Table (m)
-1.1
-1.2
-1.3
-1.4
-1.5
-1.6
-1.7
-1.8
-1.9
-2.0
-2.1
-2.2
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Time (days)


Fluctuation of Water Table for Drain Depth=2.30 m ; Spacing=316 m
Height of Water Table (m)
-1.1
-1.2
-1.3
-1.4
-1.5
-1.6
-1.7
-1.8
-1.9
-2.0
-2.1
-2.2
-2.3
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Time (days)


Fluctuation of Water Table for Drain Depth=2.40 m ; Spacing=333 m
Height of Water Table (m)
-1.1
-1.2
-1.3
-1.4
-1.5
-1.6
-1.7
-1.8
-1.9
-2.0
-2.1
-2.2
-2.3
-2.4
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Time (days)


Fluctuation of Water Table for Drain Depth=2.50 m ; Spacing=350 m
Height of Water Table (m)
-1.1
-1.2
-1.3
-1.4
-1.5
-1.6
-1.7
-1.8
-1.9
-2.0
-2.1
-2.2
-2.3
-2.4
-2.5
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Time (days)





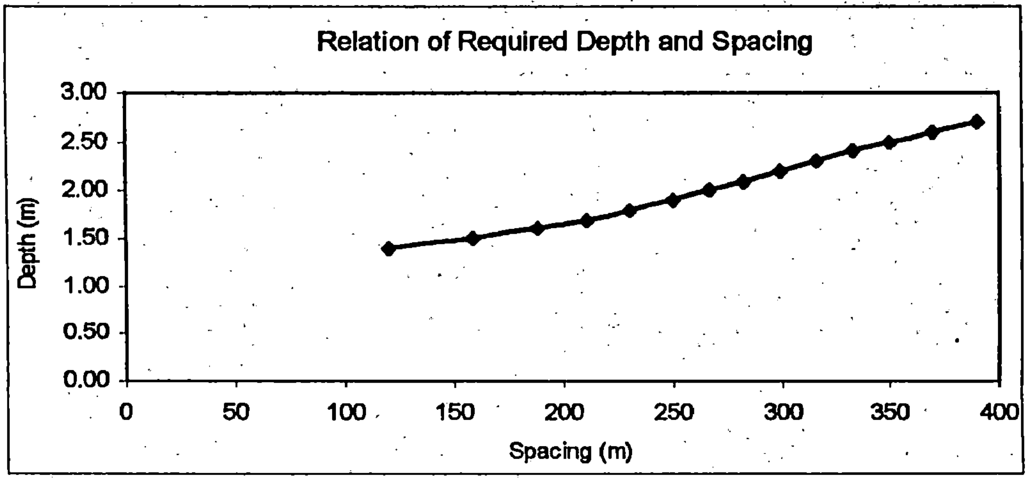
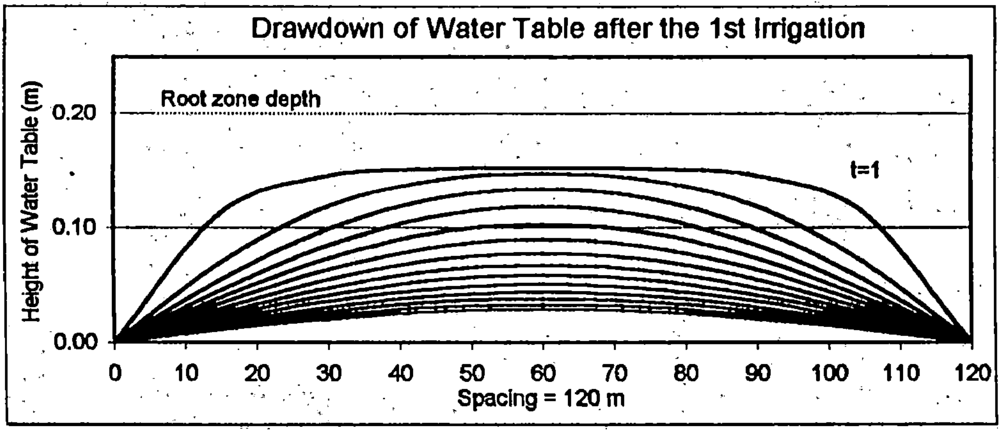
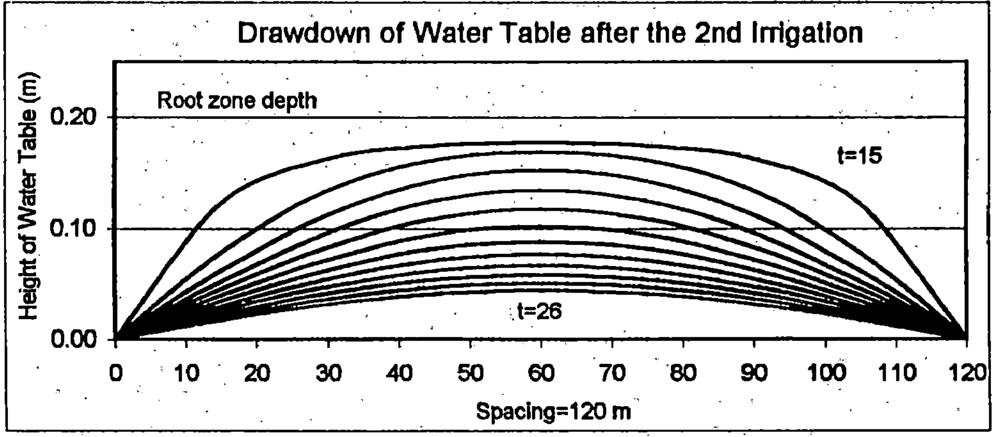
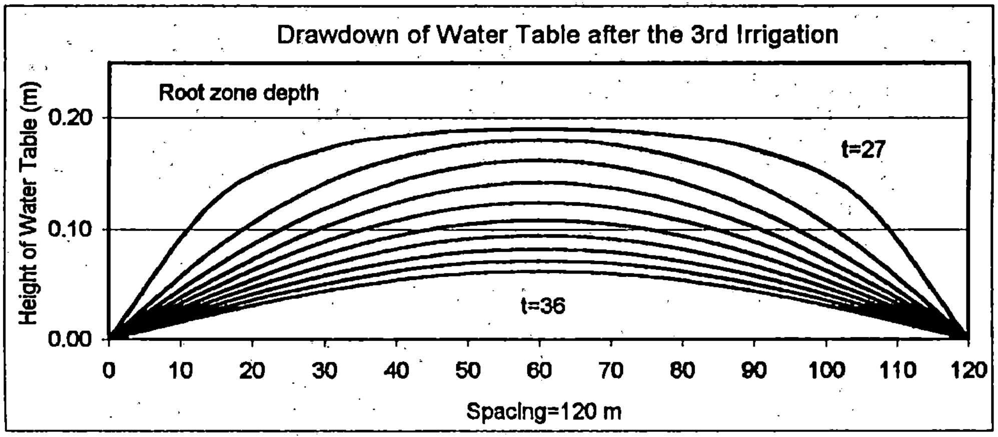


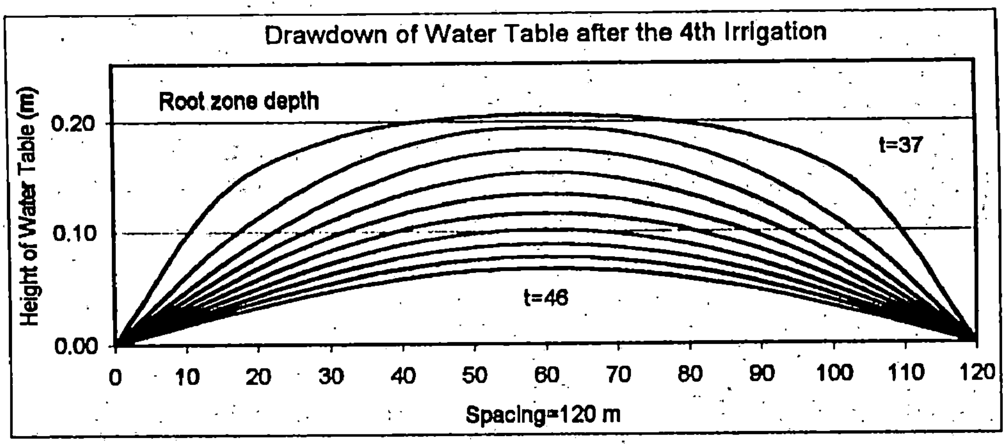
Fig. 3.3. Relation of Required Depth and Spacing

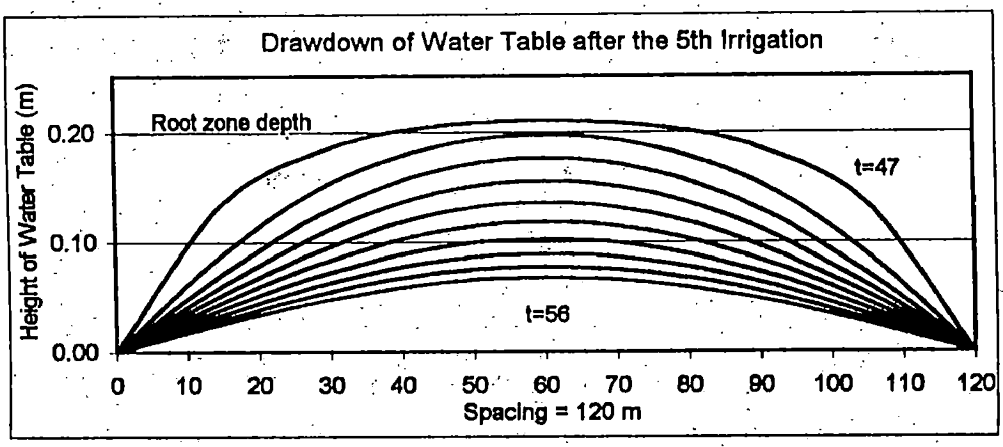
Figure 3.4. Drawdown of Water Table during Irrigation Period for Drain Depth=1.40 m and Spacing=120 m (Root zone depth=1.20 m)

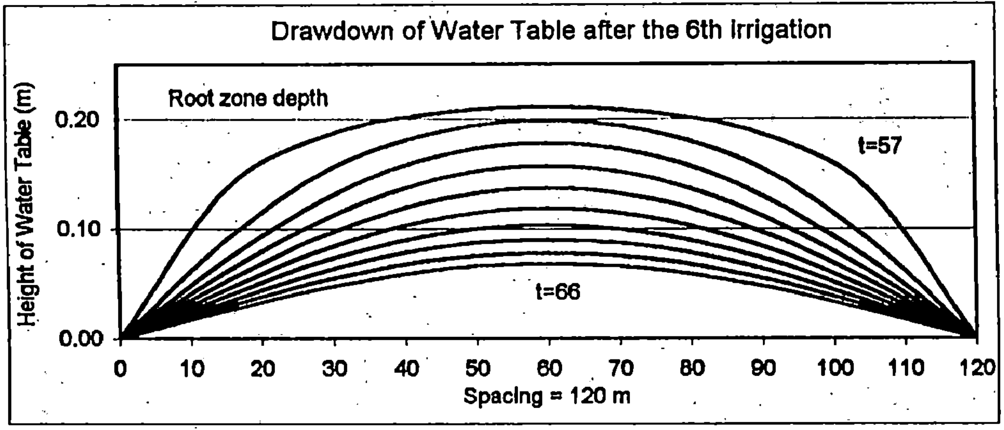


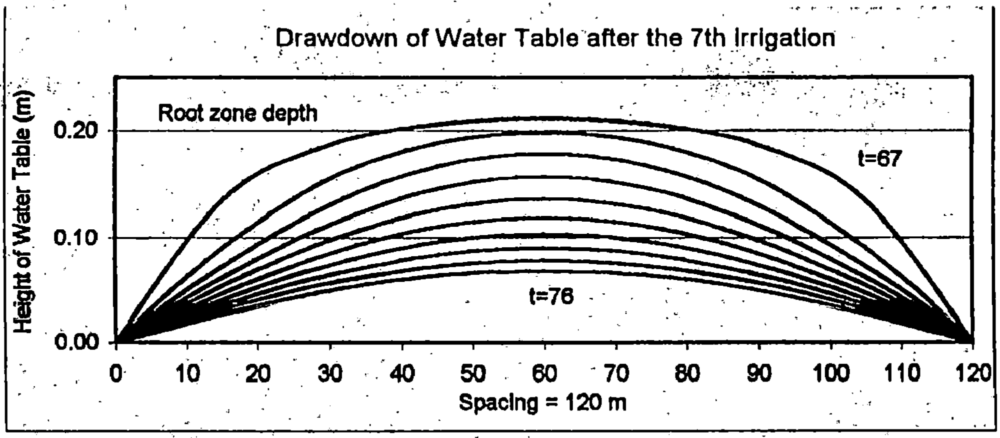


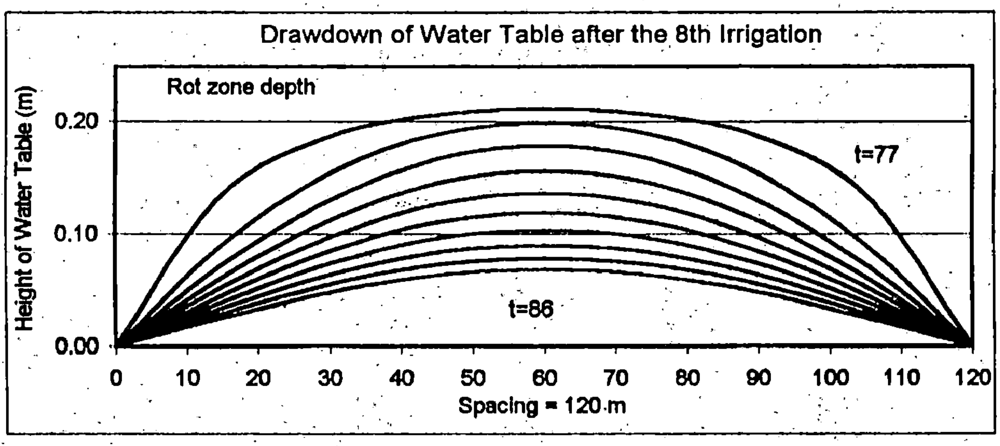


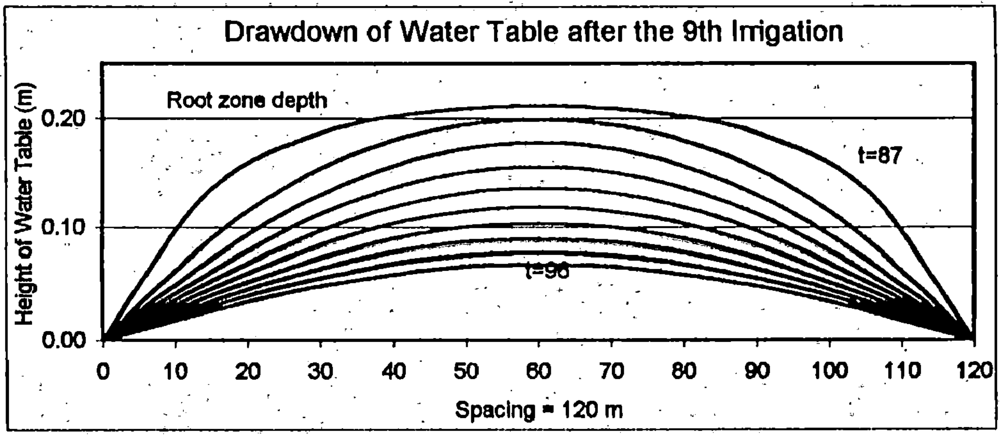

Drawdown of Water Table after the 4th Irrigation

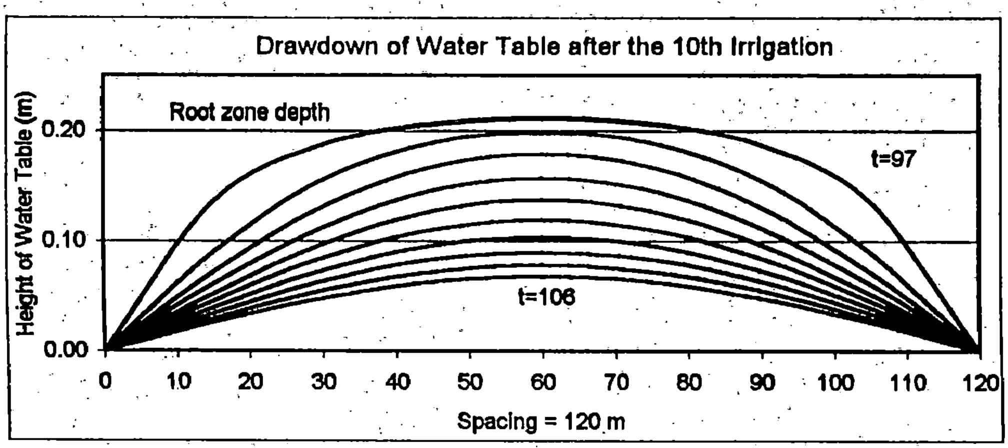

Drawdown of Water Table after the 5th Irrigation

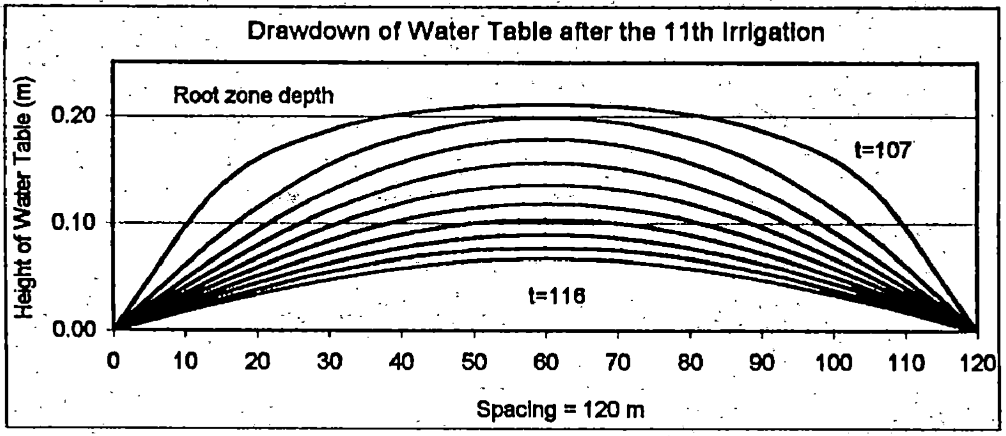

Drawdown of Water Table after the 6th Irrigation

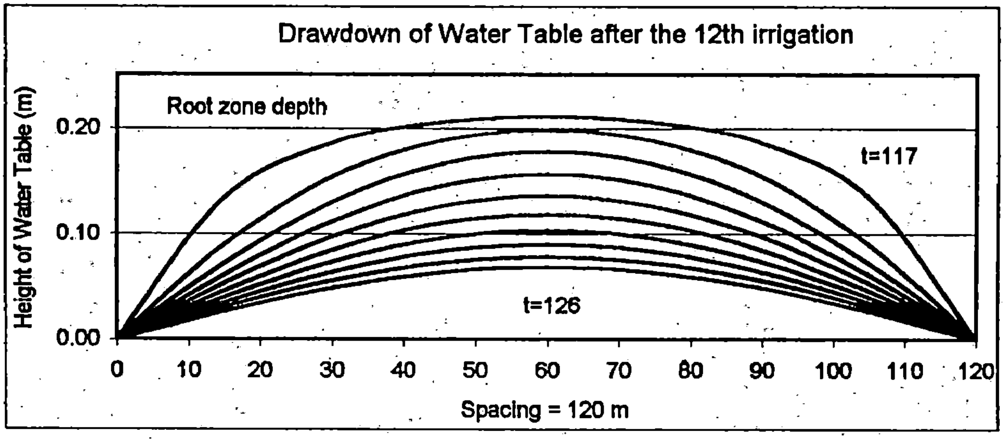

Drawdown of Water Table after the 7th Irrigation
Root zone depth
t=67
t=76
Height of Water Table (m)
0.20
0.10
0.00
0
10
20
30
40
50
60
70
80
90
100
110
120
Spacing = 120 m

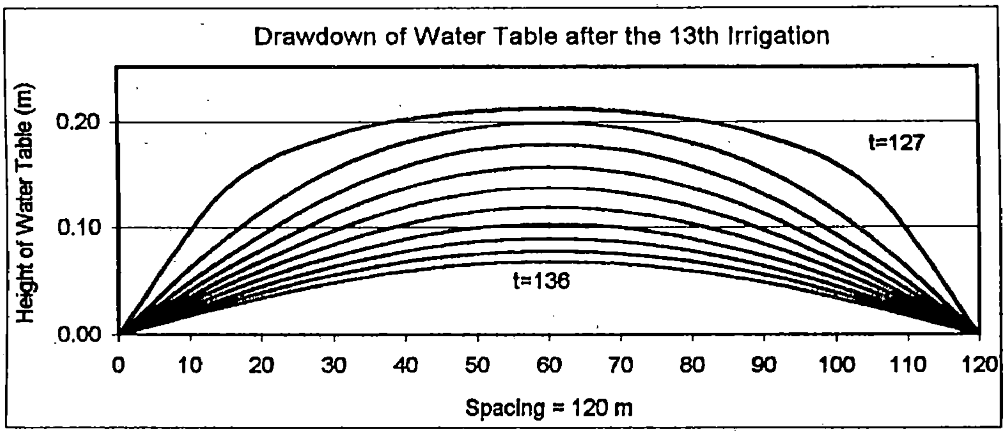

Drawdown of Water Table after the 8th Irrigation
Rot zone depth
t=77
t=86
Height of Water Table (m)
0.20
0.10
0.00
0
10
20
30
40
50
60
70
80
90
100
110
120
Spacing = 120 m


Drawdown of Water Table after the 9th Irrigation
Root zone depth
t=87
t=96
Height of Water Table (m)
0.20
0.10
0.00
0
10
20
30
40
50
60
70
80
90
100
110
120
Spacing = 120 m


Drawdown of Water Table after the 10th Irrigation
Root zone depth
t=97
t=106
Height of Water Table (m)
0.20
0.10
0.00
0
10
20
30
40
50
60
70
80
90
100
110
120
Spacing = 120 m


Drawdown of Water Table after the 11th Irrigation
Root zone depth
t=107
t=116
Height of Water Table (m)
0.20
0.10
0.00
0
10
20
30
40
50
60
70
80
90
100
110
120
Spacing = 120 m


Drawdown of Water Table after the 12th irrigation
Root zone depth
t=117
t=126
Height of Water Table (m)
0.20
0.10
0.00
0
10
20
30
40
50
60
70
80
90
100
110
120
Spacing = 120 m


Drawdown of Water Table after the 13th Irrigation
Height of Water Table (m)
0.20
0.10
0.00
t=127
t=136
0
10
20
30
40
50
60
70
80
90
100
110
120
Spacing = 120 m

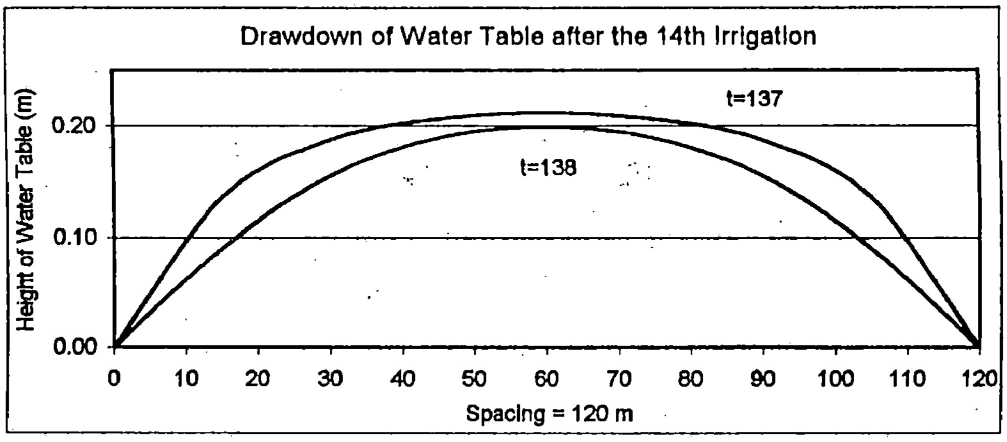

Drawdown of Water Table after the 14th Irrigation
Height of Water Table (m)
0.20
0.10
0.00
t=137
t=138
0
10
20
30
40
50
60
70
80
90
100
110
120
Spacing = 120 m

Table 3.2. Calculation of Drain Spacing and Cost for Various Depth

Depth of Drain (m)	Drain Spacing (m)	Total Length of Pipe (m)	Total Cost of Pipe (Rs)	Total Cost of Excavation (Rs)	Total Cost of Excavation and Pipe (Rs)
1.40	120.00	5000.00	525000.00	489566.89	1014566.89
1.50	159.00	3773.58	396226.42	426146.38	822372.79
1.60	188.00	3191.49	335106.38	406264.66	741371.05
1.70	211.00	2843.60	298578.20	405500.95	704079.14
1.80	231.00	2597.40	272727.27	412618.38	685345.65
1.90	250.00	2400.00	252000.00	422595.75	674595.75
2.00	**267.00**	**2247.19**	**235955.06**	**436598.20**	**672553.26**
2.10	283.00	2120.14	222614.84	452621.68	675236.52
2.20	300.00	2000.00	210000.00	467394.41	677394.41
2.30	316.00	1898.73	199367.09	484049.47	683416.56
2.40	333.00	1801.80	189189.19	499473.28	688662.47
2.50	350.00	1714.29	180000.00	515205.64	695205.64

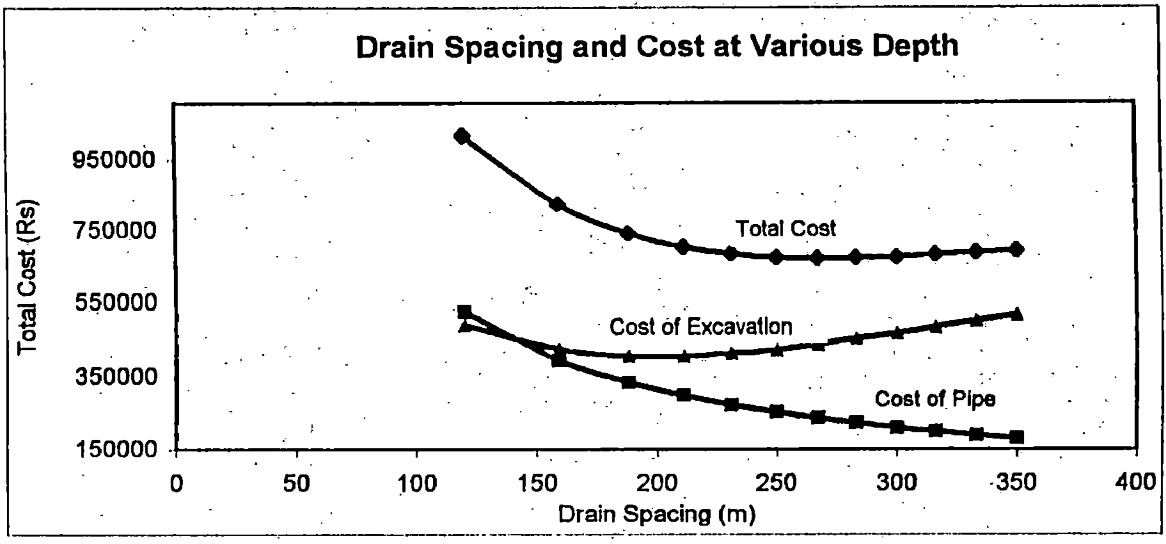


Fig. 3.5. Drain Spacing and Cost at Various Depth

3.4. CASE 2 : DRAINAGE COEFFICIENT ORIGINATING BOTH FROM LOCAL AS WELL AS EXTERNAL SOURCE

3.4.1. Statement of the Problem

The water level rise, due to the prevaling irrigation practice, in an observation well in an irrigated area is shown in figure 3.5. The drain is to be placed at a depth d_p meter below the ground surface. The rate of water table rise in the irrigated area at this position of drain is $\Delta h/\Delta t$, in which Δh is the rise above the proposed drain level in time interval Δt. Hence, the external recharge rate is $\Delta h.\phi/\Delta t$. The water table will continue to rise because of seepage from external source and local irrigation application. It is assumed that the external recharge rate is constant. The time is reckoned since water table rises above the level of proposed drain placement. Since the local irrigation has contributed to the water level rises, only the remaining irrigation application after water level in the aquifer reaches the drain level will be considered for finding the water level evolution after placement of drain pipes. It is required to determine the height of water table governed by depth and spacing of the drains so that the permissible depth of water table below ground surface is equal to 1.20 m. The water table may enter several times to the root zone depth during the cropping period but the water table is permitted to stay only for a maximum one day continously in the root zone. It is possible to achieve this goal, placing the drains at different depth and spacing. It is aimed to find the optimal depth and spacing for which the provision of drainage is economical. The drains are perforated pipe. Cost of pipe and cost of excavation in relation to the depth drain are known.

The minimization of problem can be stated as,

$$\min_{L,\, dp} \{ C = C_P + C_E \}$$

$$\text{Subject to} \quad h(L/2,N_i) > (d_p - d_r)$$

$$h(L/2,N_i+1) < d_p - d_r)$$

where :

$$h(L/2,N_i) = R.K(N_i) + \sum_{\gamma=1}^{Ni} Q(\gamma).\delta(N_i-\gamma+1)$$

N_i = time step during which the water table enters the root zone depth

$N_i + 1$ = time step during which the water table is below the root zone

C = total cost of sub surface field drainage system

C_P = cost of pipe

C_E = cost of excavation

L = spacing of drains

d_p = depth of drain below ground surfce

d_r = depth of root zone below ground surface

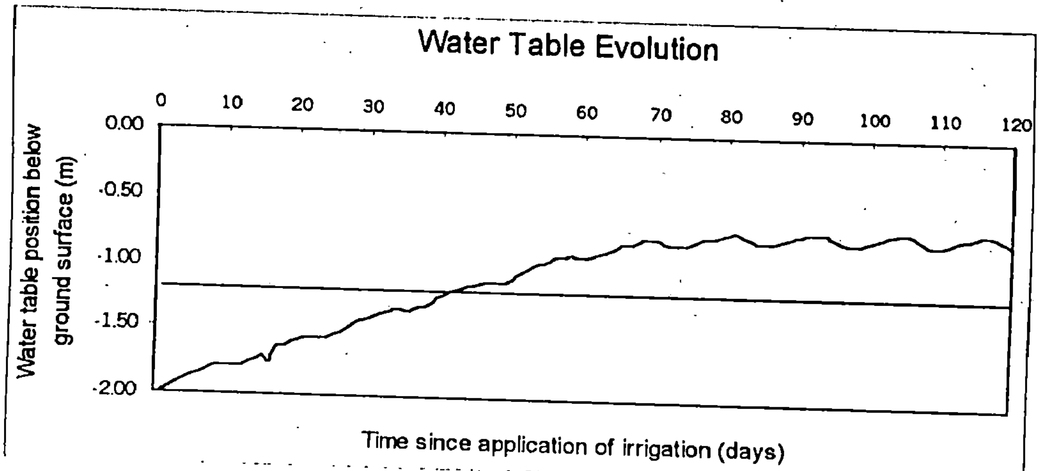


Figure 3.6. Water Level Rise due to Prevalling Irrigation Practice

The maximum water level height, h, is given by,

$$h(L/2,N) = R.K(N) + \sum_{\gamma=1}^{N} Q(\gamma).\delta(N-\gamma+1)$$

in which :

$$R = \phi \frac{\Delta h}{\Delta t}\bigg|_{h=dp}$$

$$K(N) = \frac{L^2}{8T} - \frac{4L^2}{T\pi^3} \sum_{n=1,3,5...}^{\infty} \left[\frac{1}{n^3} \exp(-n^2\pi^2 \frac{\alpha t}{L^2}) \sin(\frac{n\pi}{2}) \right]$$

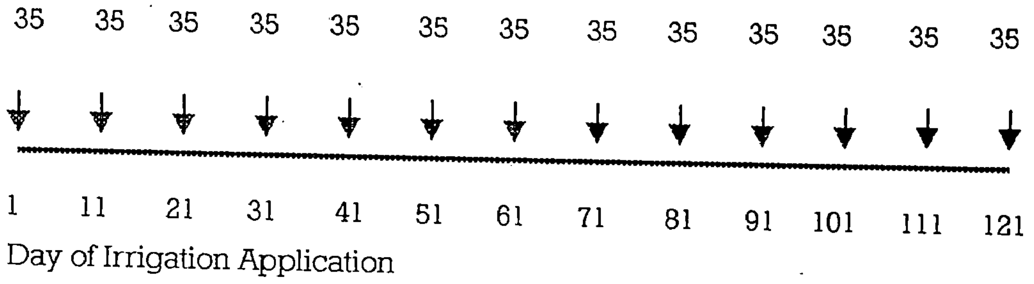
γ is counted since water from external source and local application enters drain level.

3.4.3. Data Used in the Study

The data used in the study are,

- Irrigation Application

  1. Number of irrigation for particular crop is 12 times
  2. Interval between two irrigations is 10 days
  3. Deep percolation as a recharge rate (Q) = 35 mm for each irrigation.



1. Type of soil is sandy loam with value of hydraulic conductivity (k) = 11.4 m/day.
2. The value of specific yield (ϕ) = 0.23.
3. Depth to impermeable layer from ground surface = 5.5 m
4. Depth of root zone = 1.2 m
5. The water table evolution in the irrigated area is shown in table 3.3.

Table 3.3. Water Level Rise due to Prevaling Irrigation in an Observation Well in Irrigated Area

Days	Depth to WT	Rise of WT	Days	Depth to WT	Rise of WT	Days	Depth to WT	Rise of WT
1	-1.980	0.020	41	-1.211	0.029	81	-0.725	0.002
2	-1.959	0.021	42	-1.197	0.014	82	-0.734	-0.009
3	-1.924	0.035	43	-1.176	0.021	83	-0.760	-0.026
4	-1.889	0.035	44	-1.154	0.022	84	-0.788	-0.028
5	-1.861	0.028	45	-1.143	0.011	85	-0.798	-0.010
6	-1.846	0.015	46	-1.134	0.009	86	-0.799	-0.001
7	-1.825	0.021	47	-1.136	-0.002	87	-0.781	0.018
8	-1.804	0.021	48	-1.134	0.002	88	-0.762	0.019
9	-1.792	0.012	49	-1.134	0.000	89	-0.746	0.016
10	-1.783	0.009	50	-1.093	0.041	90	-0.740	0.006
11	-1.786	-0.003	51	-1.058	0.035	91	-0.725	0.015
12	-1.784	0.002	52	-1.023	0.035	92	-0.711	0.014
13	-1.763	0.021	53	-0.995	0.028	93	-0.710	0.001
14	-1.742	0.021	54	-0.981	0.014	94	-0.720	-0.010
15	-1.708	0.034	55	-0.960	0.021	95	-0.746	-0.026
16	-1.672	0.036	56	-0.938	0.022	96	-0.777	-0.031
17	-1.644	0.028	57	-0.928	0.010	97	-0.789	-0.012
18	-1.630	0.014	58	-0.923	0.005	98	-0.791	-0.002
19	-1.609	0.021	59	-0.930	-0.007	99	-0.775	0.016
20	-1.587	0.022	60	-0.936	-0.006	100	-0.756	0.019
21	-1.576	0.011	61	-0.923	0.013	101	-0.741	0.015
22	-1.567	0.009	62	-0.908	0.015	102	-0.735	0.006
23	-1.569	-0.002	63	-0.879	0.029	103	-0.720	0.015
24	-1.567	0.002	64	-0.851	0.028	104	-0.706	0.014
25	-1.547	0.020	65	-0.829	0.022	105	-0.705	0.001
26	-1.526	0.021	66	-0.819	0.010	106	-0.715	-0.010
27	-1.491	0.035	67	-0.802	0.017	107	-0.743	-0.028
28	-1.456	0.035	68	-0.784	0.018	108	-0.774	-0.031
29	-1.428	0.028	69	-0.780	0.004	109	-0.787	-0.013
30	-1.413	0.015	70	-0.784	-0.004	110	-0.789	-0.002
31	-1.392	0.021	71	-0.804	-0.020	111	-0.773	0.016
32	-1.371	0.021	72	-0.826	-0.022	112	-0.754	0.019
33	-1.359	0.012	73	-0.829	-0.003	113	-0.739	0.015
34	-1.351	0.008	74	-0.825	0.004	114	-0.733	0.006
35	-1.353	-0.002	75	-0.804	0.021	115	-0.719	0.014
36	-1.351	0.002	76	-0.782	0.022	116	-0.704	0.015
37	-1.331	0.020	77	-0.765	0.017	117	-0.704	0.000
38	-1.309	0.022	78	-0.765	0.000	118	-0.714	-0.010
39	-1.275	0.034	79	-0.742	0.023	119	-0.742	-0.028
40	-1.240	0.035	80	-0.727	0.015	120	-0.773	-0.031

3.4.4. Result and Discussion

The rate of water table rise is determined from table 3.3. which shows the water table fluctuation for 120 days in an irrigated area. The rate of rise is different for different time and depth of proposed drain. The calculation of recharge rate as external recharge is shown in Table 3.4.

Table 3.4. Rate of Water Table Rise at Different Depth

DEPTH (m)	RISE (m)	SPECIFIC YIELD, ϕ	RECHARGE (m/day)	TOTAL IRRIGATION	REMAINING IRRIGATION
1.0	0.028	0.23	0.0064	12	6
1.1	0.041	0.23	0.0094	12	7
1.2	0.014	0.23	0.0032	12	7
1.3	0.034	0.23	0.0078	12	8
1.4	0.021	0.23	0.0048	12	8
1.5	0.035	0.23	0.0081	12	9
1.6	0.022	0.23	0.0051	12	10
1.7	0.036	0.23	0.0083	12	10
1.8	0.012	0.23	0.0028	12	11
1.9	0.035	0.23	0.0081	12	11
2.0	0.020	0.23	0.0046	12	12

To find the optimal design, maximum rate of water table rise is considered. For the present case, the maximum external recharge rate is 0.0094 m/day. It is assumed that this constant recharge rate takes place throughout the cropping period.

For different depth of placement, the maximum spacing can be known from Table 3.5. The variations of maximum water level height midway between the drains with time are shown in Figure 3.7. The variation of maximum water level height contains a steady part and an unsteady part. The steady part corresponds to the external steady drainage coefficient. The unsteady part is the response corresponding to the discontinous local irrigation application.

In Table 3.5, the evolution of maximum water level height for a particular depth of placement of the drain is shown for different spacing. The maximum spacing for a particular depth for which the water remains in the root zone continously for a maximum of one day only can be identified from the table. For example if the drains are placed at a depth 1.40 m below ground surface, the maximum allowable spacing that satisfies the drainage requirement is 64 m.

The relation between depth to drain and the feasible maximum spacing is shown in Figure 3.8. As envisaged, the maximum feasible spacing increases with increasing depth of placement of drains.

The cost of material and excavation cost are shown in Table 3.6 for different set of drain design. The variation of total cost with drain spacing is shown in Figure 3.8. It can be seen from the table that the optimal spacing is 127 m.

Table 3.5. Water Table Height during Time Step for Various Depth and Spacing (Root Zone Depth = 1.20 m)

Depth below G.S. (m)	Spacing (m)	NI (days)	Ni+1 (days)	h{NI} (m)	h {Ni+1} (m)
1.40	62.00	41	42	0.2356	0.1852
		51	52	0.2363	0.1857
Critical Height		61	62	0.2364	0.1857
0.20 m		71	72	0.2364	0.1857
		81	82	0.2364	0.1857
		91	92	0.2364	0.1857
		101	102	0.2364	0.1857
		111	112	0.2364	0.1857
	63.00	41	42	0.2395	0.1905
		51	52	0.2404	0.1911
		61	62	0.2404	0.1911
		71	72	0.2404	0.1911
		81	82	0.2404	0.1911
		91	92	0.2404	0.1911
		101	102	0.2404	0.1911
		111	112	0.2404	0.1911
	64.00	41	42	0.2434	0.1958
		51	52	0.2445	0.1965
		61	62	0.2445	0.1965
		71	72	0.2445	0.1965
		81	82	0.2445	0.1965
		91	92	0.2445	0.1965
		101	102	0.2445	0.1965
		111	112	0.2445	0.1965
	65.00	41	42	0.2473	0.2011
		51	52	0.2486	0.2019
		61	62	0.2486	0.2019
		71	72	0.2486	0.2019
		81	82	0.2486	0.2019
		91	92	0.2486	0.2019
		101	102	0.2486	0.2019
		111	112	0.2486	0.2019

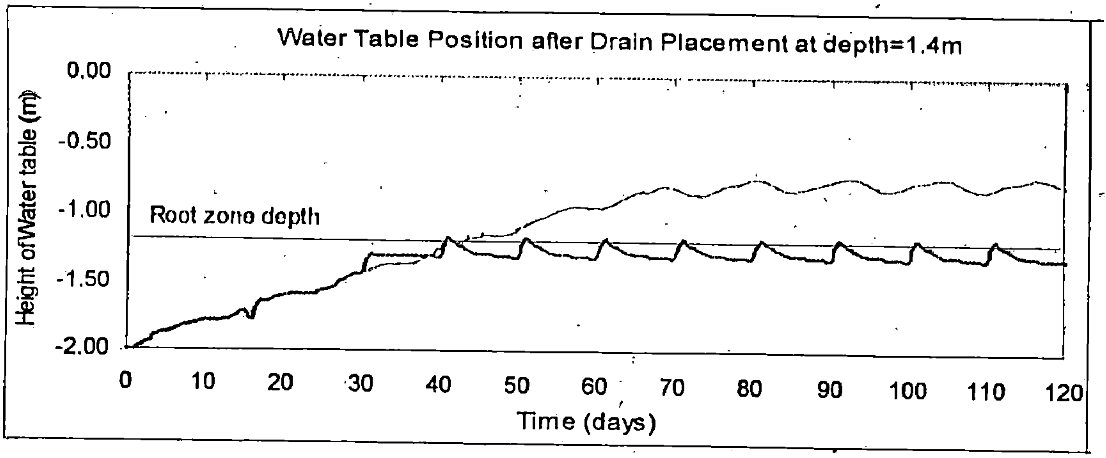
1.50	79.00	31	32	0.3084	0.2799
		41	42	0.3155	0.2851
Critical Height		51	52	0.3158	0.2854
0.30 m		61	62	0.3158	0.2854
		71	72	0.3158	0.2854
		81	82	0.3158	0.2854
		91	92	0.3158	0.2854
		101	102	0.3158	0.2854
		111	112	0.3158	0.2854
	80.00	31	32	0.3127	0.2853
		41	42	0.3204	0.2910
		51	52	0.3208	0.2912
		61	62	0.3208	0.2913
		71	72	0.3208	0.2913
		81	82	0.3208	0.2913
		91	92	0.3208	0.2913
		101	102	0.3208	0.2913
		111	112	0.3208	0.2913
	81.00	31	32	0.3171	0.2907
		41	42	0.3254	0.2969
		51	52	0.3259	0.2972
		61	62	0.3259	0.2972
		71	72	0.3259	0.2972
		81	82	0.3259	0.2972
		91	92	0.3259	0.2972
		101	102	0.3259	0.2972
		111	112	0.3259	0.2972
	82.00	31	32	0.3215	0.2961
		41	42	0.3305	0.3028
		51	52	0.3310	0.3031
		61	62	0.3310	0.3032
		71	72	0.3310	0.3032
		81	82	0.3310	0.3032
		91	92	0.3310	0.3032
		101	102	0.3310	0.3032
		111	112	0.3310	0.3032

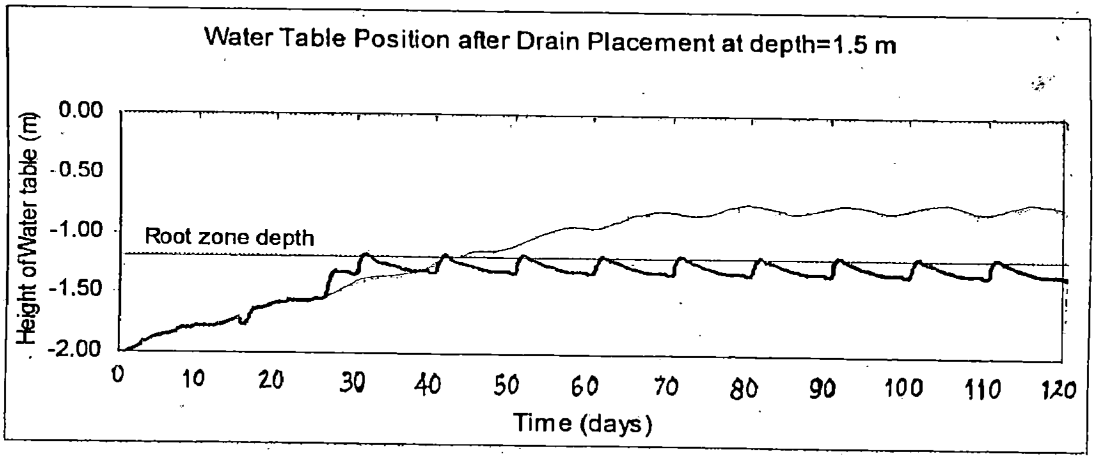
1.60 Critical Height 0.40 m	94.00	31	32	0.4029	0.3842
		41	42	0.4054	0.3862
		51	52	0.4057	0.3864
		61	62	0.4057	0.3865
		71	72	0.4058	0.3865
		81	82	0.4058	0.3865
		91	92	0.4058	0.3865
		101	102	0.4058	0.3865
		111	112	0.4058	0.3865
	95.00	31	32	0.4089	0.3907
		41	42	0.4117	0.3929
		51	52	0.4120	0.3932
		61	62	0.4120	0.3932
		71	72	0.4120	0.3932
		81	82	0.4120	0.3932
		91	92	0.4120	0.3932
		101	102	0.4120	0.3932
		111	112	0.4120	0.3932
	96.00	31	32	0.4149	0.3972
		41	42	0.4180	0.3997
		51	52	0.4184	0.4000
		61	62	0.4184	0.4001
		71	72	0.4184	0.4001
		81	82	0.4184	0.4001
		91	92	0.4184	0.4001
		101	102	0.4184	0.4001
		111	112	0.4184	0.4001
1.70 Critical Height 0.50 m	107.00	41	42	0.5020	0.4881
		51	52	0.5036	0.4895
		61	62	0.5040	0.4898
		71	72	0.5040	0.4898
		81	82	0.5040	0.4898
		91	92	0.5040	0.4898
		101	102	0.5040	0.4898
		111	112	0.5040	0.4898

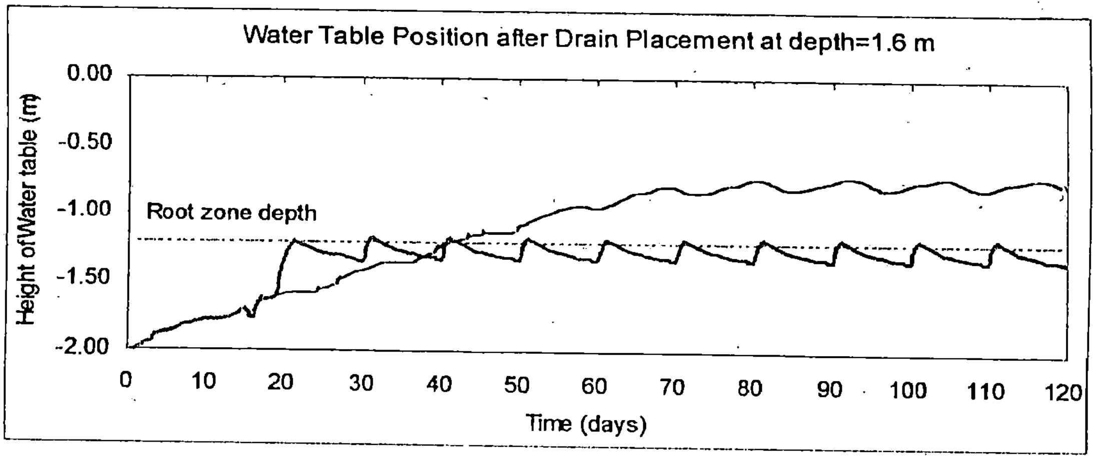
	108.00	31	32	0.5093	0.4880
		41	42	0.5111	0.4972
		51	52	0.5111	0.4972
		61	62	0.5115	0.4975
		71	72	0.5116	0.4976
		81	82	0.5116	0.4976
		91	92	0.5116	0.4976
		101	102	0.5116	0.4976
		111	112	0.5116	0.4976
	109.00	31	32	0.5070	0.4950
		41	42	0.5167	0.5033
		51	52	0.5187	0.5050
		61	62	0.5191	0.5054
		71	72	0.5191	0.5054
		81	82	0.5191	0.5054
		91	92	0.5191	0.5054
		101	102	0.5191	0.5054
		111	112	0.5191	0.5054
1.80 Critical Height 0.60 m	118.00	41	42	0.6018	0.5900
		51	52	0.6042	0.5920
		61	62	0.6048	0.5926
		71	72	0.6050	0.5927
		81	82	0.6050	0.5928
		91	92	0.6050	0.5928
		101	102	0.6050	0.5928
		111	112	0.6050	0.5928
	119.00	31	32	0.6009	0.5903
		41	42	0.6102	0.5985
		51	52	0.6128	0.6007
		61	62	0.6135	0.6013
		71	72	0.6137	0.6015
		81	82	0.6137	0.6016
		91	92	0.6137	0.6016
		101	102	0.6137	0.6016
		111	112	0.6137	0.6016

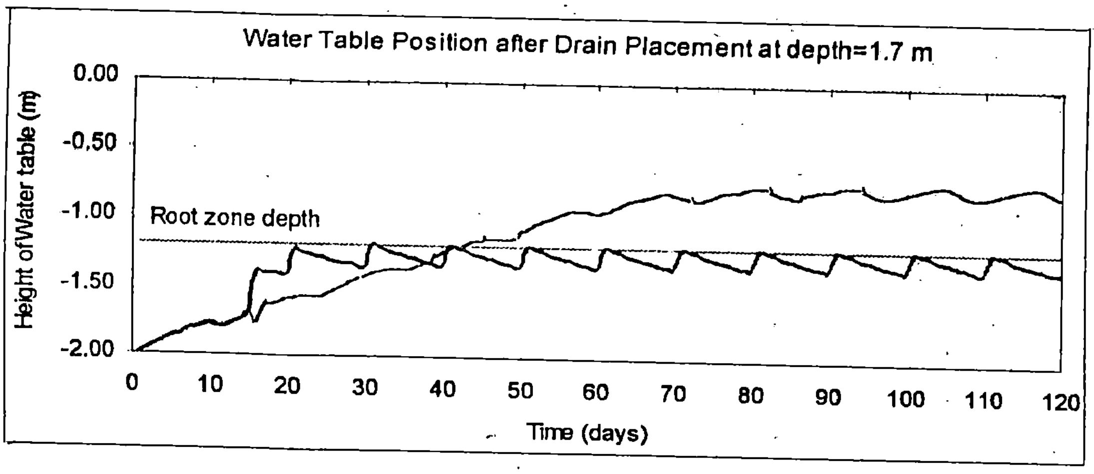
1.90 Critical Height 0.70 m	127.00	51	52	0.7000	0.6886
		61	62	0.7020	0.6903
		71	72	0.7026	0.6909
		81	82	0.7028	0.6911
		91	92	0.7029	0.6912
		101	102	0.7029	0.6912
		111	112	0.7029	0.6912
	128.00	41	42	0.7033	0.6925
		51	52	0.7095	0.6981
		61	62	0.7116	0.7000
		71	72	0.7123	0.7006
		81	82	0.7125	0.7008
		91	92	0.7126	0.7009
		101	102	0.7126	0.7009
		111	112	0.7126	0.7009
2.00 Critical Height 0.80 m	135.00	61	62	0.8009	0.7893
		71	72	0.8022	0.7905
		81	82	0.8027	0.7910
		91	92	0.8029	0.7911
		101	102	0.8030	0.7912
		111	112	0.8030	0.7912
	136.00	51	52	0.80780	0.7965
		61	62	0.81140	0.7998
		71	72	0.81280	0.8011
		81	82	0.81340	0.8016
		91	92	0.81360	0.8018
		101	102	0.81370	0.8019
		111	112	0.81370	0.8019

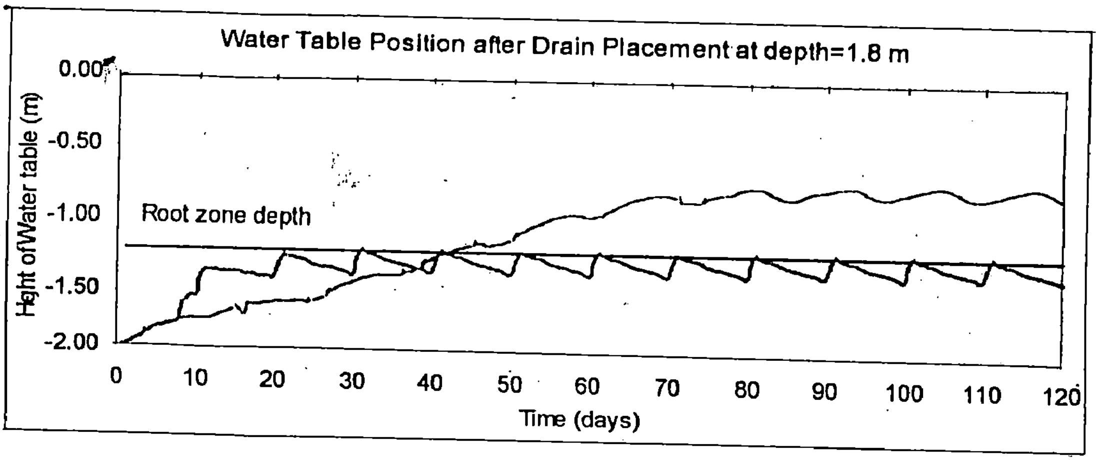
Figure 3.7. Water Table Position after Drain Placement for Different Depth

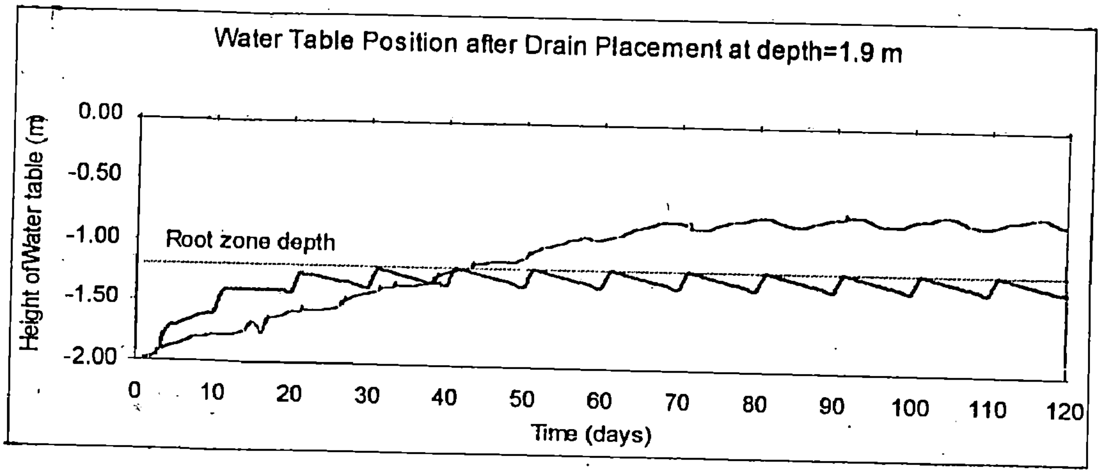


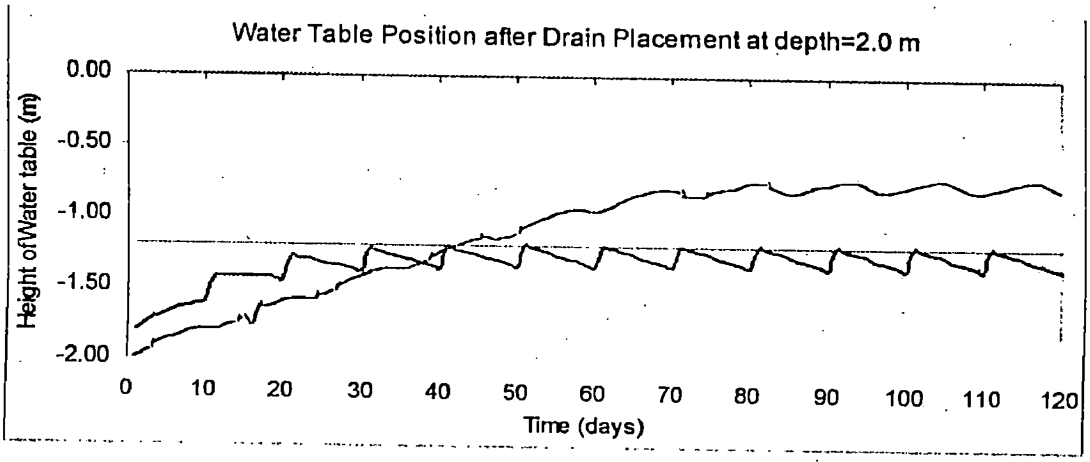





Water Table Position after Drain Placement at depth=1.7 m
Height of Water table (m)
0.00
-0.50
-1.00
-1.50
-2.00
Root zone depth
0
10
20
30
40
50
60
70
80
90
100
110
120
Time (days)


Water Table Position after Drain Placement at depth=1.8 m
Height of Water table (m)
0.00
-0.50
-1.00
-1.50
-2.00
Root zone depth
0
10
20
30
40
50
60
70
80
90
100
110
120
Time (days)


Water Table Position after Drain Placement at depth=1.9 m
Height of Water table (m)
0.00
-0.50
-1.00
-1.50
-2.00
Root zone depth
0
10
20
30
40
50
60
70
80
90
100
110
120
Time (days)



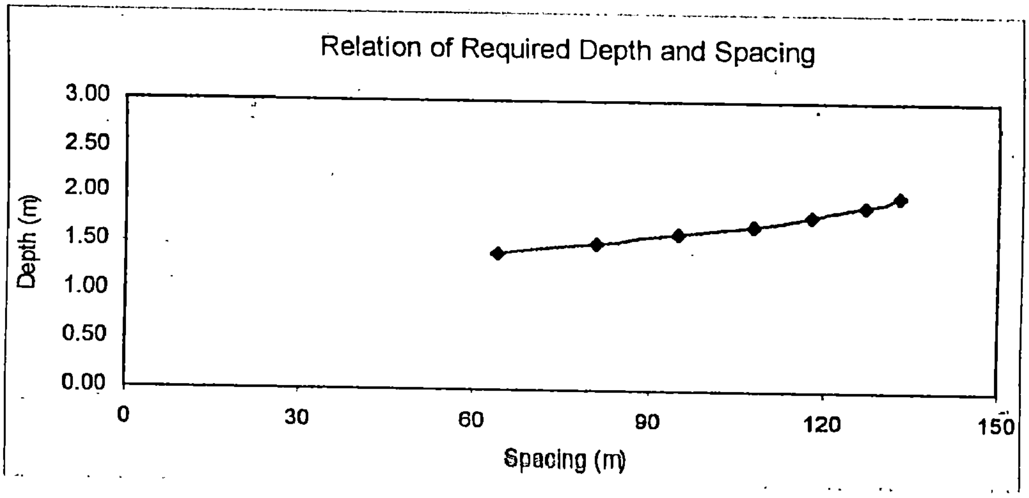


Figure 3.8. Relation of Required Depth and Spacing

Table 3.6. Calculation of Drain Spacing and Cost for Various Depth

Depth of Drain (m)	Drain Spacing (m)	Total Length of Pipe (m)	Total Cost of Pipe (Rs)	Total Cost of Excavation (Rs)	Total Cost of Excavation and Pipe (Rs)
1.40	64.00	9375.00	984375.00	917937.92	1902312.92
1.50	81.00	7407.41	777777.78	836509.56	1614287.33
1.60	95.00	6315.79	663157.89	803976.39	1467134.28
1.70	108.00	5555.56	583333.33	792228.70	1375562.03
1.80	118.00	5084.75	533898.31	807752.93	1341651.24
1.90	**127.00**	**4724.41**	**496062.99**	**831881.40**	**1327944.40**
2.00	135.00	4444.44	466666.67	863494.22	1330160.89

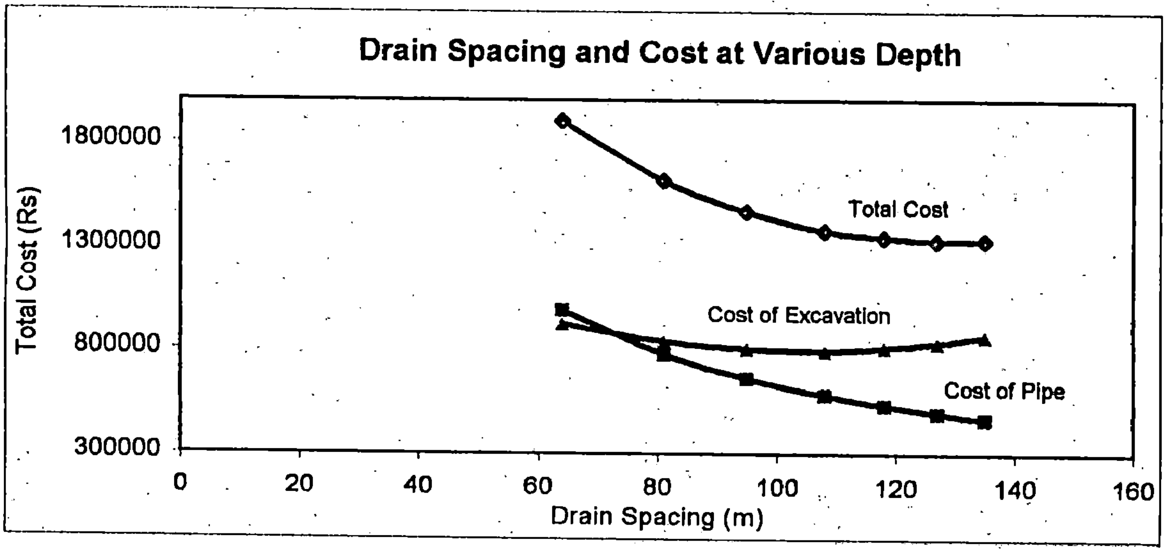


Figure 3.9. Drain Spacing and Cost at Various Depth

Chapter 4

CONCLUSIONS

Evolution of water table between parallel drains consequent to local irrigation application and seepage from external source has been analysed using discrete kernel coefficients. The kernel coefficients are obtained from Glover basic solution.

The water table can stay for a short while within the root zone soon after the irrigation application. The water table can enter several times during the cropping period. For a particular depth, there is a maximum spacing for which this requirement is satisfied. Among the set of depth of placement and maximum spacing, one single set would result in minimum cost, that includes cost of excavation and cost of material. In the present study, a procedure has been described to find the minimum cost of drainage requirement.

The discrete kernel method is very convenient for accounting discontinuous recharge and non uniform irrigation scheduling. It is found that one may save an amount of Rs. 342000 for providing field drain in an area of 60 ha.

When water logging problems are caused due to external source and local irrigation application, the spacing of the field drain is reduced considerably. For example, field drain spacing required for local irrigation application is 267 m. If in addition to local irrigation application, a drainage coefficient of 0.0094 m/day originates from external source, the required spacing of field drain is 127 m.

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Appendix 1

ECONOMICAL COST CALCULATION

- Data used in the study :

a. Irrigation application

- Total area to be drained, A = 60 ha = 600000 m², assuming the area is rectangular with size is 2000 m x 300 m.
- Recharge rate, Q = 35 mm/each irrigation

b. Drainage design

- Spacing of field drains = 250 m
- Depth of drain = 1.9 m

- Economical design

1. Size of pipe

The recharge rate (Q) as drainage coefficient, D_C = 35 mm/each irrigation. For irrigation interval = 10 day, Dc = 3.5 mm/day.

Length of one field drain = 300 m. For spacing = 250 m, it is get the area to be drained for one filed drain = 300 x 250 = 75000 m2 = 7.5 ha.

Drain slope, S = 0.001 and roughness coefficient, n = 0.016

By using equation (2.5);

Pipe diameter, $d = 51.7 \times (D_C . A . n)^{0.375} \times (S)^{-0.1875}$

$= 51.7 \times (3.5 \times 7.5 \times 0.016)^{0.375} \times (0.001)^{-0.1875}$

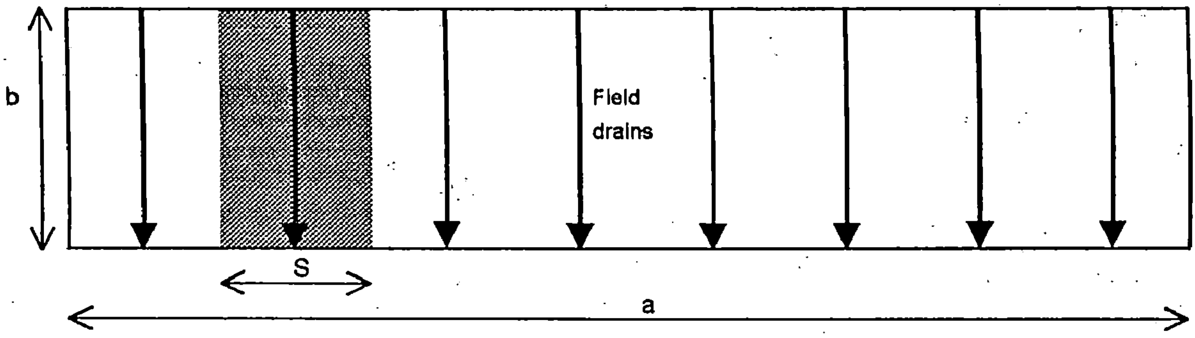
$= 136.37$ mm = 140 mm

For average, take pipe diameter = 200 m = 0.20 m

Take cost of pipe for diameter 0.2 m = Rs. 105/m

2. Length of Pipe

Area is rectangular with length = 2000 m and width = 300 m. Drains were designed for a parallel relief drain system which contains some lateral drains as shown on following figure,



By using equation (2.6) and (2.7);

Spacing of filed drains = 250 m

Number of pipe length, n = 2000/250 = 8 → n = 8

Length of pipe L = 300 m

Total length of pipe, Lt = 8 x 300 = 2400 m

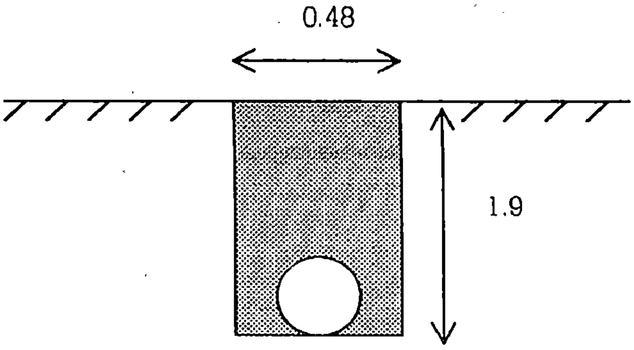
Cost of pipe = Rs. 105

Total cost of pipe = 105 x 2400 = Rs. 252000

3. Excavation Cost

Pipe diameter, Bp = 20 cm → take Be = 2.4 x 20 = 48 cm = 0.48 m

For D = 1.9 m;



Area, A = 0.48 x 1.9 = 0.912 m2

Cost of excavation at ground level, Ce = Rs 170/m3

Total length of pipe = 2400 m

Take Cr/Ce = 0.14286

By using equation (2.8),

Total cost of excavation, C_E = 170 x 0.912 x (1 + 0.14286 x (1.9/2)) x 2400

= Rs 422595.75

4. <u>Total Cost Estimate</u>

Total Cost = cost of pipe + cost of excavation

= 252000 + 422595.75 = Rs. 674595.75

Appendix 2

COMPUTER PROGRAMMING

1. The Recharge Originates only from Local Irrigation Application

```
$Debug
C       PROGRAM OF GLOVER'S FORMULA FOR
C       DESIGN OF SUB SURFACE FIELD DRAINS
C       CONSIDER THE RECHARGE ORIGINATING
C       ONLY FROM LOCAL IRRIGATION APPLICATION

        DIMENSION RECH(200),DELTA(200),RISE(200),M(50)
        OPEN(1, FILE= 'A.DAT',STATUS='OLD')
        OPEN(2, FILE= 'A.OUT',STATUS='NEW')
        PAI=3.14159265
        READ(1,*) RECHR,AK,PHI,SPAC,DEPTH,NTIME,NIRRI
        READ(1,*)(M(INDEX),INDEX=1,NIRRI)

        DO 10 I=1,NTIME
        RECH(I)=0.
10      CONTINUE

        DO 20 I=1,NIRRI
        RECH(M(I))=RECHR
20      CONTINUE

        WRITE(2,30)
30      FORMAT(2X,'RECHR',8X,'K',5X,'SP.YIELD',4X,'SPACING',3X,'DEPTH')

        WRITE(2,40)RECHR,AK,PHI,SPAC,DEPTH
40      FORMAT(5F10.2)

        T=AK*DEPTH+0.5*AK/PHI
        DO 50 N=1,NTIME
        CALL DKER(T,PHI,SPAC,N,RES)
        DELTA(N)=RES
50      CONTINUE

        DO 60 N=1,NTIME
        SUM=0.
        DO 70 NGAMA=1,N
        SUM=SUM+RECH(NGAMA)*DELTA(N-NGAMA+1)
70      CONTINUE
        RISE(N)=SUM
60      CONTINUE

        WRITE(2,*)' '
        WRITE(2,*)' DISCRETE KERNEL(N)'
        WRITE(2,80)(DELTA(N),N=1,NTIME)
```

```
80      FORMAT(10F7.3)

        WRITE(2,*)' '
        WRITE(2,90)
90      FORMAT(2X,'TIME',2X,'RECHARGE',4X,'RISE')

        WRITE(2,100)(N,RECH(N),RISE(N),N=1,NTIME)
100     FORMAT(I5,2F10.3)
        STOP
        END

C       SUBROUTINE FOR CALCULATING DISCRETE KERNEL
        SUBROUTINE DKER(T,PHI,SPAC,N,RES)
        PAI=3.14159265
        AL=SPAC
        AN=N
        ALPHA=T/PHI

        TERM11=AL**2/(8.*T)
        TERM22=4.*AL*AL/(T*PAI**3)
        IF(N.EQ.1) GO TO 120
        SUM1=0.
        SUM2=0.
        SN=1.

110     CONTINUE
        TERM=(SN*PAI/AL)**2*ALPHA
        TERM1=TERM*AN
        TERM2=TERM*(AN-1)
        TERM3=EXP(-TERM1)/SN**3
        TERM4=EXP(-TERM2)/SN**3
        TERMX=SIN(SN*PAI/2)
        SUM1=SUM1+TERM3*TERMX
        SUM2=SUM2+TERM4*TERMX
        SN=SN+2.
        IF(TERM4.GT.0.00000001)GO TO 110
        RES=TERM22*(SUM2-SUM1)
        RETURN

120     CONTINUE
        SUM1=0.
        SN=1.

130     CONTINUE
        TERM=(SN*PAI/AL)**2*ALPHA*AN
        TERM1=EXP(-TERM)/SN**3
        TERMX=SIN(SN*PAI/2)
        SUM1=SUM1+(TERM1*TERMX)
        SN=SN+2.
        IF(TERM1.GT.0.00000001)GO TO 130
        RES=TERM11-TERM22*SUM1
        END
```

2. The Recharge Originates Both from Local Irrigation and External Source

```
$Debug
C     PROGRAM OF GLOVER'S FORMULA FOR
C     DESIGN OF SUB SURFACE FIELD DRAINAGE
C     CONSIDER THE RECHARGE ORIGINATING
C     BOTH FROM LOCAL AS WELL AS EXTERNAL SOURCE

      DIMENSION DELTA(200),RISE(200),M(50),RECH(200)
      OPEN(1, FILE= 'AR.DAT',STATUS='OLD')
      OPEN(2, FILE= 'AR.OUT',STATUS='NEW')
      PAI=3.14159265
      READ(1,*) RECHR,ERECH,AK,PHI,SPAC,DEPTH,NTIME,NIRRI
      READ(1,*)(M(INDEX),INDEX=1,NIRRI)

      DO 10 I=1,NIRRI
      RECH(M(I))=RECHR
10    CONTINUE

      WRITE(2,20)
20    FORMAT(2X,'RECH',6X,'ERECH',5X,'K',8X,'PHI',6X,'L',6X,'DEPTH')

      WRITE(2,30)RECHR,ERECH,AK,PHI,SPAC,DEPTH
30    FORMAT(6F9.2)

      T=AK*DEPTH+0.5*AK/PHI
      DO 40 N=1,NTIME
      CALL DKER(T,PHI,SPAC,N,RES)
      DELTA(N)=RES
40    CONTINUE

      DO 50 N=1,NTIME
      SUM1=0.
      DO 60 NGAMA=1,N
      SUM1=SUM1+RECH(NGAMA)*DELTA(N-NGAMA+1)
60    CONTINUE
      CALL USTEP (T,PHI,SPAC,N,RES)
      RISE(N)=SUM1+RES*ERECH
50    CONTINUE

      WRITE(2,*)' '
      WRITE(2,*)' DISCRETE KERNEL(N)'
      WRITE(2,70)(DELTA(N),N=1,NTIME)
70    FORMAT(10F7.3)

      WRITE(2,*)' '
      WRITE(2,80)
80    FORMAT(2X,'TIME',5X,'RISE')

      WRITE(2,90)(N,RISE(N),N=1,NTIME)
90    FORMAT(I5,F11.3)
      STOP
      END
```

```
C       SUBROUTINE FOR CALCULATING DISCRETE KERNEL
        SUBROUTINE DKER(T,PHI,SPAC,N,RES)
        PAI=3.14159265
        AL=SPAC
        AN=N
        ALPHA=T/PHI

        TERM11=AL**2/(8.*T)
        TERM22=4.*AL*AL/(T*PAI**3)
        IF(N.EQ.1) GO TO 110
        SUM1=0.
        SUM2=0.
        SN=1.

 100    CONTINUE
        TERM=(SN*PAI/AL)**2*ALPHA
        TERM1=TERM*AN
        TERM2=TERM*(AN-1)
        TERM3=EXP(-TERM1)/SN**3
        TERM4=EXP(-TERM2)/SN**3
        TERMX=SIN(SN*PAI/2)
        SUM1=SUM1+TERM3*TERMX
        SUM2=SUM2+TERM4*TERMX
        SN=SN+2.
        IF(TERM4.GT.0.00000001)GO TO 100
        RES=TERM22*(SUM2-SUM1)
        RETURN

 110    CONTINUE

        SUM1=0.
        SN=1.
 120    CONTINUE
        TERM=(SN*PAI/AL)**2*ALPHA*AN
        TERM1=EXP(-TERM)/SN**3
        TERMX=SIN(SN*PAI/2)
        SUM1=SUM1+TERM1*TERMX
        SN=SN+2.
        IF(TERM1.GT.0.00000001)GO TO 120
        RES=TERM11-TERM22*SUM1
        RETURN
        END

C       SUBROUTINE UNIT STEP RESPONSE
        SUBROUTINE USTEP(T,PHI,SPAC,N,RES)
        PAI=3.14159265
        AL=SPAC
        AN=N
        ALPHA=T/PHI

        TERM11=AL**2/(8.*T)
        TERM22=4.*AL*AL/(T*PAI**3)
        SUM1=0.
        SN=1.

 130    CONTINUE
```

```
TERM=(SN*PAI/AL)**2*ALPHA*AN
TERM1=EXP(-TERM)/SN**3
TERMX=SIN(SN*PAI/2)
SUM1=SUM1+TERM1*TERMX
SN=SN+2.
IF(TERM1.GT.0.00000001)GO TO 130
RES=TERM11-TERM22*SUM1
RETURN
END
```

EXAMPLE INPUT AND OUTPUT FOR CASE 1

DATA INPUT :

```
3.5  1140  0.23  12000.  410.  138  14
1 15 27 37 47 57 67 77 87 97 107 117 127 137
```

DATA OUTPUT :

```
RECHR     K      SP.YIELD   SPACING   DEPTH
 3.50  1140.00     .23      12000.00  410.00

DISCRETE KERNEL(N)

 4.344   4.202   3.820   3.370   2.944   2.563   2.229   1.938   1.685   1.465
 1.274   1.107    .963    .837    .727    .632    .550    .478    .415    .361
  .314    .273    .237    .206    .179    .156    .136    .118    .102    .089
  .077    .067    .059    .051    .044    .038    .033    .029    .025    .022
  .019    .017    .014    .013    .011    .009    .008    .007    .006    .005
  .005    .004    .004    .003    .003    .002    .002    .002    .002    .001
  .001    .001    .001    .001    .001    .001    .001    .000    .000    .000
  .000    .000    .000    .000    .000    .000    .000    .000    .000    .000
  .000    .000    .000    .000    .000    .000    .000    .000    .000    .000
  .000    .000    .000    .000    .000    .000    .000    .000    .000    .000
  .000    .000    .000    .000    .000    .000    .000    .000    .000    .000
  .000    .000    .000    .000    .000    .000    .000    .000    .000    .000
  .000    .000    .000    .000    .000    .000    .000    .000    .000    .000
  .000    .000    .000    .000    .000    .000    .000    .000

TIME  RECHARGE   RISE
 1     3.500    15.203
 2      .000    14.708
 3      .000    13.370
 4      .000    11.795
 5      .000    10.303
 6      .000     8.971
 7      .000     7.802
 8      .000     6.784
 9      .000     5.898
10      .000     5.127
```

11	.000	4.458
12	.000	3.875
13	.000	3.369
14	.000	2.929
15	3.500	17.749
16	.000	16.922
17	.000	15.294
18	.000	13.468
19	.000	11.757
20	.000	10.235
21	.000	8.901
22	.000	7.739
23	.000	6.729
24	.000	5.849
25	.000	5.085
26	.000	4.421
27	3.500	19.047
28	.000	18.049
29	.000	16.274
30	.000	14.320
31	.000	12.498
32	.000	10.879
33	.000	9.461
34	.000	8.226
35	.000	7.152
36	.000	6.217
37	3.500	20.608
38	.000	19.407
39	.000	17.455
40	.000	15.346
41	.000	13.390
42	.000	11.654
43	.000	10.136
44	.000	8.812
45	.000	7.661
46	.000	6.660
47	3.500	20.994
48	.000	19.742
49	.000	17.746
50	.000	15.599
51	.000	13.610
52	.000	11.846
53	.000	10.302
54	.000	8.957
55	.000	7.787
56	.000	6.770
57	3.500	21.088
58	.000	19.825
59	.000	17.817
60	.000	15.661
61	.000	13.664
62	.000	11.893
63	.000	10.343
64	.000	8.992
65	.000	7.818
66	.000	6.796

67	3.500	21.112
68	.000	19.845
69	.000	17.835
70	.000	15.677
71	.000	13.678
72	.000	11.904
73	.000	10.353
74	.000	9.001
75	.000	7.825
76	.000	6.803
77	3.500	21.118
78	.000	19.850
79	.000	17.839
80	.000	15.681
81	.000	13.681
82	.000	11.907
83	.000	10.355
84	.000	9.003
85	.000	7.827
86	.000	6.805
87	3.500	21.119
88	.000	19.851
89	.000	17.840
90	.000	15.682
91	.000	13.682
92	.000	11.908
93	.000	10.356
94	.000	9.004
95	.000	7.828
96	.000	6.805
97	3.500	21.119
98	.000	19.851
99	.000	17.841
100	.000	15.682
101	.000	13.682
102	.000	11.908
103	.000	10.356
104	.000	9.004
105	.000	7.828
106	.000	6.805
107	3.500	21.120
108	.000	19.852
109	.000	17.841
110	.000	15.682
111	.000	13.682
112	.000	11.908
113	.000	10.356
114	.000	9.004
115	.000	7.828
116	.000	6.805
117	3.500	21.120
118	.000	19.852
119	.000	17.841
120	.000	15.682

121	.000	13.682
122	.000	11.908
123	.000	10.356
124	.000	9.004
125	.000	7.828
126	.000	6.805
127	3.500	21.120
128	.000	19.852
129	.000	17.841
130	.000	15.682
131	.000	13.682
132	.000	11.908
133	.000	10.356
134	.000	9.004
135	.000	7.828
136	.000	6.805
137	3.500	21.120
138	.000	19.852