UNIVERSITY OF SOUTHAMPTON

SCHOOL OF CIVIL ENGINEERING AND THE ENVIRONMENT

THE USE OF NUMERICAL GROUNDWATER MODEL TO IMPROVE EFFECTIVENESS OF SUBSURFACE DRAINAGE SYSTEM IN IRRIGATED FIELD

By

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ABSTRACT

SCHOOL OF CIVIL ENGINEERING AND THE ENVIRONMENT
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THE USE OF NUMERICAL GROUNDWATER MODEL TO IMPROVE EFFECTIVENESS OF SUBSURFACE DRAINAGE SYSTEM IN IRRIGATED FIELD

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The research demonstrates that Three-Dimensional Variable-Density Groundwater Flow models such as the SEAWAT model can be effectively used for design of subsurface drainage systems for controlling salt concentration in the root zone on salt affected irrigated land. The SEAWAT model was used to optimize subsurface drainage design to ensure that the salt concentration of the groundwater at the base of the root zone does not exceed pre determined levels instead of the conventional approach of maintaining the groundwater at a predetermined water table level. The study was carried out on a conceptual uniform homogenous block of irrigated flat field of shallow water table depth of 0.5 m and salt concentration of 7200 mg/l with impermeable layer at 20 m deep and impermeable field boundaries. Using the model, spacings were designed to be used as design criteria for subsurface drainage system to maintain salt concentrations of 6000, 5000 and 4000 mg/l at the base of the root zone and water table depth of 0.8 m from the soil surface. The results showed that over a wide range of irrigation water quality and aquifer hydraulic conductivity the optimum drain spacing using SEAWAT was, depending on irrigation water quality and aquifer hydraulic conductivity, wider by between 3 and 50 % and the amount of drain discharge reduced by 1 and 27 % than would be recommended using conventional design equations.

It was concluded that Three-Dimensional Variable-Density Groundwater Flow models are better for designing effective drainage systems than Conventional drain spacing design equations such as Hooghoudt.

DEDICATION

Dedicated to my beloved mother, **Obaa Yaa Aboraa**, for persevering against all odds to give me education,

and

to the loving memories of **Opanying Attah Kwasi** (my late father) who did not live long to see me to this level of my education, and **Mr. Yaw Appiah** (my late father-in-law) who was alive when I began this research but is no more.

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AUTHOR’S DECLARATION

I, Edward A. Ampofo, declare that the thesis entitled ‘The Use of Numerical Groundwater Model to Improve Effectiveness of Subsurface Drainage System in Irrigated Field’, and the work presented in the thesis are both my own, and have been generated by me as the result of my own original research.

I confirm that:

- this work was done wholly while in candidature for a research degree at this University.
- where any part of this thesis has previously been submitted for a degree or any other qualification at this university or any other institution, this has been clearly stated.
- where I have consulted the published work of others, this is always clearly attributed.
- where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.
- none of this work has been published before submission.

Signed:
Date:.11/03/2010

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I am grateful to my employers in Cape Coast (University of Cape Coast) and my sponsors, Commonwealth Scholarship Commission, London, for giving me the opportunity and financial resources respectively to carry out this research. The British Council, Manchester, is commended for successfully administering the funding during the course of the work without let or hindrance. Professors Mensa Bonsu and Turkson also deserve special mention for securing the award for me.

I owe my wife, Monica, and my children Gideon, Gyakari, Twumwaa, Amoako and Ampofo Jr., a debt of gratitude for their love, prayers, support and patience without this work could not have seen the light of day. I am grateful to Monica for supporting the family during the long periods when funding eventually stopped. Also deserve mentioning are my siblings and friends in Ghana, especially Effah Musa (Alhaji) for their prayers and moral support.

Last, but most importantly, I am grateful to my God (the all time provider) for sustaining me during the studies. It is my unshakeable faith in the Lord Jesus Christ which helped me generally to enjoy my stay in Southampton. To God is all the glory for in Him all things are indeed possible!!

DEFENITIONS AND ABBREVIATIONS

Applied recharge	:	Water areally applied to the field (mm/d). The general procedure for estimating applied recharge value is to subtract from irrigation water a quantity thought to be a representative of runoff.
Applied recharge concentration	:	Salt concentration in the applied recharge/irrigation (mg/l)
C_i	:	Salt concentration in the applied recharge/irrigation water reaches the groundwater (mg/l)
C_n	:	Salt concentration maintained at the root zone during drainage (mm/d)
Drain discharge	:	Volume of water per unit area drains take out from the aquifer (mm/d)
DSP	:	Model design drain spacing (m)
DSP_c	:	Conventional drain spacing. This is obtained by solution of the Hooghoudt's steady state equation
ET	:	Evapotranspiration (mm/d)
ET_g	:	Groundwater contribution to evapotranspiration (mm/d)
ET_m	:	Maximum evapotranspiration (mm/d). The groundwater contribution to evapotranspiration equals the ET_m when the water table is above the soil surface
EXTD	:	Extinction depth (m). The groundwater contribution is zero when the water table falls below the extinction depth
ha	:	Hactare. 1 ha = 100 m x 100 m
K	:	Aquifer hydraulic conductivity (m/d)

Leachable salt	:	The amount of salt when leached from the aquifer reduces the salt in the aquifer to approximately match both the salt in the applied recharge (or net recharge) and the drain discharge, and remaining approximately constant in the aquifer (kg)
l	:	Litre. 1 li = 10^{-3} m^3
mg	:	Milligramme. 1 mg = 10^{-6} kg
Net recharge (NRCH)	:	The of irrigation water that reaches the water table after runoff and evapotranspiration are withdrawn (mm/d)
Net recharge concentration	:	Salt concentration in the net recharge (mg/l)
RCH	:	Applied recharge (mm/d)
RCN	:	Applied recharge concentration (mg/l)
Salt load/Salt	:	Quantity salt in irrigation water or groundwater or soil solution. (kg/m^3)
Salt concentration/concentration	:	Dissolved salt in given irrigation water or groundwater or soil solution (mg/l)

LIST OF SYMBOLS

D	:	Depth of impermeable layer to water level in a horizontal drain (m)
D*	:	Molecular diffusion coefficient of salt (m^2s^{-1})
d_e	:	Depth of fictitious impermeable layer to water level in a horizontal drain (m)
d_l	:	Depth of water level in horizontal drains from soil surface (m)
$D_{i,j}$	:	Hydrodynamic dispersion coefficient (m^2s^{-1})
D_m	:	Mechanical dispersion coefficient (m^2s^{-1})
H	:	Height of water table midway between drains from the impermeable layer (m)
H	:	Water table head (m)
h_f	:	Water table head for freshwater (m)
L_{dr}	:	Horizontal drain spacing (m)
LF	:	Leaching fraction (-)
L_s	:	Linear distance travelled by salt (m)
P	:	Conductance controlling flow from sink/source to cell (m^2s^{-1})
Q	:	Discharge rate (mm/d)
Q_s	:	Volumetric flux per unit volume of water to or from aquifer (s^{-1})
R	:	Applied recharge (mm/d)
R	:	Drain radius (m)
S_f	:	Specific storage of freshwater head (m^{-1})
SS	:	Specific storage of a cell (m^{-1})
S_o	:	Specific yield of aquifer (m^{-1})
T	:	Time (s)
T	:	Tortousity (-)
μ	:	Wet entry perimeter (m)
v_i	:	Linear flow velocity (ms^{-1})
Z	:	Elevation at a measurement point from the impermeable layer (m)

α_L	:	Longitudinal dispersivity (m)
α_T	:	Transversal dispersivity (m)
β_p	:	Compressibility of bulk aquifer material (ms^2kg^{-1})
γ	:	Specific weight of water ($kgm^{-2}s^{-2}$)
Δt	:	Time step interval (s)
θ	:	Volumetric water content (-)
ρ	:	Density of aquifer water (kgm^{-3})
ρ_f	:	Density of freshwater (kgm^{-3})
D_m	:	Mechanical dispersion coefficient (m^2s^{-1})

CHAPTER ONE

INTRODUCTION

1.1 General introduction

In semiarid and arid irrigated regions, waterlogging coupled with soil salinity is a serious problem (Sharma *et al*., 2000). While in a few cases natural drainage systems can provide an adequate level of drainage for salt control, in many irrigated areas, artificial drainage systems are required (Tanji, 1990, Rao *et al*., 1988). Without proper drainage systems, salts tend to accumulate in the upper soil profile, especially when intense evapotranspiration is associated with insufficient leaching (Yeo, 1999). According to experimental and field evidence, subsurface drainage is the essential intervention necessary to maintain a suitable growing environment for crops (Sharma and Gupta, 2005). However, the efficiency of subsurface drainage systems in controlling salinity is a matter of debate.

Soil salinity poses a major problem for irrigated agriculture with the world's irrigated land being adversely affected by salinity resulting from high water tables (Ghassemi *et al*., 1995; Tanji, 1990). On the global scale, it is estimated that 20–30 million ha of irrigated land are severely affected by salinity, and another 60-80 million ha suffer salinity to varying extents (Hennessy, 1993). Gates *et al*. (2002) observed that waterlogging and salinity are age-old 'nemeses' of irrigated agriculture, and continue to plague irrigated regions around the world. Wang *et al.* (2008) in evaluating soil salinity evolution and its relation to groundwater note that agricultural irrigation is the main cause of a rise of the groundwater table and under intense evapotranspiration, causes soil salinization. The phenomenon of waterlogging and salinity continues to be a threat to land and water resources, posing a serious challenge to global irrigated crop production and causing substantial economic losses (Postel, 1999; Tanji, 1990). Amerzketa (2006) observed that the mitigation and control of soil salinity is one of the main challenges in agriculture, particularly, where irrigation is used. Therefore, addressing this degradation of the world's most productive lands, while protecting the broader natural resources base, may prove one of the great challenges of the coming years.

The issue of waterlogging and salinity is particularly acute in areas with extensive networks of unlined irrigation canals, and also where there is excess application of irrigation water. Seepage losses result in high water tables which must be managed to avoid increased secondary salinity in the root zone resulting from the capillary rise of water. In many non-irrigated lands too, dryland salinization occurs when rain water or irrigation water from high land nearby irrigation projects percolates beyond the root zone into saline groundwater (FAO, 2002). This causes the level of saline aquifer of the highland to rise, which if it reaches a level moves horizontally towards the adjoining low lying dryland and causes the lowland water table to rise from which if evaporation takes place will result in dryland salinization (FAO, 2002).

Salinity and drainage problems usually appear decades after the commencement of irrigation. This is because it takes time for the salts in the irrigation water to build up in the soil to concentrations that damage crops. Subsurface drainage however has been a remedy for waterlogging and salinization in agricultural regions (Christen and Ayars, 2001). Rao *et al.* (1998) when evaluating the impacts of subsurface drainage on waterlogged saline area, observed that on average there is a decrease of about 36 % in salt content compared with the initial value, and also the water table is controlled below the root zone thereby bringing the soil to optimum moisture content for crops. Sharma et al. (2000) studied an 8-year impact of subsurface drainage on soil properties and wheat yields in a severely affected, waterlogged, barren, sandy loamsaline soil in Karnal, India, and noted that after a few years, sufficient salt was removed from the root zone and the land reclaimed sufficiently to grow most crops of the region.

To feed the growing world population, food production will need to be double in the next 25 years (Schultz *et al*., 2005). The major part of this increase will have to come from investment in improved irrigation and subsurface drainage practices in the existing lands to both prevent land loss by salinization and bringing saline soils back into production (Ritzema *et al.*, 2007; Schultz *et al*., 2005). Subsurface drainage systems in Pakistan were designed using the conventional equations of Hooghoudt and Ernst (Sarwar et al. 2000), and extensive subsurface drainage networks have been installed in Mardan District to control waterlogging and salinization from canal irrigation and monsoon rains (Khan et al.2002). Khan et al. (2002) noted that the subsurface drainage systems had lowered water table considerably to allow adequate aeration in the active root zone. This approach if correctly designed will prevent salinization as it limits capillary rise of potentially saline water into the root zone. However, once there is equilibrium, field drain discharge is often of relatively high quality water often being only little worse than the irrigation water quality itself. It is therefore inherently wasteful of water. A lot of research has taken place to modify the conventional subsurface drainage systems in order to improve efficiency (Ritzema *et al*., 2007). In Egypt, the layout of the conventional free-flow subsurface drainage system has been modified into 'controlled subsurface drainage systems' and this has reduced drainage loss by over 40 % (El Atfy *et al*., 1991). Controlled drainage systems have water control structures such as a flashboard rise installed in the drainage outlet to allow the water in the drainage outlet to be raised or lowered as needed (Evans *et al*. 1991). Investigations into the controlled drainage systems show that it has the potential to maintain and even increase yields while increasing irrigation water use efficiency by 15 – 20 % (Wahba *et al*. 2005). Similar results are found in controlled drainage experiments in India (IDNP, 2002).

According to various studies, the design criteria (discharge rate) of the conventional drainage system are too conservative and can be reduced or modified (Ritzema *et al*. 2007). In Egypt, modifying a design discharge rate to 0.9 mm/d from 1.0 mm/d was sufficient to cope with the losses of irrigation water and maintain favourable soil salinity levels (Dayem and Ritzema, 1990). In India, studies showed that the original design discharge rate for salinity control of 2.0 mm/d could be reduced to 1.0 - 1.5 mm/d and get the same result (Ritzema *et al*., 2007; RAJAD, 1996). In Pakistan, field monitoring programmes and computer simulations indicate that the field drainage design discharge rates could be reduced from an initial value of 3.5 mm/d to 1.5 mm/d (Wolters, 2000) to get the same results. There is therefore considerable potential to increase water use efficiency and reduce wastage of scarce water.

For conventional shallow subsurface drainage systems relying on drain depths of 1.75 m – 3 m, Gupta (2002) suggested that the depths can be reduced or modified as long as the downward flux is guaranteed at critical periods. According to studies, a design groundwater table depth of 0.8 m proves sufficient for crop production in Egypt (Dayem and Ritzema, 1990), and this can be achieved with drain depth between 1.2 and 1.4 m deep compared to 1.7 m or more (Nijland, 2000). In India, Ritzema et al. (2007) and Srinivasulu *et al*. (2005) noted that under gravity flow conditions, drain depth can be reduced to 0.9 – 1.0 m. In Pakistan, the design depth can be reduced from 2.25 – 2.40 m to 1.50 – 2.10 m (Qureshi et al., 1997). However these systems were designed to only provide a given water table level given the prevailing soil conditions.

The development of drainage design models has made it possible to quantitatively investigate the performance of drainage systems on water table control. While this was a primary goal of drainage research some years ago, it is no longer sufficient. Currently, the effect of subsurface drainage on salt load control in the root zone with minimum irrigation application is of equal or greater importance for crop production (Christen and Ayars, 2001).

1.2 Objective:

When irrigated soils become saline, the widely used method for controlling salinity is to install a pipe drainage system or pumped-well to keep the water table below a critical level to control capillary rise (FAO, 1997). This is a proven approach. The problem is it removes large volumes of irrigable quality water which often contains negligible quantities of salt. Christen and Skehan (2001) in comparing salt discharges from shallow (0.7 m) and deep (1.8 m) drains noted that the shallow drain discharge was only slightly worse quality than the irrigation water.

In hot dry climates, and for most crops, evapotranspiration is more than capable of controlling water table levels. In a six year biodrainage study in Indira Ghandi Nahar Project (IGNP), India, Heuperman *et al*., (2002) examined how trees could be used to remove excess soil water through evapotranspiration. They observed that the total volume of water removed by trees from a 25 hectare irrigated area of over a six year period was 517 x 10^4 m^3, equivalent to an annual rate of 3.5 m/yr. They noted again that the drawdown of the groundwater was about 15 m or more. Therefore a drainage system that focuses more on salinity control than on water table control is worth considering since evapotranspiration could feasibly control the water table especially in arid and semiarid regions.

There are several models available to study the movement of water and salt in the soil profile (Ali et al. 2000). Most of these models have been developed to design subsurface drainage systems by using the conventional drainage equations that mostly consider only the gross amount of water removal from the soil profile. These conventional design practices for subsurface drainage have been based on the need to achieve a specific water table that ensures minimal movement of salt into the crop zone. The conventional approach is to apply the design drainage equation to calculate a drain depth and spacing that will provide a design discharge rate for a specific water table depth (Guitjens *et al.,* 1997). As a result, drainage is often from depths well below the root zone, removing salt from deep within the soil profile. Christen and Ayars (2001) noted however that removing salt from deep within the soil profile does not assist in maintaining a root zone salt balance. This has called for the need to revisit drainage design criteria so that it would be targeted more towards salt control rather than only water table management especially where there is improved irrigation design.

The main objective of this study is to assess the use of a numerical groundwater flow model that simulates water and salt movement in the soil profile, as a tool to design drain spacings that can maintain salt concentration at the base of the root zone with less water discharge.

Specific objectives performed were:

(i) To assess the applicability of the numerical groundwater model to irrigated field as a subsurface drainage design model.

(ii) To assess the capability of the model to simulate drainage flow and leaching in irrigated aquifers.

(iii) To use the model to design drain spacing that can maintain desired salt concentration at the base of the root zone with less discharge water as compared with conventional drainage design equation.

1.3 Scope of the study

Chapter 1 provides the background and detrimental effect of waterlogging and salinization in irrigated agriculture, and the need for new approach of designing subsurface drainage to maintain salt in the root zone base. Chapter 2 provides theory of groundwater models in general, reviews some groundwater models used for subsurface drainage design and discusses the choice of the SEAWAT model for use in the study. Chapter 3 assesses the applicability of SEAWAT to irrigated field as a subsurface drainage model, matching the simulated mid-drain water table heads with mid-drain water table heads obtained by solution of Hooghoudt's steady state equation, evaluating equipotential lines and salt concentration distribution in the aquifer.

Chapter 4 discusses the model's simulation of drain spacing effect on drainage flow and leaching with and without evapotranspiration and the effects of changing applied recharge concentration. The performance of the model with different aquifer permeabilites was also assessed. Chapter 5 contains estimates of drain spacings that can maintain the desired salt concentration at a water table depth of 0.8 m with less irrigation water for different aquifer permeabilities under different evapotranspiration rates.

Finally, Chapter 6 presents additional general discussions and conclusions, and makes recommendations for further studies.

CHAPTER TWO

BACKGROUND AND LITERATURE REVIEW

2.1 Introduction and context of research

This review identifies the need to leach salt from the soil profile and considers the different type of drainage systems that could be used. The chapter discusses the theory of groundwater flow and solute transport models in general, reviews the use of the WAVE model, the SWAP model and the DRAINMOD model used for subsurface drainage design. It discusses the merits of the SEAWAT model to design subsurface drainage system to target salinity control rather than water table control.

Increasing crop production to meet the requirements of the world's population will put great pressure on global water resources (Wallace and Batchelor, 1997). To sustain crop production, water must be always present in the soil, and this can only be achieved by using irrigation, rainfall or shallow groundwater. Agriculture is by far the largest consumer of fresh water, accounting for around three-quarters of the entire fresh water use (Shiklomanov, 1991). According to Liu *et al*. (2005), about half of the world's land surface is dryland and can only be made productive by using irrigation. Unfortunately, the productivity of many existing irrigated areas is in decline due to a combination of technical, economic and institutional factors. Probably the greatest technical cause of the decline is waterlogging and salinization of the soil, especially in arid and semiarid regions (Jensen *et al*., 1990).

2.2 Salinity

Salinity refers to the presence of salts in the soils and/or surface water and groundwater resources. According to Natural Resources and Water (NRW) (2006), the term is used to describe the presence of elevated levels of salts such as sodium chloride, magnesium and calcium sulphates and bicarbonates in soil and water. Smedema *et al*. (2004) noted that all rocks contain salts and when these salts are released and remain in the soil during weathering then it is termed primary or residual salinity. According to them, most excess salts are leached during the weathering process by the percolating water and may precipitate at lower depth or continue in solution and end up in the rivers. In irrigation projects in arid and semiarid regions, the salts accumulate to a level where it restricts plant growth. Such soils are termed saline (Chhabra, 1996; Smedema *et al*. 2004). Chhabra (1996) defines saline soil condition as soil which *saturation paste extract*[1] has an electrical conductivity more than 4dS/m, pH less than 8.2 and an exchangeable sodium percentage below 15 and contains very little organic matter, less than 1 %.

In addition, there is also secondary salinity which usually results from accumulation of salts in the soil when these salts were transported to the area by irrigation or capillary up-flow of water from shallow saline groundwater (Smedema *et al.,* 2004; Junior, 2000). This usually happens when there is impeded drainage in the soil. The secondary soil salinization tends to occur if the groundwater table rises above a certain critical depth.

High soil salinity is a serious worldwide environmental issue reducing the overall soil quality and thus limiting crop growth and yield (Ali *et al.*, 2000; Liu *et al*., 2005). Yurtseven *et al*. (2005) observed a decrease in water consumption in tomatoes with increase in salinity levels. Dixit *et al.* (2004) observed that the yield of wheat fell from 4.53 T/ha to 2.36 T/ha as the soil salinity rose from 0.25 dS/m to 1.63 dS/m. They also reported reductions in leaf area, stem growth, accumulated intercepted radiation and radiation use efficiency in wheat. Gutierrez *et al*. (1993) noted that the emergence and root growth of rapeseed (Brassica napus L) were delayed when soil salinity levels exceeded 6 dS/m.

2.3 Irrigation and agricultural production

One of the primary objectives of agriculture is to provide food and fibre for mankind. These needs rise as the population increases. In order to maintain the present level of food intake, the population growth rates require an increase in agriculture production of about 40 to 50 % over the next 30 to 40 years (FAO, 1992).

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[1]Saturation paste extract: Is solution extracted from a fully saturated 1:1 soil/water paste to assess soil salinity in the laboratory.

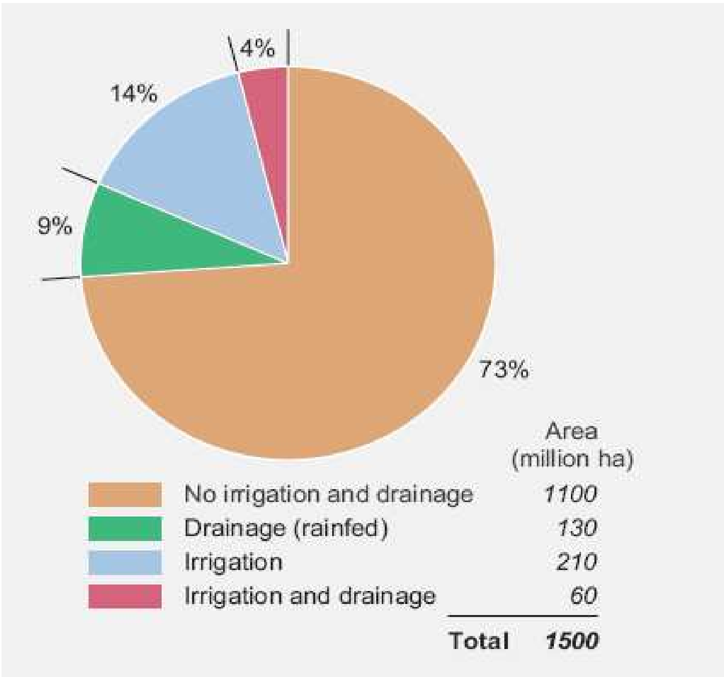
Growth of crop production can come from increases in arable land, cropping intensity and yield per unit area of cropped land (FAO, 1988). About two-thirds of the increase in arable land is expected to come from an expansion of irrigation (FAO, 1992). FAO (1992) states that the increase in food production needed in developing countries must come primarily from existing cropland, mostly irrigated land.

Irrigation has already played a major role in increasing food production over the years (Jensen *et al*., 1990). According to FAO (1992), about three-quarters of the irrigated land is presently found in developing countries. In these countries, almost 60 % of the production of major cereals is reliant on irrigation. Irrigated land presently accounts for about 16 % of the world's agricultural land (Postel, 1993**)** and yields about 36 % of the world's food (FAO, 1988).

Expansion of irrigation is needed to meet the food needs of the population. However, the present rate of irrigation expansion has slowed due among others to waterlogging and salinization (CAST, 1988; FAO, 1988). Massoud (1976) observed that more than 50 % of the world's irrigated lands are affected by secondary salinisation, sodicity and/or waterlogging. According to FAO (1992), 0.3 – 0.5 % of arable lands are being lost annualy due to soil degradation. The prime objective for agriculture in saline and waterlogged soils is to reverse the flux of water in order to promote leaching and control of the water table to provide adequate aeration and root development.

2.4 Drainage

Drainage here refers to agricultural drainage systems. Drainage describes the removal of excess water and/or excess soluble salts from the soil profile in order to maintain groundwater and/or salinity at a desired level (Nijland *et al.*, 2005; Zucker and Brown, 1998; Bos and Boers, 1994). Drainage plays an essential role in food production in humid regions where rainfall exceeds evaporation and in arid and semiarid regions where irrigation water has contributed to waterlogging and secondary salinisation (Nijland *et al.,* 2005). Hoffman (1985) observed that for productive irrigated agriculture to continue, adequate leaching and drainage is necessary to remove salt left in the root zone after irrigation. Tanji (1990) noted that drainage systems are required to prevent waterlogging and salinisation of root zones because natural drainage capacity of soils are often not sufficient to remove enough water to maintain acceptable condition. He observed that Indian civilizations in Peru and in the Salt River region of Arizona were destroyed by accumulation of salt in the soil profile due to poor drainage and soil salinisation. Nijland *et al*,. (2005), however, observed that large parts of existing agricultural lands still suffer from inadequate drainage and/or salinisation. Figure 2-1 shows the proportion of agricultural land drained worldwide. It is noted that out of the 1500 million hectares of irrigated and rainfed cropped lands, only about 13 % of the land is provided with some form of drainage.



Source: Nijland et al, 2005

Figure 2-1: Worldwide cropped lands equipped with or without irrigation and/or drainage system

2.5 The need for subsurface drainage

Drainage improvements can be achieved by using either surface or subsurface drainage systems. Surface drainage is intended to remove excess surface water from the land and it influences the water table by reducing the volume of water entering the profile. Subsurface drainage systems are intended to remove excess water from within the soil profile and this in turn reduces surface water. This is because the drains lower the water table and increase the available soil storage, thereby increasing infiltration (Wisler and Brater, 1949). Figure 2-2a shows the state of agricultural land before the introduction of drainage system. It is seen that when drainage system was introduced (Figures 2-2b and 2-2c), the water table is lowered leading to the subsequent removal of the ponding in depressions previously on the land. It is, however, observed that the water table in the subsurface drainage system (Figure 2-2c) is lower than that of the surface drainage system (Figure 2-2b). This means that the subsurface drainage system removes larger volume of water and hence salinity from the soil profile than the surface drainage system.

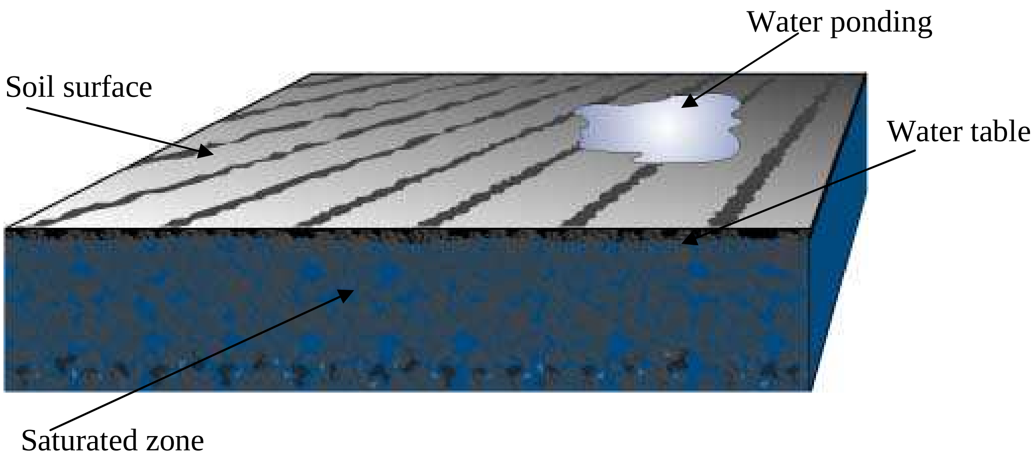


Figure 2-2a: No drainage system: Water table near soil surface and water ponding in surface depressions

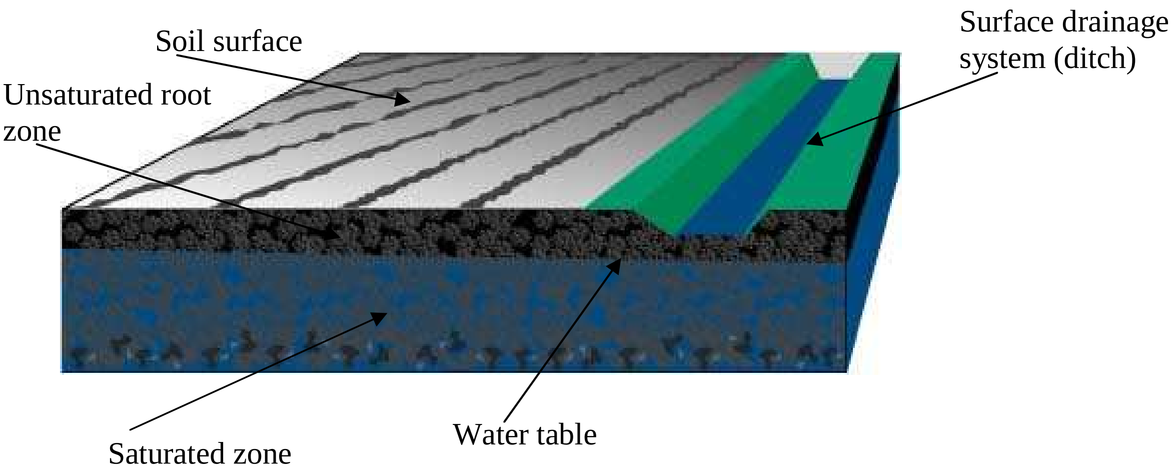


Figure 2-2b: Introduction of surface drainage system: Water table lowered, unsaturated root zone created

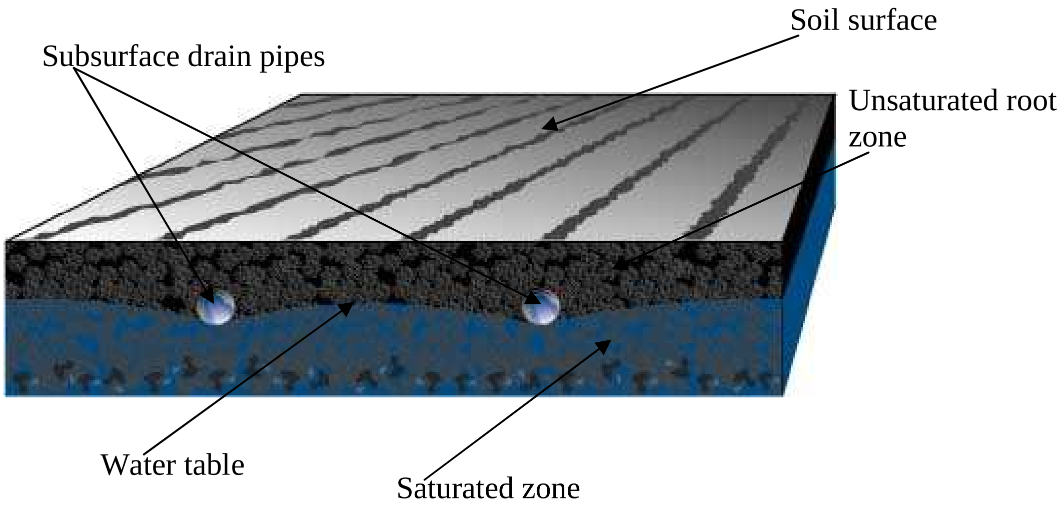


Figure 2-2c: Subsurface drainage system introduced: Water table lowered, larger unsaturated root zone created.

Source: Zucker and Brown 1998

FAO (1997) noted that the salt content of water flowing over the surface of soil changed very little even where there was a visible salt crust. Christen and Ayars (2001) observed that irrigation induced salinity is generally caused by shallow saline water tables rather than the application of saline irrigation water especially when the applied water had a very low salinity (EC< 0.4 dS/m). Because water is becoming increasingly scarce, and irrigation continues to account for about 75 % of water withdrawals worldwide, improved standards of irrigation design and management to reduce water use have been

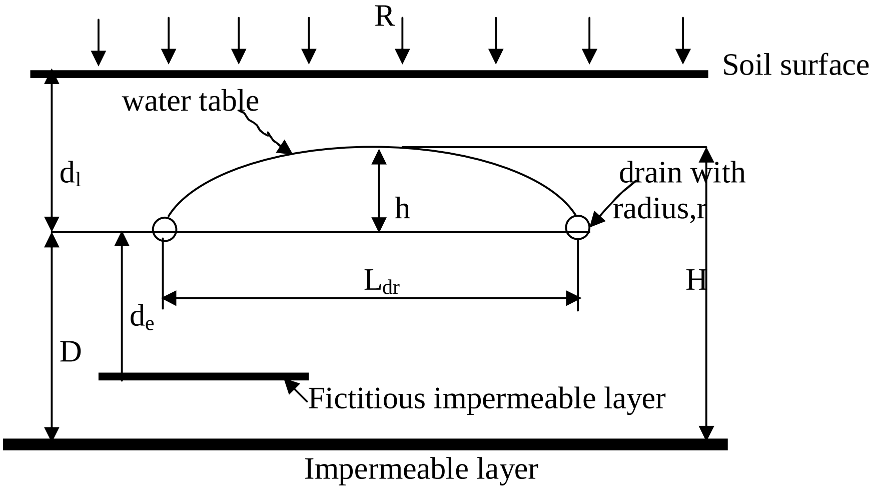


Figure 2-3: Schematic representation of homogenous soil underlain by an impervious boundary that is drained by parallel equally placed drains, two of which are shown.

where:
D = depth of impermeable layer to water level in the drain (m)
d_e = (equivalent) depth of fictitious impermeable layer to the water level in the drain (m)
d_l = depth of water level in the drain to soil surface (m)
H = height of water table midway between the drains (m)
h = mid-drain (or piezometric) head = height of water table midway between two drains (m)
R = rainfall or recharge (m/s)
q = R = discharge (m/s)
L_{dr} = drain spacing (m)
r = drain radius (m)

investigated (Kibaroglu, 2002; Mandava, 1999; Pereira, 1988). Christen and Ayars (2001) noted that, based on irrigation and management improvements, subsurface design should be targeted more towards salinity control than waterlogging. For this study therefore, subsurface drainage systems are considered because land that depends heavily on irrigation requires subsurface drainage systems to prevent the harmful build up of salts (Ward and Timble, 2004; Zucker and Brown, 1998).

The problem of subsurface drainage was investigated as early as 1862 using different lines of approach (Hathoot, 2002). The philosophy of subsurface drainage system has generally been based on maintaining a mid-drain water table below a critical depth (Ritzema, 1994). This critical depth has been derived from field studies of capillary upflow from a static water table, under conditions of low evaporation (Christen and Skehan, 2001). Conventional subsurface drainage design therefore considers only the effect of subsurface drain spacing and depth on the water table as shown in Figure 2-3. According to Guitjens *et al.*, (1997), the assumption that flow to drains occurs only as saturated horizontal flow coupled with its steady-state assumption has simplified the mathematical analysis, over more realistic transient flow analysis.

To achieve the objective of controlling the water table, many investigators have developed equations for designing subsurface drainage. Some of these equations include:-

a) The Hooghoudt/Donnan equation which is given as; $q = \frac{4K\left(H^2 - D^2\right)}{\left(L_{dr}\right)^2}$ (Ritzema, 1994) 2-1

where, K = Saturated hydraulic conductivity (m/s)

For definition of other symbols, see Figure 3,

b) The Hooghoudt's steady- state equation which is given as; $q = \frac{8Kd_e h - 4K\,h^2}{\left(L_{dr}\right)^2}$

(Smedema *et al*,. 2004; Ritzema, 1994) 2-2

Symbols are defined in Figure 2-3

c) The Kirkham equation, given as; $q = \frac{4\pi K(H-r)}{fL_{dr}}$ (Wiskow and van der Ploeg, 2003). 2-3

where,

$$f = 2\ln\left\{\frac{\sinh[\pi(2H-r)/L_{dr}]}{\sinh(\pi r/L_{dr})}\right\} - 2\sum_{n}^{\infty}(-1)^n\left\{\frac{\ln\sin h^2(2\pi nZ/L_{dr}) - \sin h^2(\pi r/L_{dr})}{\sin h^2(2\pi nZ/L_{dr}) - \sin h^2[\pi(2H-r)/L_{dr}]}\right\}$$

and Z = D + d is depth of impervious layer below the soil surface (m), and n is porosity of the aquifer.

All the other symbols are defined in Figure 2-3

There are other drainage design equations like Ernst, Richards, Bousinesq and many more found in Smedema *et al.,* (2004), Van Der Ploeg *et al.,* (1999) and Ritzema, (1994) which have been used in several drainage design models.

The Hooghoudt steady state equation has been widely used for drainage design and is the basic design equation used in the DRAINMOD model (Skaggs, 1980). Other subsurface drainage design models that use the Hooghoudt steady state equation include the WAVE (Water and Agrochemical in soils, crops and Vadose Environment) (El-Sadek *et al.,* 2001) and the SWAP (Soil Water Atmosphere Plant) (van Dam et al., 1997). El-Sadek *et al.,* (2001) computed drainage discharges of the DRAINMOD, the WAVE and the SWAP models and concluded that all the three models perform equally well in relation to the observed discharge (Details of these models are found in section 2.8).

In all approaches of the conventional subsurface drainage designs, the water table height midway between the drains has been the focus of interest since this is the highest point of the saturated zone and the area of major concern for salinity control (Guitjens *et al*., 1997). Based on the use of the above equations, the typical standard drain spacings and depths for different soil types for rainfed agriculture are as shown in Table 2-1. However, these approaches only consider the gross amount of water removed, and do not consider the flow path and the quantities of salt left in the soil profile. Numerical groundwater flow models coupled with salt movement models would have that potential to provide improved drainage designs for salt control in the root zone that could result in wider spacing and hence reduced cost while at the same time using less water than conventional drainage designs.

Table 2-1: Standard drain spacing and depth

Soil type	Soil permeability	Parallel Drain Spacing (m) for			Drain depth (m)
		Fair drainage	Good drainage	Excellent drainage	
Clay loam	Very low	21	15	11	0.91 – 1.07
Silty clay loam	Low	29	20	14	1.00 – 1.07
Silt loam	Moderately low	40	27	18	1.07 – 1.23
Loam	Moderate	61	43	29	1.12 – 1.31
Sandy loam	Moderately high	91	64	46	1.22 – 1.37

Source: Write and Sands (2001)

2.6 Theory of groundwater model

Groundwater models may be used to predict the effects of hydrological (like groundwater abstraction) on the behaviour of the aquifer. These models' calculations are based on mathematical equations, often with numerical (approximation) solutions; they are, therefore, called numerical models (Haitjema, 1995).

For the model calculations, the following are needed (Rushton 2003):

(a) Hydrological input and is usually inflow into the aquifer or the recharge, which may vary in time and in space.

(b) Hydraulic parameters which usually concern the physical properties used in the model that are more or less constant with time but variable in space. These include topography, thickness of soil layers and their hydraulic conductivity, porosity and storage coefficient, dispersion and diffusion coefficients.

(c) Initial and boundary conditions which relate to levels, pressure and hydraulic head on the one hand (head conditions), and groundwater recharge, discharge, inflow and outflow on the other hand (flow conditions)

The numerical groundwater model used for the study is a combined groundwater flow model and solute (salt)-transport (hydrodynamic dispersion) model into a single model. A groundwater model can be defined as being a simplified version of the real groundwater system (de Ridder and Boonstra, 1994). A groundwater flow model solves groundwater flow equation whilst solute (salt) transport model solves solute (salt)-transport equation. Groundwater model describes the flow and/or the salinity characteristics when appropriate assumptions and constraints are made. It provides the representation of the system, the relationships between the various components, and between the system and its environment.

2.6.1 Groundwater Flow Model

The general governing equation of groundwater flow in 3-Dimensional, Cartesian form for time variant flow in an isotropic nonhomogeneous porous medium is given by Manguerra and Garcia, (1997), Bear and Verruijt, (1990), and Rushton and Redshaw (1979) as:

$$\frac{\partial}{\partial x}\left(Kx\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Ky\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(Kz\frac{\partial h}{\partial z}\right)\pm Qs = So\frac{\partial h}{\partial t} \qquad \text{2-4}$$

where,

$K = K_x, = K_{y=}, K_z$ = hydraulic conductivity (m/s) along the x, y, and z coordinate axes respectively.

h = h(x, y, z,) = total piezometric head (m)

Q_s = source or sink term (s^{-1}) and is the volumetric flux per unit volume of aquifer.

t = time (s)

S_o = specific storage or specific yield (m^{-1}) of the porous medium

x, y, z = principal coordinate axes

Initial and boundary condition

Initial head, also known as 'starting head' is the head (usually at time, t, = 0) specified at the beginning of the first *time-step*[2]. For a numerical groundwater flow model, a head

[2] *Time-step is the length of time taken for the calculation for head (or salinity) at each cell node*

distribution at the beginning of each time-step is required to calculate the head distribution at the end of that time-step. For each time-step after the first, the head distribution at the start of one time-step is set equal to the head distribution at the end of the previous time-step by the model (McDonald and Harbaugh, 1988).

The initial condition in general form is thus given as:-

$h(x, y, z, t) = h_o(x, y, z, 0)$ for all x, y, z $\in \partial D$ 2-5

where:

$h(x, y, z, t)$ = hydraulic head (m)

$h_o(x, y, z, 0)$ = a known initial head (ie specified head at time, t = 0) (m)

x, y, z = principal coordinate axes

t = time (s)

∂D = boundary of considered domain (ie flow region)

Boundaries are the representation of physical features of groundwater systems (like streams, drains, recharge, etc) that have effects on the head in and flow of groundwater into the considered domain. The boundary conditions and their mathematical representation depend on the nature of this effect. The boundary conditions express the way in which the considered domain interacts with its environment.

To obtain a solution to the groundwater flow equation, it is a mathematical requirement that boundary conditions be specified along the entire boundary of the domain. In solving for groundwater flow, however, the boundary conditions are not simply mathematical constraints; they generally represent the sources and sinks of water within the domain (Reilly, 2001).

Boundary conditions are grouped into (Franke et al. 2001):-

a) Specified head (Dirichlet) boundary condition and mathematically is expressed as:

$h(x, y, z, t) = \text{constant}$ 2-6

.

b) Specified flow (Neumann) boundary condition and mathematically given as:

$$K\frac{\partial h(x, y, z, t)}{\partial \omega} = \text{constant} \qquad 2\text{-}7$$

c) Head- dependent flow (Cauchy) boundary condition and is given as:

$$K\frac{\partial h(x, y, z, t)}{\partial \omega} + ch = \text{constant} \qquad 2\text{-}8$$

where:

h = head in the model domain (m)

ω = directional coordinate normal to the boundary (m)

c = constant.

For the groundwater flow model used for the study, recharge is represented as specified flow boundary condition; river, drain and evapotranspiration are all represented as head-dependent flow boundary conditions.

Sources and sinks

Accurate information about the sources and sinks within the aquifer is essential for developing groundwater models. Sources and sinks can either be areally distributed or be point sources or sinks. Sources are recharges into the aquifer through infiltration of irrigation or rainfall. There are a variety of methods for estimating recharge (Collis-Geirge, 1977; Howard and Lioyd, 1979; Gates *et al*., 2002). Rainfall or applied irrigated water minus direct runoff and evapotranspiration is assumed to infiltrate into the soil. Detailed equations for sources and sinks for aquifers are provided by McDonald and Harbaugh, (1988).

2.6.2 Solute (Salt) -Transport Model

A solute (salt)-transport model predicts the changes in solute mass storage in an aquifer due to advection, dispersion, sink/sources, and chemical reactions. The governing equation for 3-dimensional salt-transport in groundwater is (Zheng and Wang, 1999; Manguerra and Garcia, 1997):

$$\frac{\partial}{\partial t}(\theta C)=\frac{\partial}{\partial x_i}\left(\theta D_{ijk}\frac{\partial C}{\partial x_j}\right)-\frac{\partial}{\partial x_i}(\theta v_i C)\pm q_s+Rn \qquad 2\text{-}9$$

where,

θ = volumetric water content (-) or porosity of the subsurface medium

C = salt concentration (kgm^{-3})

t = time (s)

D = hydrodynamic dispersion tensor coefficient (m^{2}s^{-1})

Q_s = source or sink flux per unit volume of aquifer (s^{-1})

C' = sink or source salt concentration (kgm^{-3})

Rn = chemical reaction term

$x_{i,j}$ = distance along the respective Cartesian coordinate axis (m)

v_i = linear pore velocity(ms^{-1}); and it relates to Darcy flux as $v_i = q/\theta$

q_sC' = the rate of quantity of salt added or removed per unit volume of aquifer (kgm^{-3}s^{-1})

i,j, k = position of cell in the x, y, and z directions respectively (-)

$\frac{\partial}{\partial t}(\theta C)$ is the rate of quantity of salt per unit volume of soil (kgm^{-3}s^{-1}), and is the change in mass of the solute storage in the aquifer.

$\frac{\partial}{\partial x_i}(\theta D_{ij}\frac{\partial C}{\partial x_j})$ (kgm^{-3}s^{-1}) is the dispersion term that describes the spreading of the solute over a greater region than would be predicted solely from the average groundwater velocity vectors due to mechanical dispersion and molecular diffusion. It is expressed mathematically as (Zheng and Wang, 1999):

$$\frac{\partial}{\partial x_i}\left(\theta D_{ij}\frac{\partial C}{\partial x_j}\right) = \frac{\partial}{\partial x}\left(\theta D_{ij}\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial y}\left(\theta D_{ij}\frac{\partial C}{\partial z}\right) + \frac{\partial}{\partial z}\left(\theta D_{ij}\frac{\partial C}{\partial x}\right) \qquad 2\text{-}10$$

D_{ij}, known as hydrodynamic dispersion coefficient (m^{2}s^{-1}), is the sum of mechanical dispersion and the molecular diffusion coefficients. This is expressed as (Bear and Verruijt, 1990; Berner, 1980):

$$D_{ij} = D_m + D^* = [\alpha_T V + (\alpha_L - \alpha_T) V_i V_j / V] + D_o^* / T^2 \qquad 2\text{-}11$$

where,

D_m = mechanical dispersion coefficient (m^{2}s^{-1})

D^* = molecular diffusion coefficient (m^{2}s^{-1})

α_L and α_T = longitudinal (m) and transversal (m) dispersivities respectively. The α_L describes the effects of soil heterogeneity on mechanical dispersion along the flow of the fluid, and α_T describes the effects perpendicular to the flow and they are dependent on the size of the study area (Langevin, et al., 2004).

V = average velocity of the flow (ms^{-1})

V_i, V_j = velocity of flow along the principal axes of dispersion (ms^{-1})

D_o* = molecular diffusion coefficient of the salt in free-water (m^2s^{-1})

T = tortuosity (-)

$\frac{\partial}{\partial x_i}(\theta v_i C)$ ($kgm^{-3}s^{-1}$), is the advection term that describes the transport of miscible solute at the same velocity as the groundwater flow. This is expressed mathematically as (Zheng and Wang, 1999):

$$\frac{\partial}{\partial x_i}(\theta v_i C) = \frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)C + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)C + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)C \qquad \text{2-12}$$

The sink/source term, q_sC', represent the salt mass entering the aquifer through a source or leaving the aquifer through a sink. Solutes entering the flow fields by dissolution of minerals from the main domain are not treated as being part of the source term but rather as part of the chemical reaction term, Rn, in Equation 2-9. The Rn is viewed as 'internal' sink or source which represents the change in solute mass storage caused by the change in transient groundwater storage, and it does not cause mass to leave or enter the model domain. Sinks or sources can be either areally distributed or point. Areally distributed sinks or sources include recharge from infiltrated irrigated water or rainfall, and evapotranspiration. Point sinks or sources include pumps, drains, and rivers and constant-head dependent boundaries.

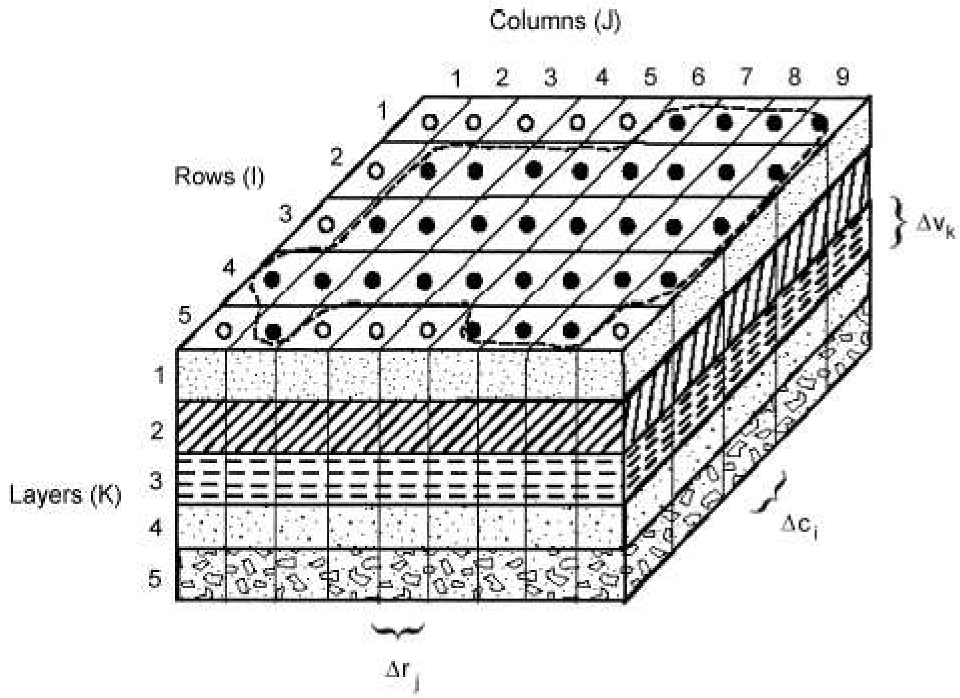
2.7 Numerical Analysis of Groundwater Model

Numerical groundwater models can be used to solve the non-linearity and spatial variation problems which are usually oversimplified or even neglected when equations are solved analytically (de Ridder and Boonstra, 1994). Except for very simple systems, analytical solutions of groundwater equations are rarely possible (McDonald and Harbaugh, 1988; Kabat and Beekma, 1994). The partial differential equation of the groundwater model can be solved by numerical approximation. The two best known methods are finite-difference and finite-element methods. For this study, the finite-difference method is adopted because of its simplicity and flexibility.

2.7.1 Discretisation

The aquifer system described by the groundwater model is divided into a mesh of blocks called cells by two sets of parallel, orthogonal lines and vertically by parallel, horizontal planes so that each cell formed by the discretisation forms a rectangular block (Figure 2-4). The locations of the blocks are described in terms of rows, columns and layers and an indexing system i, j and k are used to identifying them. In the model the assumption is that the row, column and layer directions are oriented along the x, y and z coordinate axes respectively. With the Cartesian coordinate system, the width of the cells in the row direction is designated Δr_j; the width of cells in the column direction is designated Δc_i; and the thickness of the cells is designated Δv_k (Figure 2-4). The subscripts j, i, and k indicate the number of the column, row and layer respectively.

The fixed grid system model is based on the block-centred formulation that places a discrete node at the centre of each cell (Figure 2-5). The partial derivatives of the model are replaced by terms calculated in space and time from the differences in hydraulic head or concentration at these points. These lead to systems of simultaneous linear algebraic difference equations whose solution yields values of head or concentration at specific nodes and times. These values constitute an approximation to the time-varying head or concentration distribution that would have been given by an analytical solution of the partial equation of the flow or solute transport.



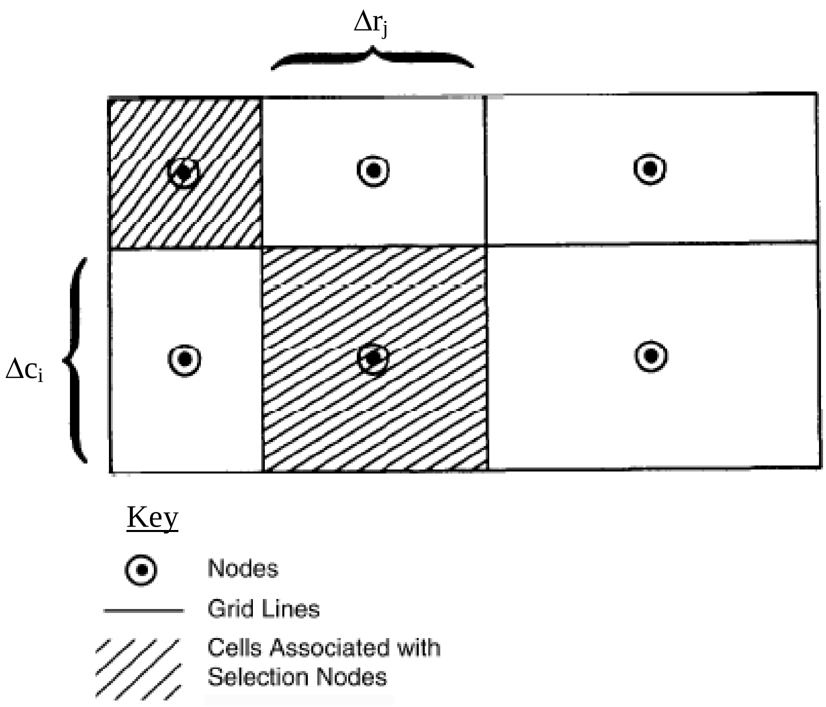
------ Aquifer boundary

- Active cell

o Inactive cell

Source: Zheng and Wang, 1999

Figure 2-4: Discretisation of an aquifer system with cell dimensions



Source: McDonald and Harbaugh, 1988

Figure 2-5: Block-centred grid system

2.7.2 Finite-Difference Approximation

The development of groundwater equation in finite-difference form follows the application of the continuity equation. The mass balance for a node, i, j, k and six adjacent nodes, i+1,j,k; i-1,j,k; i,j+1,k; i,j-1,k; i,j,k+1and i,j,k-1 of a 3D grid system is expressed in algebraic form as:

$$A_{i-1,j,k}h^{t+1}_{i-1,j,k} + A_{i+1,j,k}h^{t+1}_{i+1,j,k} + A_{i,j-1,k}h^{t+1}_{i,j-1,k} + A_{i,j+1,k}h^{t+1}_{i,j+1,k}\ A_{i,j,k-1}h^{t+1}_{i,j,k-1}$$
$$+ A_{i,j,k+1}h^{t+1}_{i,j,k+1} + (-A_{i-1,j,k} - A_{i+1,j,k} - A_{i,j-1,k} - A_{i,j+1,k} - A_{i,j,k-1} - A_{i,j,k+1} + RC_{i,j,k})h^{t+1}_{i,j,k}$$
$$= - SS_{i,j,k}\, h^t \Delta x_j \Delta y_i \Delta z_k / \Delta t - Q_{i,j,k} \qquad \text{2-13}$$

where:

A = conductance (m^2d^{-1}) and is the product of hydraulic conductivity and cross-sectional area divided by the distance (length of the flow path) between the nodes.

$RC_{i,j,k} = P_{i,j,k} - SS_{i,j,k}\Delta x_j \Delta y_i \Delta z_k/\Delta t$ (m^2s^{-1}) and is a flow into the $cell_{i,j,k}$ from external features or sources such as rivers, wells, area recharge.

$P_{i,j,k}$ = conductance controlling the flow from sink or source the external sources to the $cell_{i,j,k}$ (m^2s^{-1})

$SS_{i,j,k}$ = specific storage of cell i, j, k (m^{-1})

$\Delta x_j \Delta y_i \Delta z_k$ = volume of $cell_{i,j,k}$ (m^3)

Δt = time step interval (s) = t+1 - t

$Q_{i,j,k}$ = sink or source flow rate (m^3s^{-1}) that is independent on head of cell i, j, k

t = old time-level with known head (s)
t +1 = new time-level with unknown head (s)
h = hydraulic head (m) of cell i, j, k

Equation (13) can be expressed in the general matrix form as:

$$[A]\{h\} = \{q\} \qquad 2\text{-}14$$

where:

[A] = matrix of the coefficients of head at time step t+1 for all active nodes in the mesh

{h} = vector of head values at the time step t+1

{q} = vector of terms at right hand side of Equation (2-14)

For the salt transport equations, the algebraic equations are expressed as:

$$\alpha_{i-1,j,k} C^{t+1}_{i-1,j,k} + \alpha_{i+1,j,k} C^{t+1}_{i+1,j,k} + \alpha_{i,,j-1,k} C^{t+1}_{i,,j-1,k} + \alpha_{i,j+1,k} C^{t+1}_{i,j+1,k} + \alpha_{i,j,k-1} C^{t+1}_{i,j,k-1}$$
$$+ \alpha_{i,j,k+1} C^{t+1}_{i,j,k+1} + \alpha_{i,j,k} C^{t+1}_{i,j,k} = \alpha_{i,j,k} C^{t}_{i,j,k} + C^{t}_{s}\Delta t \qquad 2\text{-}15$$

where, $\alpha = (D + q)\, \Delta x\, \Delta y\, \Delta z$

2.8 Subsurface drainage models

Many subsurface drainage models of varying degrees of complexity and dimensionality have been developed to quantify the basic physical and chemical processes affecting water flow and salt transport in the root zone (Simunek and Bradford, 2008). These models have been used for wide range of applications in research and the management of natural subsurface systems.

The selection of subsurface drainage models for practical purposes involves several considerations. One of these is that the model is well tested and widely used. Among the numerous models mostly applied in the world include:

2.8.1. The WAVE model

The WAVE model (Water and Agrochemicals in the soil, crop and Vadose Environment) (Vanclooster *et al.*, 1995) is a process-based, deterministic, numerical and integrated model that simulates the movement of water and the transfer and solutes in the soil-crop continuum. The modules in the WAVE model simulate among others the flow of water and the transport of reactive and non-reactive solutes in the soil. A detailed description of the modules of the WAVE model and the soil processes that the model can simulate is found in Vanclooster *et al.* (1995). In addition, the WAVE model simulates lateral subsurface drainage flow to drains when a drainage subprogram is integrated in the model (El-Sadek *et al.*, 2001). The WAVE model was developed for temperate regions (Vanclooster *et al.,* 2000; Vereecken *et al.,* 1991), but has been successfully applied in semiarid Mediterranean regions (Fernandez *et al.*, 2002) and tropical regions (Duwig *et al*. 2003).

The WAVE model calculates the soil water flow per unit time using the Richards equation based on Darcy's law. The drainage component of the model uses Hooghoudt's steady-state equation (Equation 2-1) to calculate the drainage flux (El-Sadek *et al*., 2001). The equivalent depth, d_e, (m) in Hooghoudt's equation is determined as a function of the depth of the impermeable layer below the drain base, D (m), drains spacing, L_{dr} (m), and the wet entry perimeter of the drain, u (m) and is given as:

For $D < 1/L_{dr}$:

$$d_e = \frac{D}{\frac{8D}{\pi L_{dr}} \ln\frac{D}{u} + 1} \qquad 2\text{-}16$$

For $D > 1/L_{dr}$:

$$d_e = \frac{\pi L_{dr}}{8 \ln\frac{L_{dr}}{u}} \qquad 2\text{-}17$$

The WAVE model has been tested and successfully used in different fields including the analysis of flow behaviour in controlled laboratory experiments (Mallants *et al*., 1996), field experiments (Droogers *et al.,* 1997) and regional scale assessments (Vanclooster *et* *al.*, 1995). However, El-Sadek *et al*. (2001) in comparing WAVE simulated drainage discharge with DRAINMOD and SWAP models concluded that WAVE provides a relatively less accurate estimate of the discharge. Despite the successful use of the WAVE model in different areas, its usage for drainage system focuses mainly on water table control (El-Sadek *et al*., 2001) not on salt control.

2.8.2 SWAP model

The SWAP model (Soil Water Atmosphere Plant) (van Dam *et al*., 1997; Kroes *et al*., 2001) is a numerical one dimensional model that simulates among other things, water flow, solute movement and drainage flow in the soil profile. SWAP is a modification of SWACROP which was itself a combination of a soil water flow model, SWATRE, and a crop growth model (CROPR) (Feddes *et al*., 1978; Belmans *et al*., 1983; Kabat *et al*., 1992) to incorporate solute transport and regional drainage (van Dam *et al*., 1997). The model has been widely applied in a range of areas including the design of drainage systems (Kroes *et al*., 1999), design criteria for drainage in relation to actual transpiration and crop yields (Van Wijk and Feddes, 1986; Feddes, 1988) and to study the interaction between irrigation, drainage and crop yields (Bastiaanssen *et al*., 1996).

SWAP solves the Richards' equation numerically subject to specified initial and boundary conditions and uses known hydraulic functions to yield per time step, the recharge to the top of the water table. The hydraulic functions which relate to volumetric water content, soil water pressure head and hydraulic conductivity are described by the van Genuchten-Mualem (VGM) parameters (Van Genuchten 1987; Mualem, 1976). In the SWAP model, the drain discharge rate is computed using the steady state equations of Hooghoudt (equation 2-1) and Ernst (Ritzema, 1994). The drain discharge rate depends on the simulated groundwater level midway between the drains. The difference in hydraulic properties of the layered soil profile determines whether the Hooghoudt or Ernst equation should be used. The Hooghoudt's equation describes only flow to drains in a homogeneous profile with the drains above or on top of an impervious layer or in a two-layered profile with the drains located at the interface between the two layers whilst the Ernst's equation describes water flow to drains in a two-layered profile when the drains are situated in either the top or bottom layer (Van Dam et al., 1997).

In the SWAP model the equivalent depth, d_e, is solved using the equation:

$$d_e = \frac{\pi L_{dr}/8}{\pi L_{dr}/8D + \ln(D/L_{dr}) + \ln(L_{dr}/\pi r_o)} \qquad 2\text{-}18$$

where,

d_e = equivalent depth of the aquifer below the drain base and is a reduced value of D (m)

D = depth of impermeable layer below the drain base (m)

L_{dr} = drain spacing (m)

r_o = outside radius of the drain (m)

The SWAP simulates convection, diffusion and dispersion, and non-linear adsorption of solutes (salt) (Van Dam *et al*,. 1997). This permits the simulation of salt transport, including the effect of salinity on crop growth. The detailed discussions of the salt transport in the soil and other hydrologic processes can be found in Van Dam et al. (1997).

According to Sarwar et al (2000), most of the drainage systems in Pakistan were designed using the SWAP model. They, however, state that all these projects have failed in terms of maximizing the contribution of groundwater through capillary rise and at the same time minimizing capillary salinization and are therefore requiring the modification of the approach.

2.8.3 The DRAINMOD model

DRAINMOD is a deterministic hydrologic model developed for the design and evaluation of drainage and associated water table management systems (Skaggs, 1980; 1986). The model has been extensively used to analyse the effect of drainage on water table fluctuations (Skaggs, 1980; Fouss *et al*., 1987; Skaggs, 1999), and the reliability of DRAINMOD has been verified on a wide range of soils, crops and climatological conditions (Skaggs, 1982; Gayle *et al*., 1985; Fouss *et al*., 1987). For a specified drainage system (spacing and depth), the model uses soil physical properties and weather data (precipitation and potential evaporation) to predict subsurface drainage rates, water table position and the soil water content in the unsaturated zone (Robinson, 1990).

The model simulates the effects of different combinations of surface drainage and subsurface drainage water management systems on the water table by performing a water balance midway between parallel drains. The model computes the water balance on a thin section of soil extended from an impermeable layer at a known depth below the soil surface.

The water balance in the soil for a time increment of Δt can be written as (Skaggs, 1999):

$$\Delta V_a = D + ET + DS - I \qquad 2\text{-}19$$

where,

ΔV_a = change of water free pore space or air volume (m)

D_s = subsurface drainage (m)

ET = evapotranspiration (m)

DS = deep seepage (m)

I = infiltration (m)

The method used in DRAINMOD to calculate drainage rates is based on the Dupuit-Forchheimer (D-F) assumptions and considers flow in the saturated zone only (Borin et al. 2000). DRAINMOD calculates the subsurface drainage flux into the drains using the Hooghoudt's steady state equation (Equation 2-2) with a correction for convergence near the drains (van Schilfgaarde, 1974). The Hooghoudt equation assumes an elliptical water table below the soil surface. In the event of the water table rising to the soil surface causing surface water ponding, the D-F assumptions do not hold and hence the application of Hooghoudt approach is limited (Singh, 2006). In this case, DRAINMOD calculates the subsurface drainage flux using the Kirkham equation (Equation 2-3). Detailed calculations of the infiltration rate, evapotranspiration and deep seepage by DRAINMOD are provided in Skaggs (1980). The model has been modified to predict soil salinity as affected by irrigation water quality and drainage system design (Kendal et al., 1995; Merz and Skaggs, 1998).

It is recognised that the model has been widely tested, widely used and appears to be reliable (Gayle *et al.,* 1985; Robinson, 1990; Singh *et al.,* 2006). Borin *et al*. (2000) analysed the use of DRAINMOD to predict the water table depth and drain outflow and noted that even with limited soil input data (texture and porosity), simulated values matched well with measured values. It was noted that DRAINMOD considers the effect of the drainage system more on water table (Skaggs, 1999) than salt loads within the root zone. Singh et al. (2006) calibrated and validated the model for the design subsurface of a drainage system and stated that a drain depth of 1.05 m and a drain spacing of 25 m is sufficient enough to maximize crop production while minimizing subsurface drainage and its associated nitrate-nitrogen (NO_3-N) loss. They acknowledged the need to further reduce subsurface drainage but with the use of DRAINMOD to design the drainage system, they noted that installing drains at shallower depth (<1.05 m) though it might help reduce outflow, the shallow water table in combination with a wetter soil profile tended to increase runoff. Schilling and Helmers (2008) in using the DRAINMOD to simulate hydrologic response from drained agricultural systems noted that if the groundwater quality is to be properly evaluated then further in-depth research is needed. This implies that a model that does not only consider just water table control but salinity as well is appropriate and needed.

In irrigated agriculture, the objective of a drainage system is to maintain the water table deep enough to allow adequate aeration in the active root zone, to meet leaching requirements, and to minimize capillary salinization. On the other hand, the water table should be high enough to maximize the contribution of the soil water replenishment through capillary rise (Feddes, 1990). These contrasting objectives have made drainage design more difficult and complex. Most drainage systems were designed using models that were based on steady-state approach of Hooghoudt or Ernst and other similar equations (Ritzema, 1994). However, according to Sarwar *et al*. (2000), drainage systems installed in Pakistan were designed using the steady-state equations of

Hooghoudt and Ernst models but have failed because the steady-state approach does not allow studying the impact of different hydrological conditions on the necessary drainage capacity to be considered.

The looming world water scarcity has prompted a reassessment of the impacts and benefits of the huge water consumption of the irrigated sector (Cosgrove and Rijsberman, 2000). This has thrown a challenge down for the irrigation sector to produce more food using less water while simultaneously controlling soil and groundwater salinity (Bastiaanssen et al., 1996). It therefore seems inevitable that sustainable water management programmes need to be introduced on irrigation schemes. The optimization of such management can be encouraged by a drainage system that can reduce the need for leaching by discharging less water in order to maximize the contribution of soil water replenishment through capillary rise and control capillary salinization. This could be realised if the drainage system was designed using a model that can simulate variable-density groundwater flow. According to Guo and Langevin (2002), where there is spatial and/or temporal variation in fluid density, a representation of variable groundwater flow is necessary to characterise and predict groundwater flow rates, travel paths, and residence times. They noted that for the study of saline aquifers, the density variation between the recharge and that of the native aquifer can affect storage times and recovery efficiencies as well as capillary rise.

In reality, the recharge to and discharge from groundwater vary with time. In order to solve these unsteady-state problems, a transient numerical groundwater model that uses gridded system to discretise the model region into smaller increments needs to be considered. The discretization allows better handling of complexity in terms of spatial and temporal variability (Harbaugh *et al*., 2000). Transient numerical groundwater models provide an opportunity to capture the full range of all influencing parameters, many of which are seasonally variable and interact with each other.

One such transient groundwater model is SEAWAT (Guo and Langevin, 2002). The SEAWAT model is a 3-dimensional numerical groundwater model that simulates variable-density, transient groundwater flow and solute flow in the porous media.

Unlike the SEAWAT model, many groundwater flow models including those discussed are constant-density flow models and therefore the flow equations used are based on fluid volume conservation. These models are then used purposely to control water tables. However, Bear (1997) points out that the use of an equation based on volume balance is inappropriate when fluid density gradients are present. Evans and Raffensperger (1992) compared the mass- and volume – based stream functions for variable-density groundwater flow and concluded that mass fluxes rather than volume fluxes must be used to describe the flow of groundwater if there is variation in fluid density (ie recharge and groundwater).

2.8.4 The SEAWAT Model

The SEAWAT model (Langevin et al., 2003) combines a modified version of the MODFLOW model (McDonald and Harbaugh, 1988) and the MT3DMS (Modular 3-Dimensional Transport of Multi-Species) model (Zhen and Wang, 1999) into a single programme to solve the coupled flow equation (Equation 2-4) and solute equation (Equation 2-10). SEAWAT solves the variable–density flow equation by reformulating the matrix equations in terms of fluid mass rather than fluid volume and has the potential to deal with salinity. The SEAWAT code was developed using the MODFLOW concept of a process that solves a fundamental equation using a specified numerical method. SEAWAT contains all of the processes distributed with MODFLOW except that MODFLOW numerically solves constant-density groundwater flow (Equation 2-4) whilst SEAWAT solves variable density groundwater flow equation (Equation 2-20) (Guo and Langevin, 2002). The SEAWAT code uses a one-step lag between solutions of flow and transport to minimize complexity and run times (Langevin, 2001). This means that MT3DMS runs for a time step, and then MODFLOW runs for the same time step using the last concentrations from MT3DMS to calculate the density terms in the flow equation. For the next time step, velocities from the current MODFLOW solution are used by the MT3DMS to solve the transport equation.

In many groundwater flow models, it is assumed that the density of groundwater is spatially and temporally constant. To simulate groundwater flow in an environment with the aquifer having higher concentration of salt than the primary source of aquifer recharge, the assumption of constant density is not valid (Langevin, 2001).

The governing equation for variable-density flow in terms of equivalent freshwater head as used in SEAWAT is thus (Guo and Langevin, 2002):

$$\frac{\partial}{\partial x}\left\{\rho K_x\left(\frac{\partial h_f}{\partial x}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z_1}{\partial x}\right)\right\}+\frac{\partial}{\partial y}\left\{\rho K_y\left(\frac{\partial h_f}{\partial y}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z_1}{\partial y}\right)\right\}$$
$$+\frac{\partial}{\partial z}\left\{\rho K_z\left(\frac{\partial h_f}{\partial z}+\frac{\rho-\rho_f}{\rho_f}\frac{\partial Z_1}{\partial z}\right)\right\}=\rho S_f\frac{\partial h_f}{\partial t}+\theta\frac{\partial \rho}{\partial C}\frac{\partial C}{\partial t}-\bar{\rho}q_s \qquad 2\text{-}20$$

where,

ρ = density of saline aquifer water (kgm^{-3})

ρ_f = density of freshwater (kgm^{-3})

$K = K_x = K_y = K_z$ = hydraulic conductivity head (ms^{-1}) along the x, y, and z coordinate axes respectively.

h_f = equivalent freshwater head (m)

Z_1 = elevation at the measurement point (m)

S_f = specific storage, in terms of freshwater head (m^{-1})

C = salt concentration that affect aquifer water (kgm^{-3})

θ = porosity (-)

$\bar{\rho}$ = source/sink water density (kgm^{-3})

q_s = source/sink volumetric flow rate per unit volume of aquifer (s^{-1})

The derivations of the variable-density groundwater flow used in the SEAWAT are based on the concept of freshwater head, or equivalent freshwater head, in a saline groundwater environment. The detailed derivations of the variable-density groundwater flow equation can be found in Guo and Langevin (2002). According to Langevin (2001), equation 2-20 is valid when the aquifer water density variations are caused by salt concentration rather than by temperature, therefore for SEAWAT, temperature is assumed to be spatially and temporally constant thus the effects of temperature on groundwater density are not considered.

In SEAWAT, the variable-density groundwater flow equation (Equation 2-4) and solute transport equation (Equation 2-10) are not simultaneously solved, but rather a one time step lag is used.

The literature review has clearly shown that the conventional drainage system designed by the WAVE, SWAP, DRAINMOD models and others that target watertable control with a view to controlling salinity within the soil profile have been largely unsuccessful. The study seeks to create a better understanding of the scope for using variable density numerical models to design subsurface drainage systems that target concentration control within the soil profile. The effect of the drain spacing on the salt concentration distribution within the rooting zone will be part of the study. The resulting effect and its relation for different recharge quality and aquifer types will be assessed with particular emphasis on the ‘acceptable’ salt concentration levels and water table depth.

CHAPTER THREE

ASSESSING THE APPLICABILITY OF THE SEAWAT MODEL TO IRRIGATED FIELDS AS A SUBSURFACE DRAINAGE DESIGN MODEL

3.1 Introduction

The conventional drainage design equations used for subsurface drainage system are based on maintaining the water table at a certain height in order to prevent secondary salinization. This approach often produces drainage water with salt concentration which is very little different from the quality of the irrigated water (Christen and Skehan, 2001). If drainage systems could be designed to directly target salt concentration control at the base of the root zone rather than the water table, it could reduce the waste of irrigated water.

This Chapter assesses the applicability of the SEAWAT, a numerical variable density groundwater model, to irrigated fields to ascertain if it is possible to be used to design subsurface drainage systems that could control both water table and salt concentration at the base of the root zone with less irrigation water. This assessment was necessary because the SEAWAT model was developed for saltwater intrusion in coastal aquifers and brine migration in continental aquifers, and has been mostly used as such (Langevin, et al., 2003).

3.2 SEAWAT model construction

SEAWAT is a modular 3-dimensional finite-difference computer programme that combines MODFLOW and MT3DMS to approximate the coupled governing nonlinear groundwater flow and salt transport equations. The input packages in MODFLOW (Recharge, Drain and Evapotranspiration,) and MT3DMS (Advection, Dispersion and Source/Sink mixing) were used to simulate all the associated flow and salinity fluxes into and out of the aquifer system.

The SEAWAT-2000 version was used for the study and the software was obtained from Waterloo Hydrogeologic Inc.

The model was applied to a 100 m long by 10 m wide transect (xx’) on a hypothetical field with impermeable layer 20 m deep below the land surface. The transect is assumed to contain three parallel horizontal subsurface drain pipes set 35 m apart (Figure 3-1) and 2 m deep. The aquifer was considered saline and was isotropic homogeneous silty loam. The base of the aquifer and the field surface were assumed flat.

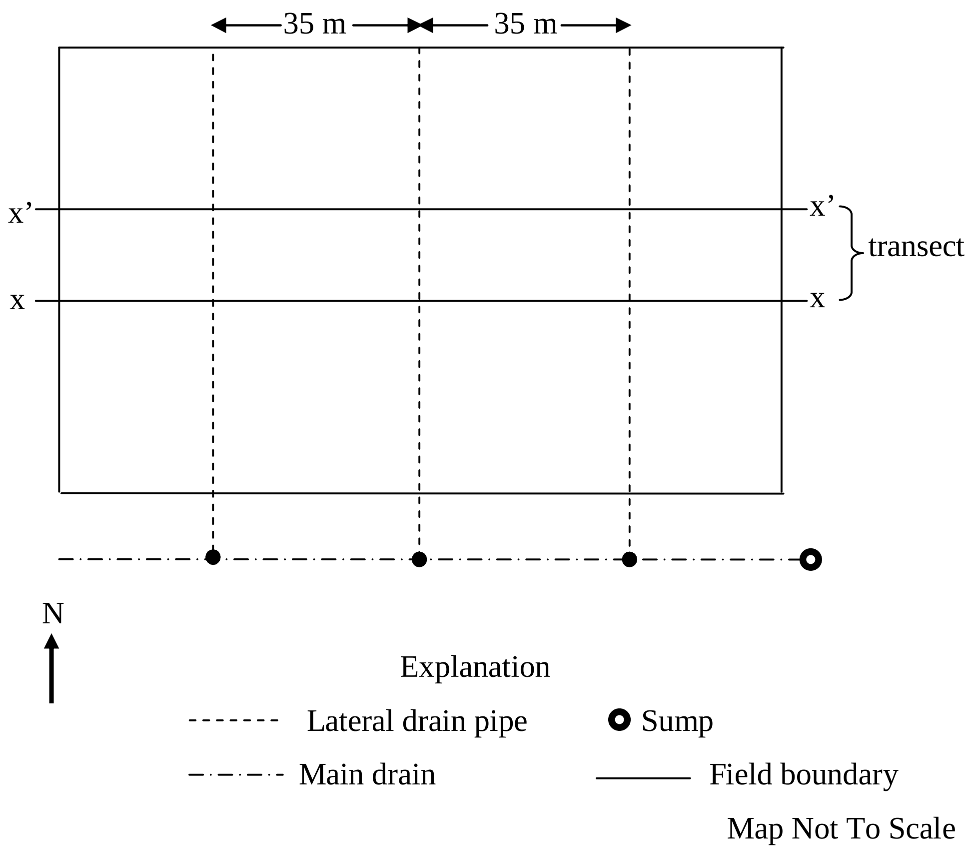


Figure 3-1: Conceptual site plan

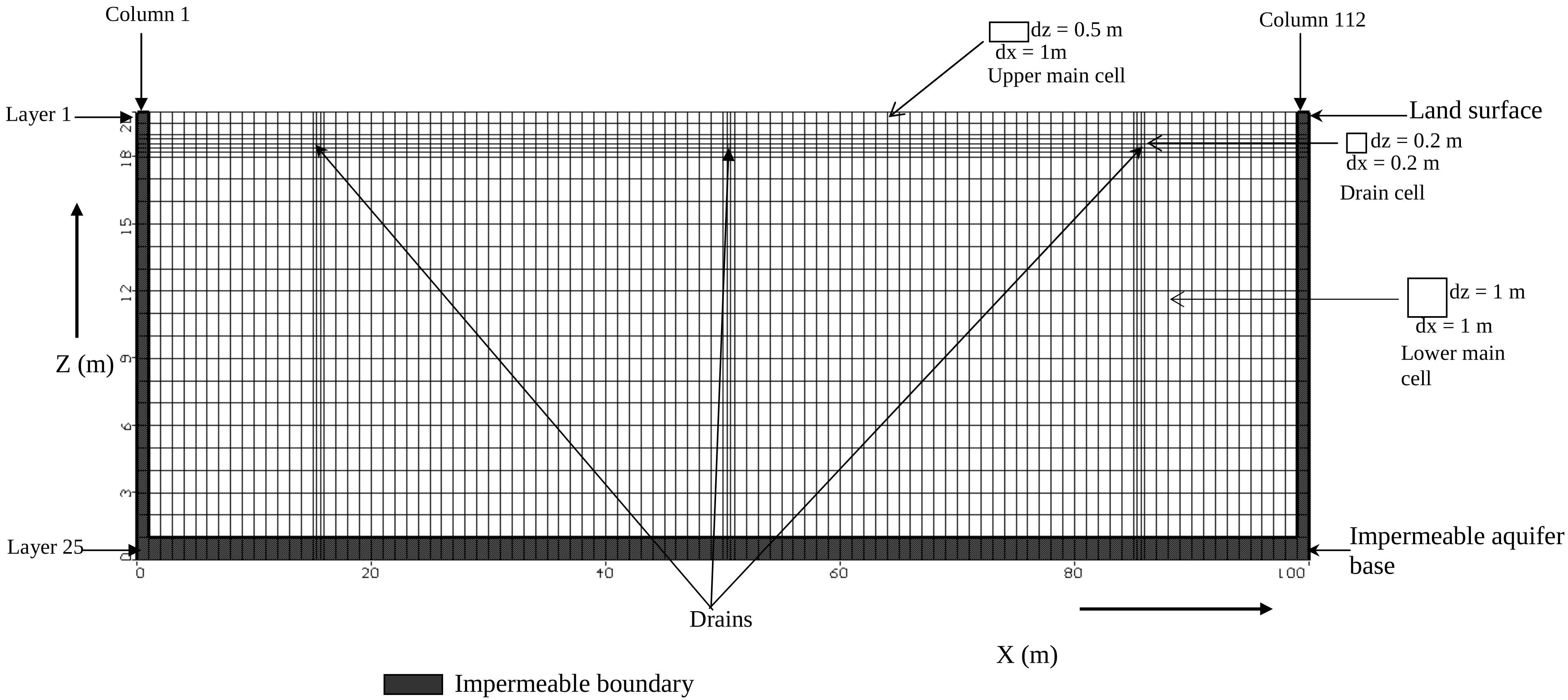


Figure 3-2: Finite-difference grid for the transect showing various cell sizes

Simulation of variable-density flow requires more layers compared to that needed for constant-density flow systems (Langevin, 2001). Accordingly, the transect was discretized into equal finite-difference grid of cells with 1 row, 100 columns and 20 layers with each cell measured 1 m horizontal and 1 m vertical (Figure 3-2). In layer 2, a row of cells to house the drains in 3 columns equally spaced (at the drain spacing) were subdivided into square cells (0.2 m per side), termed in this study 'drain cells', to more accurately approximate the size of the drains. Thus 0.2 m drain cell means drains cell measured 0.2 m horizontal and 0.2 m vertical. The layer (s) above and a layer below the drain layer were subdivided into two each to more accurately capture the radial flow of the groundwater towards the drains. This brought the grid into 103 columns and 24 layers (Figure 3-2). A uniform hydraulic conductivity of 0.8 m/d (applicable to a silty loam) was initially assigned to all layers except the impermeably layer at the base which was assigned a hydraulic conductivity of 10^{-7} m/d (applicable to a very poorly permeable layer) to prevent/minimize salt entering the model domain through advection.

3.2.1 Input data

Aquifer parameters

The aquifer parameter having the greatest effect on groundwater flow was found to be the hydraulic conductivity, thus a homogeneous isotropic value of 0.8 m/d was assigned to reflect a silty loam field. The aquifer was assigned a specific yield of 0.2, applicable to a medium textured soil (Johnson, 1967) and a storativity of 10^{-6}, calculated using the equation:-

$$Ss = \gamma \left(\beta_p + n\beta_w\right) \qquad 3\text{-}1$$

where, γ is specific weight of water ($kgm^{-2}s^{-2}$), β_p is the compressibility of bulk aquifer material = 1×10^{-9} ($ms^2\ kg^{-1}$), (Fine and Millero, 1973), n is the total porosity and β_w is the compressibility of water = 4.6×10^{-10} ($ms^2\ kg^{-1}$) (Fine and Millero, 1973).

For solute transport, the processes that cause solute dispersion are mechanical dispersion and molecular diffusion. The relevant aquifer parameters for solute transport include porosity (total and effective), dispersivity and diffusion coefficients. A uniform total porosity of 0.30 (applicable to silty loam) was assigned and an effective porosity of 0.2 (Sanders, 1998). The effective porosity value of 0.2 gave the same value as the specific yield (Langevin, 2001).

The longitudinal dispersivity, $\alpha_{L,}$ is proportional to the distance travelled by the solute (salt), and the constant of proportionality has been assigned different values by different researchers. Gelhar (1986) and Xu and Eckstein (1995) gave a value of 0.1 to the constant proportionality whilst Dong-Ju *et a*l. (2002) gave it 0.3. The longitudinal dispersivity, α_L, in this case was estimated using the formula:-

$$\alpha_{L=} 0.1L_s \text{ (Gelhar, 1986; Xu and Eckstein, 1995)} \quad 3\text{-}2$$

where L_s is the mean linear distance travelled by the solute (m), and was taken as distance from the centre of one model cell to the centre of the next, and this was equalled the horizontal distance of a main model cell.

The transverse dispersivity, α_T is less than the longitudinal dispersivity in the order of magnitude of -1 (Bear and Verruijt, 1990).

The molecular diffusion coefficient, D*, was estimated using the formula:

$$D^* = D_o/ T^2 \text{ (Berner, 1980; Shen and Chen, 2007)} \quad 3\text{-}3$$

where, D_o is the free molecular diffusion coefficient of salt = 1.73 x 10^{-4} m^2/d and T is the tortuousity = 1.8 (Kutilek and Nielsen, 1994).

Initial and boundary conditions

The initial water table head throughout the domain was set to 19.5 m (or 0.5 m below the soil surface) relative to the base of the aquifer which was at 20 m deep. The groundwater in the aquifer was assigned a concentration of 7200 mg/l (7.2 kg/m^3) and the density of was determined the formula:

$$\rho = \rho_f + \partial\rho/\partial C \times C \qquad \text{(Langevin, et al., 2003)} \quad 3\text{-}4$$

where, ρ is the density of groundwater (kg/m^3); ρ_f is the density of pure water (kg/m^3); $\partial\rho/\partial C$ is the density change per salt concentration change in the aquifer = 0.7 for salt concentrations ranging from zero to that of seawater (Langevin, et al., 2003). The term is zero when the density groundwater flow is constant; and C is the salt concentration of the water (kg/m^3).

In order to prevent flow into or from the model domain, no flow boundaries were assigned along the northern, southern, western and eastern boundaries. The bed of the aquifer was represented as an impermeable barrier (no flow boundary) with a hydraulic conductivity of 1×10^{-7} m/d, an approach used by Swain *et al.*, 1996.

Drains

The dynamic exchange of water between the aquifer and the drains was simulated using the drain (DRN) package within the SEAWAT programme. This assigned a head-dependent flux to each cell intersected by the drains.

Drain data included the following:- drain head (the free surface of water in the drain), drain invert (bottom) elevation and hydraulic conductivity between the drain and the aquifer (drain conductance). At the steady state conditions, the drain conductance was determined using the equation, and on the assumption that discharge was equal to the recharge:-

$$Q_d = CD\,(h - d_r) \quad \text{(McDonald and Harbaugh, 1988)} \qquad 3\text{-}5$$

where, Q_d was drain discharge (m^3/d); CD was drain conductance (m^2/d); h was aquifer head or initial head (m) and d_r was drain head (m) (depth of water in the drain).

Recharge

The recharge in this study refers to irrigation water applied to the field with a specified salt concentration after runoff is withdrawn. It was assumed that there was no runoff, and all the irrigation water was infiltrated hence recharge was taken as irrigation water and is termed applied recharge in the study. Therefore applied recharge and irrigation water were used interchangeably. The applied recharge was assigned arbitrarily, a value of 10 mm/d with concentration initially set equal to zero, and then to 3000 mg/l.

Evapotranspiration

The evpotranspiration was not considered in this chapter because the model simulated head was verified with mid-drain head obtained by the solution of Hooghoudt's steady state equation which does not take evapotranspiration into consideration.

Table 3-1 summarizes the main input data used for the model simulations of the aquifer. The model showed sensitivity to the drain conductance, drain cell dimension, porosity and longitudinal dispersivity, therefore they were selected for adjustment using Hooghoudt calculated mid-drain water table heads as the response.

Table 3-1: Main input data specified for the SEAWAT simulations

Parameter (unit)	Value
Aquifer thickness (m)	20
Initial groundwater salt concentration (mg/l)	7200
Initial groundwater density (kg/m^3)	1,005.04
Initial water table elevation (m)	19.5
Applied recharge (mm/d)	10
Applied recharge concentration (mg/l)	0; 3000
Applied recharge density (kg/m^3)	1,000; 1,002.1
Aquifer hydraulic conductivity, K, (m/d)	0.8
Aquifer bottom layer hydraulic conductivity (m/d)	1 x 10^{-7}
Total porosity	0.3
Porosity	0.2
Specific yield	0.2
Specific storativity (m^{-1})	1 x 10^{-6}
Longitudinal dispersivity, α_L, (m)	0.1
Transverse dispersivity, α_T, (m)	0.01
Molecular diffusion coefficient, D* (m2/d)	5 x 10^{-5}
Drain elevation (m)	18
Drain spacing (m)	35
Drain conductance (m^2/d)	1500
Drain cell (m)	0.5 m per side

The model was run on a daily basis for periods of:- 30 days (0.08 year), 180 days (0.49 year), 365 days (1 year), 730 days (2 years), 1825 days (5 years), 3650 days (10 years), 5475 days (15 years) and 7300 days (20 years).

3.3 Verification of SEAWAT model performance on irrigated field

Because the model is mostly used for saltwater intrusion in coastal aquifers and therefore considered its 'debut' use on irrigated field for this study, it was verified by running for water table heights midway between drains (mid-drain heads) at hydraulic conductivities ranging from 0.2 to 1.6 m/d and compared the simulated mid-drain heads with mid-drain heads obtained from solution of Hooghoudt's steady state equation (Equation 2-2) at corresponding hydraulic conductivities.

The equivalent depth, d_e, in the Hooghoudt equation (Equation 2-2) was determined using the equation:

$$d_e = \frac{L_{dr}}{8\left[\frac{\left(L_{dr} - D\sqrt{2}\right)^2}{8DL_{dr}} + \frac{1}{\pi}\ln\left(\frac{D}{r_o\sqrt{2}}\right)\right]} \qquad \text{(Wesseling, 1979)} \qquad 3\text{-}6$$

where,

r_o = outside drain radius (m)

For definitions of other symbols, see Figure 2-3.

The r_o is essential in determining the equivalent depth, d_e, for the Hooghoudt calculation. In the analysis, different values of r_o were used to determine equivalent depths which were in turn used to calculate heads that matched well with simulated heads for known drain cells dimensions.

Each d_e obtained was used to calculate mid-drain heads for aquifers with saturated hydraulic conductivities ranging from 1.2 to 0.2 m/d. Table 3-2 lists the parameters and their values for the Hooghoudt calculation. The value of parameters marked with * were constant throughout the calculations.

Table 3-2: Hooghoudt calculation parameters

Hooghoudt Parameter	Values
*Discharge, q (m/d)	0.01
*Drain spacing, L (m)	35.0
*Drain depth, d (m)	2.0
*Thickness of aquifer, D, below drains (m)	18.0
Calculated equivalent depth, d_e (m)	2.5, 2.9, 3.3 (using r_o = 0.05, 0.1, 0.2 m respectively)
Saturated hydraulic conductivity, K (m/d)	1.6, 1.4, 1.2, 1.0, 0.8, 0.6, 0.4, 0.2

The mid-drain head was simulated for different drain cells of 0.1 m, 0.2 m and 0.5 m per side and each simulated mid-drain head compared with the Hooghoudt calculated mid-drain head, h_c. For each drain cell, the model was run for drain conductances: 500, 1000, 1500 and 3000 m^2/d, and for hydraulic conductivities ranging from 0.2 to 1.6 m/d.

During the comparison it was noted that for all drain conductances and hydraulic conductivities:

a) The simulated mid-drain heads for the 0.1 m drain cells matched well with Hooghoudt calculated heads corresponding to the drain spacing of 35 m and an equivalent depth, d_e, of 2.5 m (Table 3-3a).

b) The simulated mid-drain heads for the 0.2 m drain cells matched well with Hooghoudt calculated heads corresponding to the drain spacing of 35 m and an equivalent depth, d_e, of 2.9 m (Table 3-3b)

c) The simulated mid-drain heads for the 0.5 m drain cells matched well with Hooghoudt calculated heads corresponding to the drain spacing of 35 m and an equivalent depth, d_e, of 3.3 m (Table 3-3c)

Table 3-3a: Comparison of simulated mid-drain heads for 0.1 m drain cells (Longitudinal dispersivity, α_L = 0.5 m) and Hooghoudt calculated mid-drain heads at d_e = 2.5 m for different hydraulic conductivities.

Hydraulic conductivity (m/d)	Drain conductance, CD (m^2/d)				Hooghoudt calculated mid-drain head for d_e = 2.5 m (cm)
	500	1000	1500	3000	
	Simulated *mid-drain head (cm)	Simulated mid-drain head (cm)	Simulated mid-drain head (cm)	Simulated mid-drain head (cm)	
1.6	31.0	30.7	30.5	30.4	35.7
1.4	36.2	36.5	36.7	36.6	40.5
1.2	41.7	41.4	41.3	41.2	46.7
1.0	50.9	50.7	50.5	50.4	55.2
0.8	61.7	61.5	61.4	61.2	67.4
0.6	82.4	82.1	82.0	82.8	87.0
0.4	119.3	118.9	118.7	118.3	122.9
0.2	199.8	199.6	199.5	199.2	198.2
R^2	0.9997	0.9996	0.9995	0.9995	1.0000

Table 3-3b: Comparison of simulated mid-drain heads for 0.2 m drain cells (Longitudinal dispersivity, α_L = 0.5 m) and Hooghoudt calculated mid-drain heads at d_e = 2.9 for different hydraulic conductivities.

Hydraulic conductivity (m/d)	Drain conductance, CD (m^2/d)				Hooghoudt calculated mid-drain head for d_e = 2.9 m (cm)
	500	1000	1500	3000	
	Simulated mid-drain head (cm)	Simulated mid-drain head (cm))	Simulated mid-drain head (cm)	Simulated mid-drain head (cm)	
1.6	27.5	27.1	27.0	26.9	31.3
1.4	31.0	30.7	30.6	30.4	35.5
1.2	36.7	36.4	36.1	36.1	41.1
1.0	43.3	43.0	42.8	42.7	48.7
0.8	55.2	54.8	54.7	54.6	59.8
0.6	73.2	72.9	72.8	72.7	77.6
0.4	106.5	106.2	106.1	106.0	110.8
0.2	196.9	196.5	195.1	195.0	197.1
R^2	0.9989	0.9989	0.9991	0.9991	1.0000

Table 3-3c: Comparison of simulated mid-drain heads for 0.5 m drain cell (Longitudinal dispersivity, α_L = 0.5 m) and Hooghoudt calculated mid-drain heads at d_e = 3.3 m for different hydraulic conductivities.

Hydraulic conductivity (m/d)	Drain conductance, CD (m^2/d)				Hooghoudt calculated mid-drain head at d_e = 3.3 (cm)
	500	1000	1500	3000	
	Simulated mid-drain head (cm)	Simulated mid-drain head (cm)	Simulated mid-drain head (cm)	Simulated mid-drain head (cm)	
1.6	23.3	23.0	22.9	22.8	27.8
1.4	27.3	26.9	26.8	26.7	31.6
1.2	31.2	30.9	30.8	30.6	36.6
1.0	37.1	37.4	37.3	37.1	43.5
0.8	48.9	48.6	48.5	48.4	53.6
0.6	63.4	63.1	62.9	62.8	68.3
0.4	93.2	92.9	92.8	92.7	100.7
0.2	177.5	177.2	177.0	176.9	181.8
R^2	0.9995	0.9996	0.9995	0.9995	1.000

Note: Calculated Hooghoudt heads are based on steady state recharge of 10 mm/d

*mid-drain head is the water table height above drains midway between drains

Generally the simulated heads for the different drain cell dimensions correlated well (R^2 = 0.99) with the Hooghoudt calculated heads. It, however, was decided to discount the 0.1m drain cells because the simulated water table levels in the drains area were actually above the drains for all drain conductances and hydraulic conductivities. For all the different drain grid cells and the hydraulic conductivities, the drain conductance of 500 m^2/d also generated drain water table levels above the drains and was therefore not considered further.

The other inputs such as porosity and longitudinal dispersivity that were peculiar to the model were then adjusted to simulate mid-drain heads for hydraulic conductivity of 0.8 m/d with drain cells of 0.2 m and 0.5 m, and compared with the Hooghoudt calculated mid-drain heads for the same hydraulic conductivity and equivalent depths of 2.9 m and 3.3 m respectively.

Table 3-4a: Simulated heads for different porosities, drain conductances and longitudinal dispersivities for 0.2 m drain cells and Hooghoudt calculated mid-drain head for d_e = 2.9 m (Hydraulic conductivity = 0.8 m/d)

Drain conductance (m^2/d)	Effective porosity (%)	Longitudinal dispersivity, α_L				Hooghoudt calculated mid-drain head at d_e = 2.9 (cm)
		0.01 m	0.1 m	0.5 m	1.0 m	
		Simulated mid-drain head (cm)	Simulated mid-drain head (cm))	Simulated mid-drain head (cm)	Simulated mid-drain head (cm)	
1000	10	54.6	54.8	55.0	54.7	59.8
	20	54.5	54.7	54.9	54.6	
	30	54.4	54.6	54.8	54.5	
1500	10	54.5	54.7	54.9	54.5	
	20	54.4	54.5	54.7	54.4	
	30	54.2	54.4	54.7	54.3	
3000	10	54.3	54.6	54.8	54.4	
	20	54.2	54.4	54.7	54.3	
	30	54.0	54.3	54.6	54.2	

Table 3-4b: Simulated heads for different porosities, drain conductances and longitudinal dispersivities for 0.5 m drain grid cells and Hoooghoudt head for d_e = 3.9 m (Hydraulic conductivity = 0.8 m/d)

Drain conductance (m^2/d)	Effective porosity (%)	Longitudinal dispersivity, α_L				Hooghoudt calculated mid-drain head at d_e = 3.3 (cm))
		0.01 m	0.1 m	0.5 m	1.0 m	
		Simulated mid-drain head (cm))	Simulated mid-drain head (cm)	Simulated mid-drain head (cm)	Simulated mid-drain head (cm)	
1000	10	48.5	48.6	48.9	48.5	53.6
	20	48.4	48.6	48.8	48.5	
	30	48.3	48.5	48.6	48.2	
1500	10	48.4	48.7	48.8	48.4	
	20	48.3	48.6	48.6	48.3	
	30	48.2	48.4	48.5	48.1	
3000	10	48.3	48.5	48.6	48.4	
	20	48.1	48.5	48.5	48.2	
	30	48.0	48.3	48.4	48.0	

Tables 3-4a and 3-4b list the simulated heads for different porosities, drain conductances and longitudinal dispersivities and for the hydraulic conductivity of 0.8 m/d. The simulated values compared well in all cases. From Table 3-4a, the percentage error between the simulated head and the calculated head ranged between 10.7 % and 8.9 . The percentage difference for the drain cell dimension of 0.5 m for all model parameters also ranged between 11.6 % and 9.6 % (Table 3-4b).

Though there were marginal differences in percentage difference, the longitudinal dispersivity, $\alpha_{L,}$ of 0.01 m generally had relatively higher difference and was therefore discounted. The constant of proportionality of the relation between longitudinal dispersivity and distance covered by solute (model domain cell length) should always be less than one (Gelhar, 1986; Xu and Eckstein, 1995), therefore the α_L value of 1.0 m also was discounted.
Table 3-5 lists the adjusted parameters and their corresponding values considered acceptable for the model.

Table 3-5: Adjusted model parameters

Model parameter	Range of values
Effective porosity	10 – 20 %
Drain cell dimensions	(0.2 - 0.5) m horizontal and (0.2- 0.5) m vertical
Drain conductance	1000 – 3000 m^2/d
Longitudinal dispersivity	(0.1 – 0.5) L_s*

*L_s is length of horizontal side of the model cell

3.4 Confirming the effectiveness of the model on the irrigated field

The model was set up within the adjusted parameters to model discharges in groundwater, hydraulic head, soil concentration and flow magnitude when drains are installed in the irrigated field.

3.4.1 Changes in applied recharges, drain discharges and salt balance in the aquifer

The changes in the recharges, discharges and salt balance in the aquifer over a 20 year period are shown in Table 3-6. The salt load remaining in the aquifer declined by about 98 % from 28,080 kg to about 450 kg over 20 year period. The salt concentration of the effluent was initially high but declined over the time period (as observed by Johnston 1993).

Table 3-6: Characteristics of applied recharge and drain discharge when the applied recharge was pure water

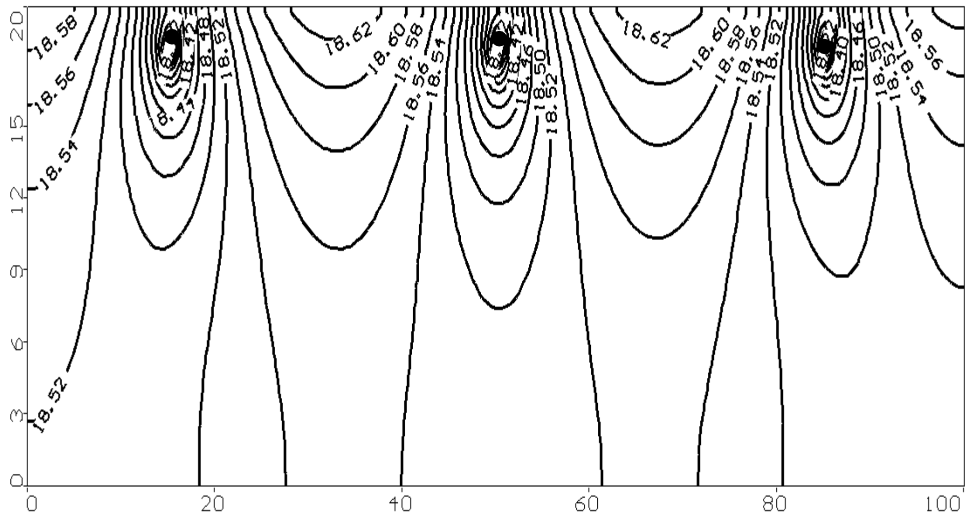
Time (year)	Applied recharge (applied water)			Drain discharge					Salt remaining in the aquifer		
	Total volume (m^3)	Rate (mm/d)	Density (kg/m^3)	Total volume (m^3)	Rate (mm/d)	Salt conc. (mg/l)	Density (kg/m^3)	Total salt removal (kg)	Total salt (kg)	Mean salt conc. (mg/l)	Density (kg/m^3)
0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	28,080.0	7,200.0	1,005.0
0.08	300.0	10.0	1,000.0	300.0	10.0	5,321.4	1003.7	1,596.3	26,484.0	6,790.8	1,004.8
0.49	1,800.0	10.0	1,000.0	1,799.9	10.0	3,613.5	1002.5	6,499.4	21,581.0	5,533.6	1,003.9
1	3,650.0	10.0	1,000.0	3,649.6	10.0	2,718.3	1001.9	9,996.4	18,084.0	4,636.9	1,003.3
2	7,300.0	10.0	1,000.0	7,299.6	10.0	1,917.2	1001.3	14,073.0	14,007.0	3,591.5	1,002.5
5	18,250.0	10.0	1,000.0	18,248.3	10.0	1,154.1	1000.8	20,072.0	8,008.8	2,053.5	1,001.4
10	36,500.0	10.0	1,000.0	36,501.3	10.0	623.7	1000.4	24,789.0	3,292.1	844.1	1,000.6
15	54,750.0	10.0	1,000.0	54,750.6	10.0	445.5	1000.3	26,838.0	1,243.0	318.7	1,000.2
20	73,000.0	10.0	1,000.0	73,002.8	10.0	340.2	1000.2	27,631.0	449.9	115.3	1,000.1

Conc. = concentration

3.4.2 Hydraulic-head distribution

A vertical cross-section of the aquifer showing the distribution of hydraulic head at times 0.08 year and 20 years is provided in Figures 3-3a and 3-3b. In all cases, as expected there was a high hydraulic gradient around the drains decreasing towards the midpoint. The equipotentials clearly show evidence of vertical, horizontal and the radial elements of flow as described by Smedema *et al*. (2004) whilst the nearly vertical equipotentials towards the base of the aquifer clearly show that horizontal flow dominate at this depth. This is in conformity with Skaggs (1980) findings when he solved the 2-dimensional Richards equation for the DRAINMOD.

Depth elevation (m)

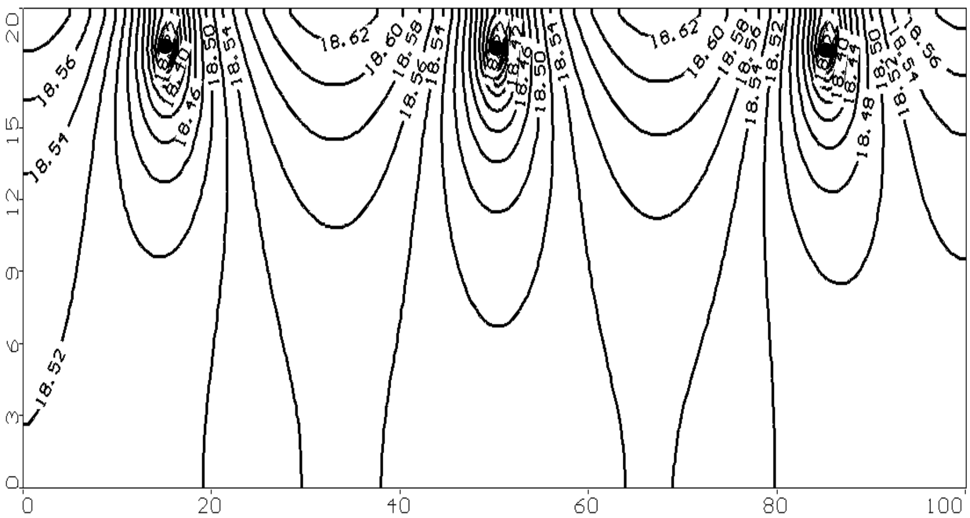


Horizontal distance (m)

• Drain Head contour unit: metres

Figure 3-3 (a): Hydraulic-head distribution: Year 0.08

Depth elevation (m)



Horizontal distance (m)

• Drain Head contour unit: metres

Figure 3-3 (b): Hydraulic-head distribution: Year 20

3.4.3 Advective velocity vectors

The magnitude of the groundwater velocity vectors in years 0.08 and 20 are illustrated in Figures 3-4a and 3-4b respectively. As expected the magnitude increases towards the drains reflecting the increased hydraulic gradients around the drain areas (Figure 3-3). The magnitudes close to the bed of the aquifer are nearly zero. As expected, mid-way between the drains, the recharge extended deeper into the aquifer, before turning to approach the drains.

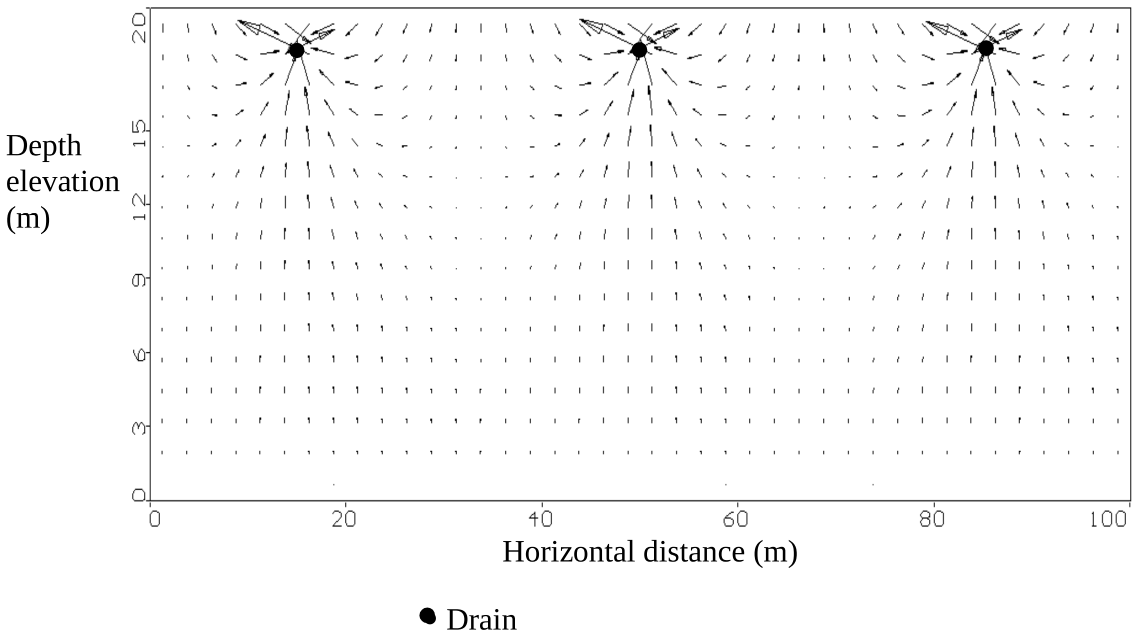


Figure 3-4(a): Flow velocity vectors at year 0.08

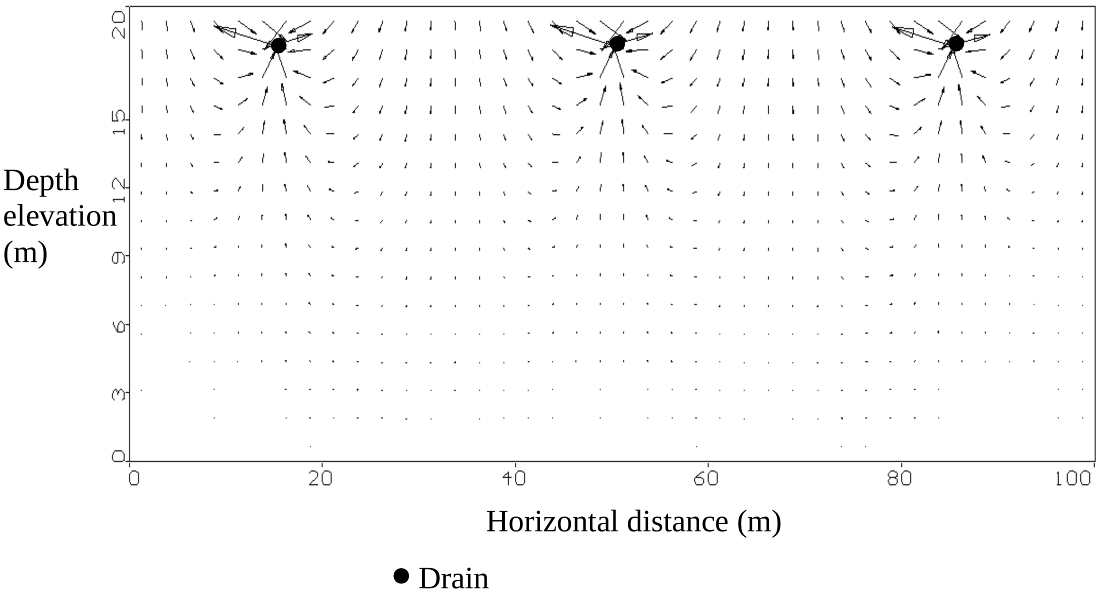
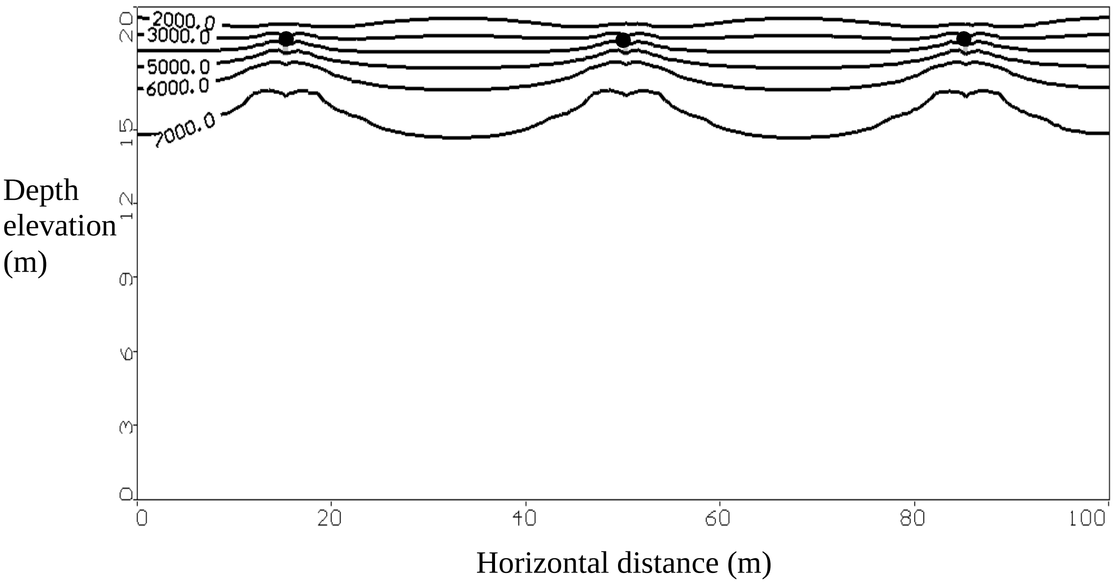


Figure 3-4(b): Flow velocity vectors at year 20

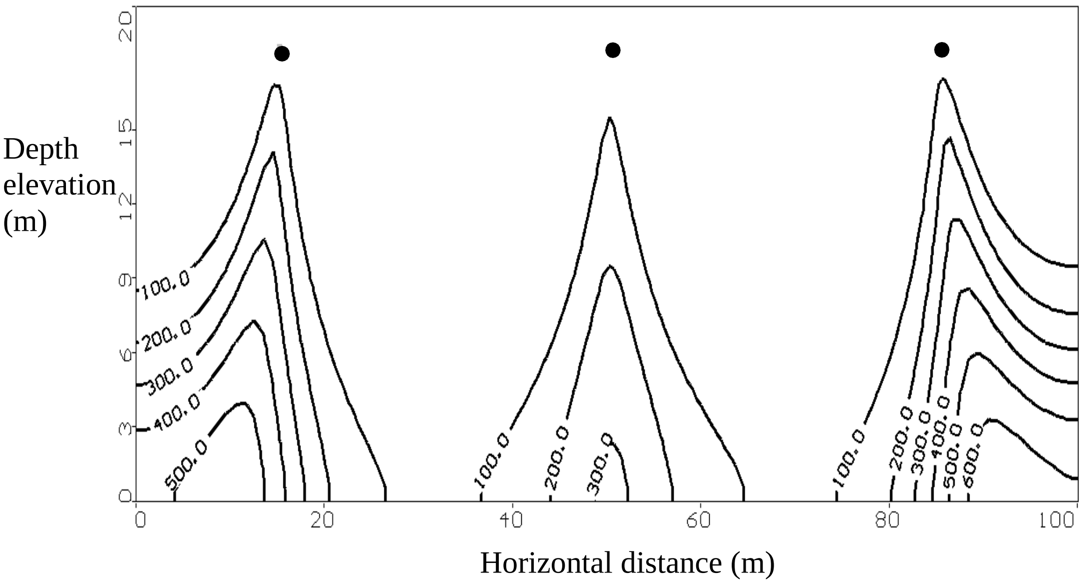
3.4.4 Groundwater salt concentration

The salt concentration in the aquifer for years 0.08 and 20 are illustrated in Figures 3-5a and 3-5b. At time zero the groundwater concentration was uniform at 7200 mg/l. As expected there was a systematic reduction of salt concentration with time. This provides evidence that the recharge mixed with the groundwater and was subsequently diluted as the salt was removed by the drains. After 20 years the salt concentrations had fallen to below 100 mg/l throughout most of the domain. However, in the corners and immediately below the drains, relatively high salt concentrations remained. The upconing of the salt concentration (Figure 3-5b) indicates that sufficient groundwater had been removed by the drains thereby causing the interface between the diluted ground water and the saline groundwater to move up from the underlining more concentrated part of the aquifer as described by Masterson and Portnoy (2006).



● Drain Salt concentration contour units: mg/l

Figure 3-5(a): Salt concentration distribution at year 0.08



● Drain Salt concentration contour units: mg/l

Figure 3-5(b): Salt concentration distribution at year 20

3.4.5 Discharges when using applied recharge salt concentration of 3000 mg/l

Table 3-7 shows the input/output characteristics when the salt concentration of the applied water was 3000 mg/l. The rate of salt reduction was exponential and similar to when the recharge used was pure water. The rate of the salt reduction, however, was lower than when the applied recharge was pure water. By 20 years, the initial salt load of 28,080 kg in the aquifer, notwithstanding the 30 kg per day added by the recharge had fallen by about 57 %, with a final discharge salt concentration similar to that in the recharge.

Table 3-7: Characteristics of applied recharge and drain discharge when the recharge contained 3000 mg/l salt concentration

Time (year)	Applied recharge			Drain discharge					Salt remaining in the aquifer		
	Total volume (m^3)	Rate (mm/d)	Density (kg/m^3)	Total volume (m^3)	Rate (mm/d)	Salt conc. (mg/l)	Density (kg/m^3)	Total salt load removed (kg)	Total salt load (kg)	Mean salt conc. (mg/l)	Density (kg/m^3)
0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	28,080.0	7,200.0	1,005.0
0.08	300.0	10.0	1,002.1	300.1	10.0	5,813.3	1,004.1	1,744.0	27,237.0	6,983.8	1,004.9
0.49	1,800.0	10.0	1,002.1	1,799.9	10.0	5,004.0	1,003.5	9,007.2	24,473.0	6,275.1	1,004.4
1	3,650.0	10.0	1,002.1	3,649.6	10.0	4,545.2	1,003.2	16,590.0	22,440.0	5,753.8	1,004.0
2	7,300.0	10.0	1,002.1	7,299.4	10.0	4,104.2	1,002.9	29,961.0	20,020.0	5,133.3	1,003.6
5	18,250.0	10.0	1,002.1	18,249.0	10.0	3,639.0	1,002.6	66,411.0	16,420.0	4,210.3	1,003.0
10	36,500.0	10.0	1,002.1	36,500.0	10.0	3,394.1	1,002.4	123,883.0	13,698.0	3,512.3	1,002.5
15	54,750.0	10.0	1,002.1	54,750.0	10.0	3,282.6	1,002.3	179,722.0	12,609.0	3,233.1	1,002.3
20	73,000.0	10.0	1,002.1	73,000.0	10.0	3,217.4	1,002.2	234,867.0	12,214.0	3,131.8	1,002.2

Conc. = concentration

3.4.6 Salt concentration dynamics in the aquifer

Apart from the model's ability to simulate total salt load in the aquifer, it is also able to simulate salt concentration throughout the soil profile. Figure 3-6a shows the salt concentration dynamics (between two drains) at 0.75 m depth below the soil surface when the recharge was pure water. As expected, the salt concentration was lower near the drains, and highest midway between them as observed by Sharma *et al*. (2000) and the effect is most apparent during the initial period of drainage. After a short period (0.49 year) the situation reversed with the area midway between the drains having a relatively lower salt concentration than around the drains.

Figure 3-6 b reveals that the initial salt concentration of 7200 mg/l was maintained at 1.5 m depth for about two years before it started to decline. This was caused by the long time being needed for percolation to move from the soil surface to the lower region of the aquifer.

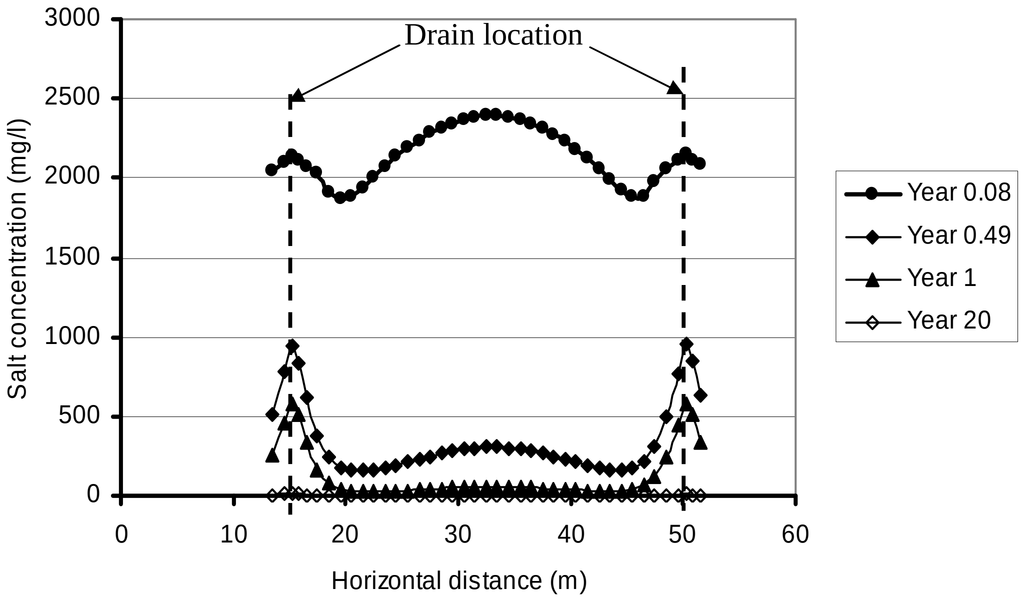


Figure 3-6(a): Salt concentration pattern at a depth of 0.75 m below the soil surface for pure water recharge

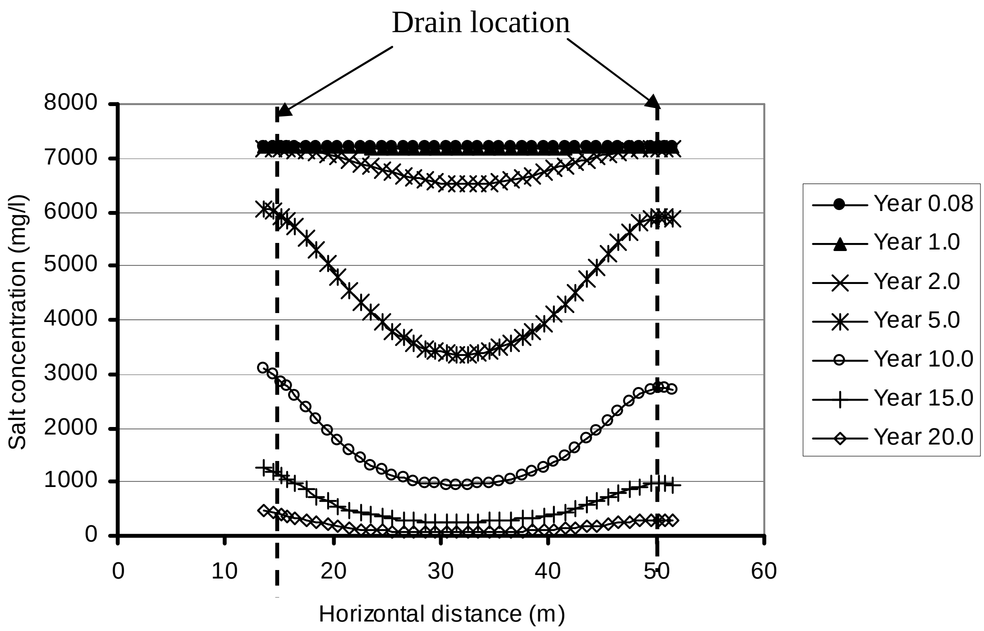


Figure 3-6(b): Salt concentration pattern at 17.5 m below the soil surface for pure water recharge

Figures 3-7a and 3-7b show the salt concentration distribution between two drains at depths of 0.75 m and 17.5 m respectively when the concentration of the recharge was 3000 mg/l. The trend is similar to that observed when the recharge was pure water (Figures 3-6a and 3-6b) except that the rate of decline was relatively much slower.

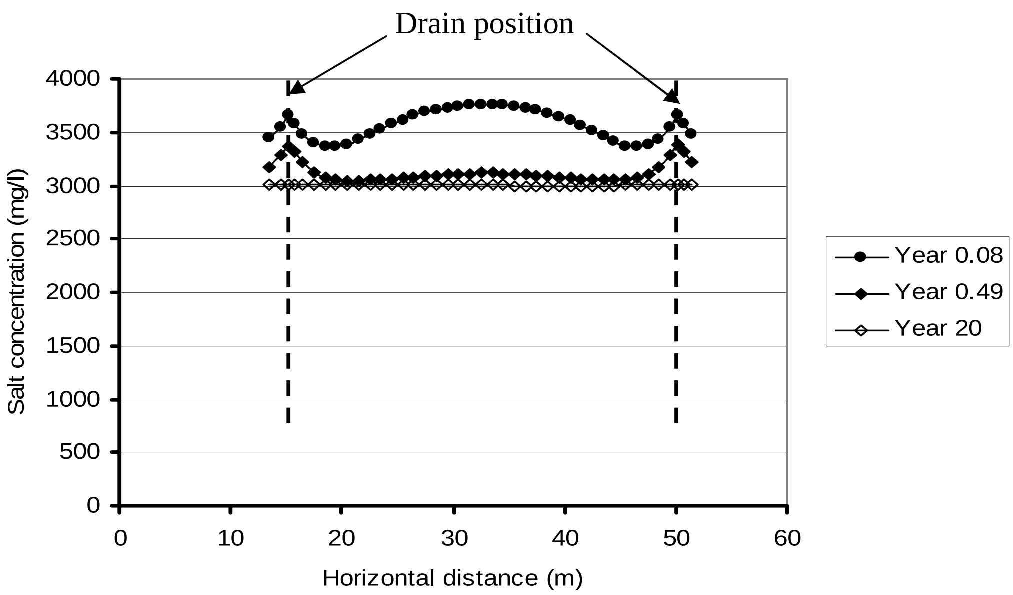


Figure 3-7(a): Salt concentration distribution pattern at a depth of 0.75 m below soil surface when recharge concentration was 3000 mg/l.

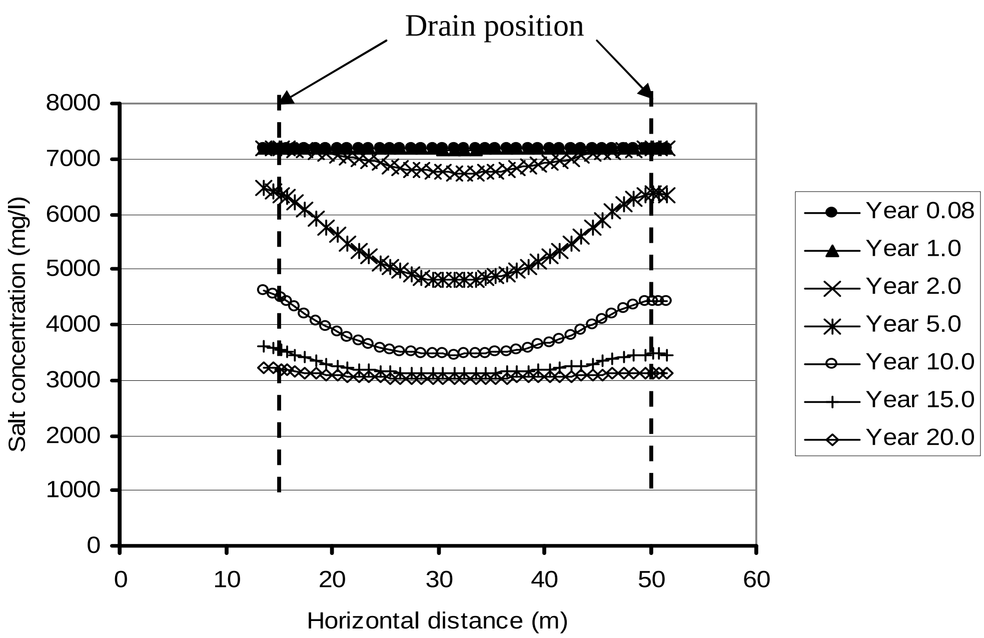


Figure 3-7(b): Salt concentration distribution pattern at a depth of 17.5 m below soil surface when recharge concentration was 3000 mg/l

3.4.7 Mid-drain salt concentration dynamics

Areas midway between drains generally experience higher water table, hence determining the salt concentration at this position is important in evaluating the effectiveness of any drainage system.

Figures 3-8a and 3-8b show the salt concentrations midway between two drains at selected depths when recharge was pure water and applied recharge having a concentration of 3000 mg/l respectively. In both cases the there was a rapid fall of the initial aquifer concentration and in less than 2 years of drainage, the concentration within the 2.5 m depth from the soil surface had reduced to a level equal to the concentration in the applied recharge suggesting that the ‘leachable’ phase in the 2.5 m depth was passed in less than 2 years. This indicates that the top 2.5 m layer of a saline aquifer is desalinized in less than 2 years of drainage. The rate of salt concentration reduction decreased with depth. In general, the salt concentration increases with depth reflecting a phenomenon of relatively freshwater penetrations and seeps through a saline aquifer during the drainage as noted by Johnston (1993).

Referring to Figure 3-8a, after 2 years, the salt concentration had decreased by 99.9 % at 2.5 m depth, and 10.3 % at 17.5 m depth. After 20 years, the mid-drain concentrations remaining at all depths were negligible; indicating a total replacement of the water in the aquifer, hence the discharge concentration was identical to that of the applied recharge.

Figure 3-8b shows that after 2 years, the initial concentration had fallen by 58 % and 7 % at 2.5 m and 17.5 m depths respectively. After 20 years, the initial concentration had fallen to about 3000 mg/l, more or less the same as the concentration in the applied recharge, thereby providing effluent at a concentration of 3000 mg/l.

The rapid fall of salt concentration in the aquifer was because the less saline water from the applied recharge when it entered the saline aquifer enhanced salt mobilization to the drains. The difference in the rate of salt fall showed the expectation that irrigation water with low salt concentration has greater potential for salt mobilization during drainage.

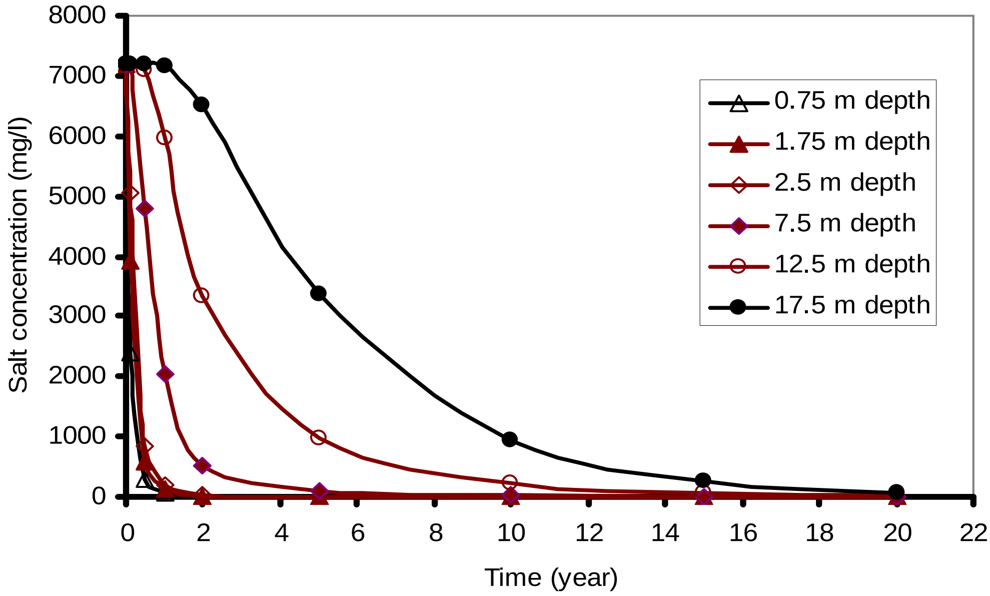


Figure 3-8(a): Temporal mid-drain salt concentration in different depths when the applied recharge was pure water.

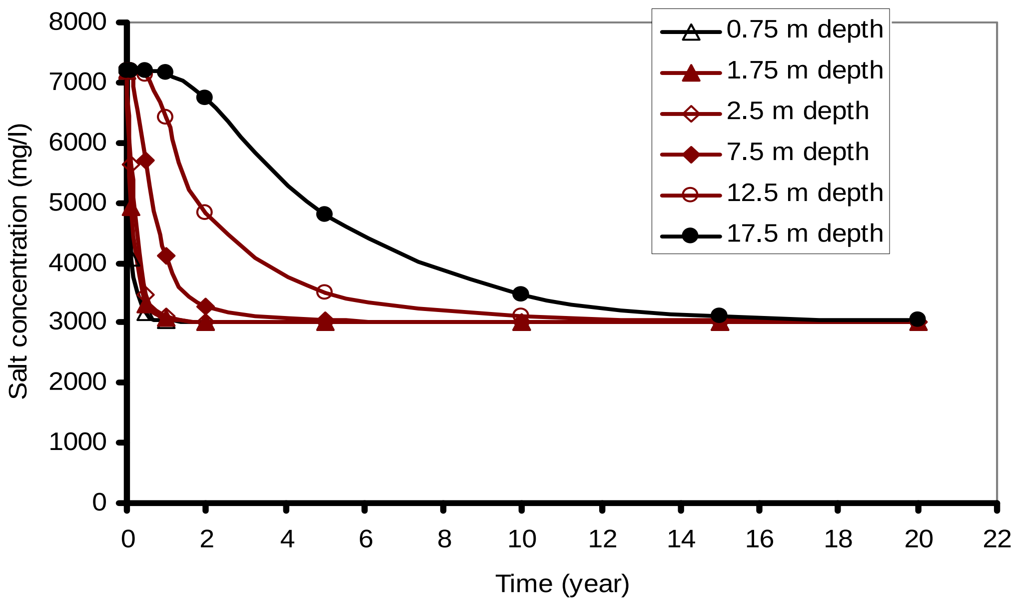


Figure 3-8(b): Temporal mid-drain salt concentration in different depths when applied recharge salt concentration was 3000 mg/l

3.5 Discussions and conclusion

The simulated mid-drain heads compared well with the heads calculated using the Hooghoudt's equation and this provides confidence in the model's capability and applicability to be used on irrigated fields. The equipotential lines show evidence of vertical, horizontal and radial elements of flow that are usually associated with flow to subsurface drains (Ritzema, 1994; Smedema *et al*., 2004). The equipotentials also confirmed a curved water table reflecting a typical water table between two drains that are subject to uniform recharge (Ritzema, 1994).

The leaching patterns are both realistic and reasonable, and allow the model to be used to develop unique flow and leaching behaviour. This is because the upcones of salt towards the drains from deep within the aquifer (Figure 3-5b) were similar to salt concentration pattern as observed by Bear and Verruijt (1990), and Materson and Portnoy (2006). Also, it was observed that the reduction of salt in the aquifer ceased when the concentration level in the aquifer equaled the concentration level in the recharge. This suggests that the salt concentration of the discharge eventually became the same as that of the recharge as observed by Christen and Skehan (2001). The timing depended on the recharge and/or groundwater concentration. This indicates that the quality of irrigation water has a direct bearing on the amount of salt left in aquifer.

In addition, the model was able to predict salt concentration in the individual layers and this can be helpful in managing irrigation and drainage to maintain an 'acceptable' concentration level in the root zone. The model ensured that the salt concentration at the base of the root zone does not exceed predetermined levels as against the conventional drainage systems that maintain the groundwater at a predetermined level. It can therefore be concluded that the SEAWAT model can be used as subsurface drainage model on irrigated fields to target concentration in the root zone instead of controlling water table as currently being proposed by Christen and Ayars (2001) on irrigated field. Christen and Ayars (2001), in evaluating conventional subsurface drainage systems that targets water table control, noted that using very good quality irrigation water (ranged between 0.05 and 0.8 ds/m) required leaching requirement in the range of 10 to 47 % as against the expected 5 – 10 % to maintain a salt free root zone. They noted that this was higher than necessary to maintain a salt balance in the root zone.

CHAPTER FOUR

MODEL SIMULATION OF DRAINAGE AND LEACHING IN IRRIGATED FIELD

4.1 Introduction

Chapter 3 provided confidence of the model's applicability as an irrigated field drainage design model. This chapter seeks to assess the model's simulation of drainage flow and leaching in irrigated field for different drain spacings when no and/or evapotranspiration is included. The chapter also assesses; the drainage flow and the leaching with changing applied water quality, and the performance of the model with different aquifer permeabilities.

Drainage flow and leaching in the soil profile is influenced not only by drain spacings but also evapotranspiration, quality of the applied water and aquifer permeability among others. Evapotranspiration and particularly groundwater contribution to the evapotranspiration used in the model is usually an important component of water balance in the soil and its simulation has received increasing attention in irrigated areas. In arid and semarid regions with shallow groundwater, large amount of crop water requirements can be met from the groundwater contribution to evapotranspiration (Khan et al, 2006).

4.2 Methodology

The SEAWAT (Guo and Langevin, 2002) model was applied to 36 hectare homogeneous block of land of length 600 m and width 600 m of the hypothetical field to simulate drainage flow and leaching for drain spacings of 30, 45, 60, 90, 150, 200 and 250 m. Drain depth was 2.0 m. The aquifer was assumed to be composed of silty loam.

4.2.1 Spatial and temporal discretization

The aquifer was discretized into a grid of cells (Figure 4-1). The grid consisted of 60 rows, 60 columns and 20 layers. Each cell with the exception of the cell in which the drains were laid (drain cells) had a uniform volume of 10 m x 10 m x 1 m. The drain cells had dimensions of 0.2 m horizontal and 0.2 m vertical in order to more accurately approximate the drain size. The base of the aquifer, used as reference, had an elevation of zero. The top of layer 1 which coincided with the land surface had an elevation of 20 m relative to the base. The grid system was based on blocked-centered formulation and therefore the salt concentrations and hydraulic heads applied to the centre of the cells.

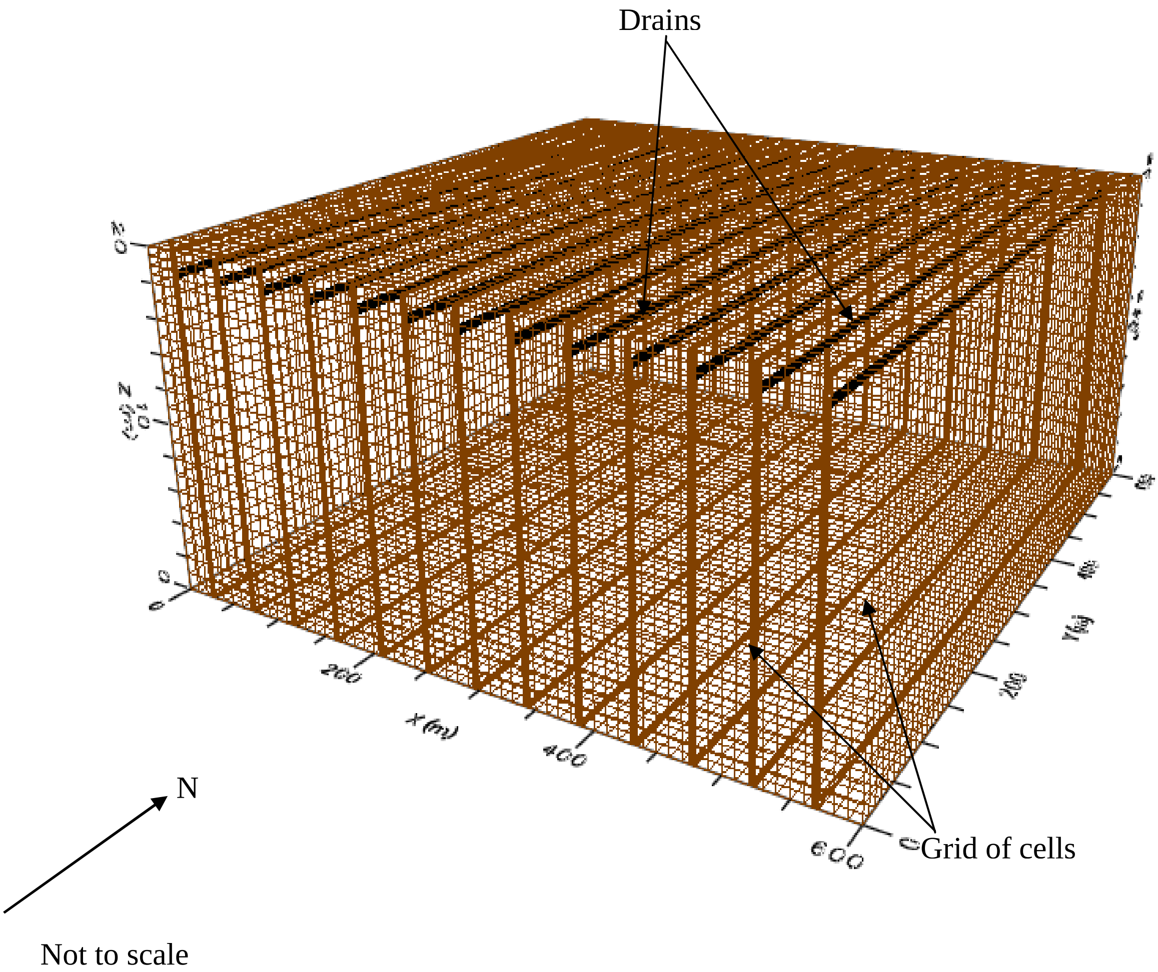


Figure 4-1: Simulated 3-dimensional grid of the aquifer with drains.

4.2.2 Input data

The model input data and the method used to determine them were the same as described in Chapter 3. However, the few changes and additions made are:

Recharge

The applied recharge value was based on a water application rate of 56 mm per 7 days (8 mm/d) similar to the value used by Cavero et al.(2000) in simulating maize stress using the CROPWAT and EPIC models, with a salt concentration of 1500 mg/l (or 2 dS/m) (FAO, 1994).

Evapotranspiration

The SEAWAT model simulates only evapotranspiration from the saturated zone (water table), termed in this study 'groundwater contribution to total (potential) evapotranspiration' (ET_g). The evapotranspiration (ET) package in SEAWAT model withdraws groundwater as a function of depth to the water table to simulate the ET_g. The ET_g reached maximum evapotranspiration, ET_m, or became equal potential evapotranspiration when the water table was at or above the land surface. The ET_g, on the other hand, attained a value of zero when the water table was at or below the extinction depth. The extinction depth is the depth in the aquifer from the land surface below which evapotranspiration process ceases. The model simulates ET_g as a linear fraction of potential evapotranspiration based on maximum water extraction when water table is at the surface and zero extraction when water table is at the extinction depth. The ET package requires three parameters (McDonald and Harbaugh, 1988):- maximum evapotranspiration rate, ET_m; evapotranspiration surface, SURF, (that is when the water table coincides with the land surface), and extinction depth, EXTD.

Since the model does not model the unsaturated zone, it treats all applied water as entering the saturated zone. To enable simulation of groundwater extraction by evapotranspiration, it was assumed that if irrigation water is applied correctly, crop water stress will be avoided and that all water not draining to deep percolation is available for evapotranspiration. Therefore to maximize the water table dependent evapotranspiration function on evapotranspiration rate, the extinction depth was set as deep as possible, 20 m in this study, a value equal to the depth of the aquifer.

The maximum evapotranspiration, ET_m, was assigned a value calculated using the equation:

$$ET_m = RCH\ (1-LF)\ (FAO,\ 1994) \qquad 4\text{-}1$$

where, RCH was the applied recharge (mm/d), and LF was a fraction of the applied recharge that reached the water table after evapotranspiration. The LF was assigned a value of 22 %, a value FAO (1994) noted that when used avoids excess accumulation of salt within the root zone (FAO, 1994).

For this study, the percentage of irrigation water that reached the water table after evapotranspiration and runoff were withdrawn is referred to as net recharge and is treated, with the assumption that there was no runoff, as:

$$NRCH = RCH - ET \qquad 4\text{-}2$$

where, NRCH is net recharge rate (mm/d), RCH is applied recharge (mm/d) and ET is evapotranspiration rate (mm/d).

It must be stated though that since evapotranspiration is a function of water table elevation, the net recharge rate actually is a result of the model's simulation as drain discharge.

Drains

The dynamic exchange of water between the aquifer and the drains was simulated using the drain (DRN) package within the SEAWAT programme. This assigned a head-dependent flux to each cell intersected by the drains.

Drain data included the following:- drain head (the elevation of the water in the drain relative to the base of the aquifer), drain invert (bottom) elevation relative the base of the aquifer and hydraulic resistance between the drain and the aquifer (drain conductance). The drain was assumed to run half-full and be of negligible thickness. The drain head was assigned a value 18.1 m and the drain invert elevation 18.0 m. The drains were assumed to be laid parallel to each other with each having a length of 300 m.

Table 4-1: Main inputs specified for the model simulations of drainage flow and leaching in the field.

Parameter (unit)	Value
Aquifer thickness (m)	20
Initial groundwater salt concentration (mg/l)	7,200
Initial groundwater density (kg/m^3)	1,005.04
Initial water table elevation (m)	19.5
Applied recharge (mm/d)	8
Applied recharge concentration (mg/l)	1500
Applied recharge density (kg/m^3)	1001.5
Maximum evapotranspiration rate (mm/d)	6.24
Extinction depth (m)	20
Saturated hydraulic conductivity, K, (m/d)	0.8
Aquifer bottom layer hydraulic conductivity (m/d)	1×10^{-7}
Total porosity	0.3
Effective porosity	0.2
Specific yield	0.2
Specific storativity (m^{-1})	1×10^{-6}
Longitudinal dispersivity, α_L, (m)	1
Transverse dispersivity, α_T, (m)	0.1
Molecular diffusion coefficient, D* (m^2/d)	5×10^{-5}
Drain elevation (m)	18
Drain spacing (m)	30, 60, 90, 150, 200 and 250
Drain conductance (m^2/d)	3,000
Drain cell (m)	0.2 m per side

Table 4-1 summarizes the input of the model for the simulation of drainage flow and leaching. The model was first run when there was no evapotranspiration was included and the run when evapotranspiration was included for all the subsequent works.

When evapotranspiration was not considered, the applied recharge quantity was the same as the net recharge. On the other hand as expected when evapotranspiration was considered, the net recharge was less than applied recharge.

Also investigated were the effects of recharge quality, and aquifer permeability on drainage flow and leaching when evapotranspiration was included.

To evaluate the impact of applied recharge quality on drainage flow and leaching for different drain spacings, the applied recharge concentration was varied from 1500 mg/l to 1000 mg/l and 700 mg/l but keeping the same applied recharge of 8 mm/d.

To study the effect of aquifer permeability on drainage flow and leaching, two different homogeneous and one non-homogeneous aquifers were considered. The two homogenous aquifers adopted were isotropic hydraulic conductivities of 1.216 m/d and 0.514 m/d respectively whilst the non-homogeneous aquifer included two zones with an isotropic hydraulic conductivity of 0.8 m/d throughout the upper 10 m section and 0.08 m/d throughout the lower 9 m section. The lowest layer was assigned as a no flow boundary with a hydraulic conductivity of 10^{-7} m/d. The applied recharge was 8 mm/d with salt concentration of 1500 mg/l.

The simulations were undertaken for 12 time periods:- 30 days (0.08 year), 180 days (0.49 year), 365 days (1 year), 730 days (2 years), 1095 days (3 years), 1460 days (4 years), 1825 days (5 years), 2190 days (6 years), 2555 days (7 years), 2920 days (8 years), 3285 days (9 days) and 3650 days (10 years).

4.3 Results and Discussion

Case (a): The no evapotranspiration case.

4.3.1 Water table depth and drain discharge characteristics

Drain spacing affected the water table depth but had minimal effect on the quantity and quality of the discharge water. The steady state water table depth for drain spacings of 30 m, 60 m and 90 m were 1.54, 1.13 and 0.61 m respectively. Water table depths for spacings in excess of 90 m reached the land surface, indicating that for only water table control, drain spacings should not exceed 90 m, contrary to the observation by Cater and Camp (1994) that spacing not in excess of 20 m effectively controlled the water table below the land surface for conventional drain spacing.

At steady state all the drains yielded the same drain discharge rate equal to the applied recharge rate (8 mm/d) suggesting that drain spacing had no effect on the discharge and this demonstrates that the model has achieved mass balance correctly. Figure 4-2 shows the salt concentration in the drain discharges over time for the different spacings. The discharge concentrations decreased exponentially with time for all drain spacings but remained higher than the applied recharge concentration (1500 mg/l) even after 10 years. The increase in concentration above that of the applied recharge emanated from deep within the aquifer indicated that not all the leachable salt (salt to be drained so that salt entering in the aquifer from the applied recharge becomes equal salt leaving the aquifer) had been drained out by 10 years of leaching for all the spacings. The drain discharge concentration increased marginally with spacing for about five years, thereafter, the discharge concentrations were almost the same for all drain spacings (Figure 4-2). This indicates that spacing had no effect on drain discharge concentration. but the difference cleared after about five years.

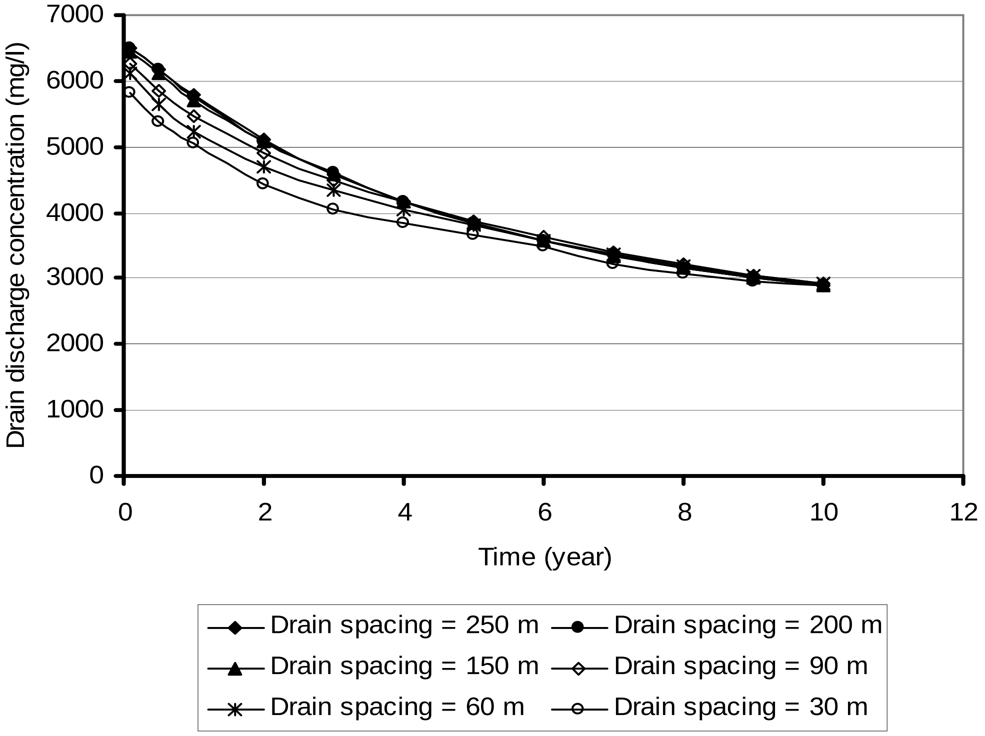


Figure 4-2: Leached salt concentrations over time for different drain spacings

4.3.2 Salt remaining in the aquifer salt and leached

Table 4-2 shows temporal changes in aquifer salt and the percentage of the initial aquifer salt leached for different drain spacings. Irrespective of the drain spacings, more than 30 % of the initial aquifer salt was leached during 1 year of drainage and about 70 % leached by year 5 notwithstanding the 43,800 kg/ha/year of salt applied in the recharge. This caused a rapid decline of the initial aquifer salt during that period for all drain spacings. This can be attributed to the greater differences between the applied recharge salt concentration and the initial aquifer salt concentration. However, after 10 years, all the spacings were leaching the same amount of salt which was over 75 % of the original salt in the aquifer suggesting that greater portion of the respective 'leachable' aquifer salts had been leached. 'Leachable salt' is the salt when leached from the aquifer reduces the salt in the aquifer to approximately match both the salt in the applied recharge (or net recharge) and the drain discharge, and remaining approximately constant in the aquifer. The leachable aquifer salt for drain spacing of 30 m was 80.3 % of the initial aquifer salt, and 79.8 %, 79.3%, and 78.6 % for drain spacings of 60 m, 90 m and in excess of 90 m respectively. This indicates that with no evapotranspiration, same amount of salt is leached irrespective of the drain spacings.

Table 4-2: Salt remaining in aquifer, leached aquifer salt and 'leachable' aquifer salt when no ET was included in model

Drain spacing (m)	Salt in aquifer (kg/ha)			Leached aquifer salt as a percentage of *initial aquifer salt			'Leachable' aquifer salt (kg/ha)
	1 year	5 years	10 years	1 year	5 years	10 years	
30	194,191	85,986	69,420	31	69	75	225,420
60	189,456	83,114	61,931	33	70	78	224,190
90	183,697	74,704	60,956	35	73	78	222,630
150	177,324	78,943	68,352	37	72	76	220,800
200	175,303	77,886	67,293	38	72	76	220,800
250	175,900	78,432	67,084	37	72	76	220,800

*Initial salt in the aquifer = 280,800 kg/ha

Table4-3: Relationship between total leached salt and salt in the applied recharge when no ET was included in model

	Total leached salt (kg/ha)			Leached salt/*Applied recharge salt (dimensionless)		
Drain spacing (m)	1 year	5 years	10 years	1 year	5 years	10 years
30	131,194	414,310	650,167	3.0	1.9	1.5
60	135,148	416,689	656,872	3.1	1.9	1.5
90	140,901	425,094	657,842	3.2	1.9	1.5
150	147,266	420,847	650,439	3.4	1.9	1.5
200	149,271	421,889	651,481	3.4	1.9	1.5
250	148,665	421,422	651,681	3.4	1.9	1.5

*Applied recharged salt = 43,800 kg/ha/year

The relationship between the total salt leached and the salt applied is shown in Table 4-3. All spacings leached over 3 times more salt than was applied up to year 1, then declining to 1.9 times and to 1.5 times more salt than the applied by year 10. The excess salt more likely is derived from deep in the aquifer since the concentrations at the base of the root zone were static and the same for all the drain spacings (Figure 4-3a). The same salt in the drain discharge for the spacings shows that when there was no evapotranspiration, spacing had no effect on the discharge salt concentration.

4.3.3 Mid-drain salt concentration distribution at the base of the root zone

Figure 4-3a shows the distribution of the mid-drain salt concentration at 1.5 m below the soil surface for different drain spacings. There was a rapid exponential fall of the concentration and became stable after more or less year 2 for all the drain spacings. It was noted that the stabilized concentration was the same as the recharge concentration indicating that the initial salt in the rooting depth was flushed out within 2 years of drainage irrespective of length of the drain spacing. The rapid aquifer concentration fall could be attributed to the large concentration gradient between aquifer concentration and the applied recharge concentration. Notwithstanding the applied recharge concentration of 1,500 mg/l, the initial aquifer concentration of 7,200 mg/l fell rapidly by about 75 % by year 2 for all drain spacings, then to about 80 % by 5 years and remained constant (Figure 4-3a) at a concentration level equal to the concentration of the applied recharge for all drain spacings. This indicates that all spacings could maintain the same salt concentration level at the base of the root zone, although at different water table depths. This indicates that the salt concentration at the base of the root zone was affected by the applied recharge concentration but not necessarily drain spacing. Therefore, when evapotranspiration was not included, the salt concentration in the rooting zone can be controlled using any drain spacing.

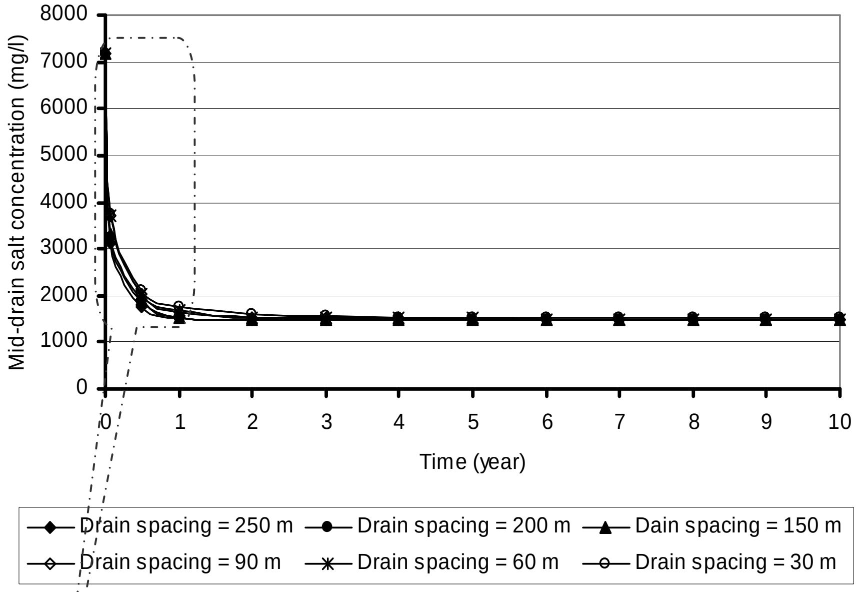


Figure 4-3(a): Mid-drain salt concentration at 1.5 m depth for different drain spacings

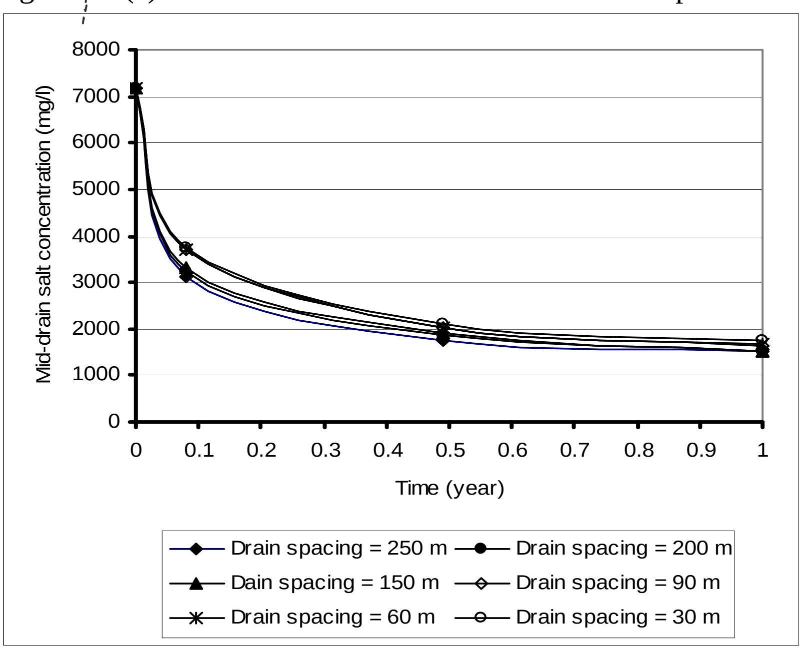


Figure 4-3(b): Mid-drain salt concentration at 1.5 m depth for different drain spacings at drainage between 0 and 1 year

4.4 Case (b): Evapotranspiration included in the model

4.4.1 The effect of drain spacing on water table and drain discharge

The SEAWAT model was used to investigate the influence of evapotranspiration on the effects of drain spacing on water table, the concentration of recharge that entered the groundwater (net recharge concentration), groundwater contribution to the evapotranspiration and the drain discharge characteristics.

Generally water table depths from the soil surface decreased with increasing drain spacing as per the no evapotranspiration case except that the depths were greater for the corresponding drain spacing. At steady state of the water table drawdown remained approximately constant (ie the rate of applied recharge approximately matched the sum of the drain discharge and evapotranspiration rates), the water table depth, initially 0.5 m below the soil surface (19.50 m elevation), fell to 1.72 m for 30 m drain spacing but rose to 0.42 m below the surface for 250 m drain spacing (Table 4-4). Water table depths for spacings of 150 m, 200 m and 250 m which rose to the soil surface when there was no evapotranspiration, remained below the surface when there was evapotranspiration indicating the capability of evapotranspiration to drawdown water tables as stated by Heuperman *et al.* (2002).

Table 4-4: Groundwater contribution to evapotranspiratin, ET_g, water table depth and net recharge characteristics for different spacings

Drain spacing (m)	ET_g (mm/d)	Drain discharge rate (mm/d)	Water table depth at steady state (m)	Net recharge concentration (mg/l)	Net recharge density (kg/m^3)
30	5.70	2.30	1.72	5,217	1,003.65
60	5.73	2.27	1.61	5,286	1,003.70
90	5.76	2.24	1.47	5,357	1,003.75
150	5.85	2.15	1.12	5,581	1,003.91
200	6.01	1.99	0.77	6,030	1,004.22
250	6.07	1.93	0.42	6,218	1,004.35

ETg = groundwater contribution to evapotranspiration rate

As would be expected, with increased drain spacing the height of water table increased and drains discharge decreases (Table 4-4). In addition, as spacing increases more water is evapotranspired from the shallow water table, this increases water use efficiency and the salt concentration at the base of the root zone.

4.4.2 Salt remaining in the aquifer salt and leached salt

Table 4-5 shows the salt remaining in the aquifer, the leached salt as a percentage of the initial aquifer salt and 'leachable salt' (amount of salt when leached from the aquifer reduces the salt in the aquifer to approximately match both the salt in the applied recharge or net recharge and the drain discharge, and remaining approximately constant in the aquifer) for different drain spacings. The salt remaining in the aquifer at all times

Table 4-5: Salt remaining in aquifer, leached aquifer salt and 'leachable' salt

Drain spacing (m)	Salt in aquifer (kg/ha)			Leached aquifer salt as a percentage of *initial aquifer salt			'Leachable' aquifer salt (kg/ha)
	1 year	5 years	10 years	1 year	5 years	10 years	
30	267,200	233,425	215,232	4.8	16.9	23.3	90,067
60	267,325	235,364	217,915	4.8	16.2	22.4	86,381
90	267,884	237,444	220,826	4.6	15.2	21.4	82,270
150	269,870	243,808	229,375	3.9	13.2	18.3	70,061
200	273,223	254,792	244,868	2.7	9.2	12.8	48,887
250	274,859	260,792	253,248	2.1	7.1	9.8	37,428

*Initial salt in the aquifer = 280,800 kg/ha

Table 4-6: Relation between total leached salt and salt in the applied recharge

	Total leached salt (kg/ha)			Total leached salt/*Applied recharge salt (dimensionless)		
Drain spacing (m)	1 year	5 years	10 years	1 year	5 years	10 years
30	57,400	266,375	503,568	1.31	1.22	1.15
60	57,275	264,436	500,885	1.30	1.21	1.14
90	56,716	262,356	497,975	1.29	1.20	1.14
150	54,730	255,992	489,425	1.25	1.17	1.12
200	51,378	245,008	473,932	1.17	1.12	1.08
250	49,876	239,408	465,623	1.14	1.09	1.06

*Applied recharge salt load = 43,800 kg/ha/year increased with increasing drain spacing (Table 4-5). This is primarily caused by the evapotranspiration rate utilizing the shallow groundwater results in a decrease in drainage discharge with small amount of salt (Christen and Ayars, 2001). At wider spacing the salt concentration at the base of the root zone increased which in turn leads to less of the leachable salt being leached. The ‘leachable’ salts, ranged from 32 % to 13 % of the initial aquifer salt (280,800 kg/ha) for drain spacings of 30 m and 250 respectively. However, the leached salts accounted for over 70 % of the respective ‘leachable’ salts for all the drain spacing for 10 years of drainage.

The relationship between the total leached salt and the applied salt for different drain spacings is shown in Table 4-6. The total leached salt decreased with increasing drain spacing could be attributed to less water being discharged as a result of more water loss through evapotranspiration for wider drain spacings. All spacings removed more salt than the salt in the recharge by 10 years indicating that none of the spacings had completely leached the corresponding ‘leachable’ salts by that period.

4.4.3 Mid-drain salt concentration dynamics at the base of the root zone

The mid-drain salt concentration levels at the base of the root zone for different drain spacings are shown in Figure 4-4. For all spacings, notwithstanding the recharge concentration of 1500 mg/l, there was rapid fall of aquifer concentration within the first 0.08 year (30 days) (Figure 4-4) and then it either increased or continued to fall depending on the spacing before becoming stabilized (Figure 4-4a). The initial rapid fall of the salt concentration in the aquifer was due to less concentrated applied recharge (or net recharge) which diluted the salt at the water table causing more salt leaching at the beginning of the drainage. The later increase (rise) in salt concentration at the base of the root zone (Figure 4-4) was because when the recharge initially entered the aquifer salt concentration gradient was created at the root zone which gradually reduced through diffusion from high salt concentration beneath the water table till the salt concentration stabilised and at wider drain spacing the later concentration level was greater than when concentration initially fell to. For all spacings, the salt concentration at the corresponding water tables became stable by year 3 but at different levels. This indicates that all

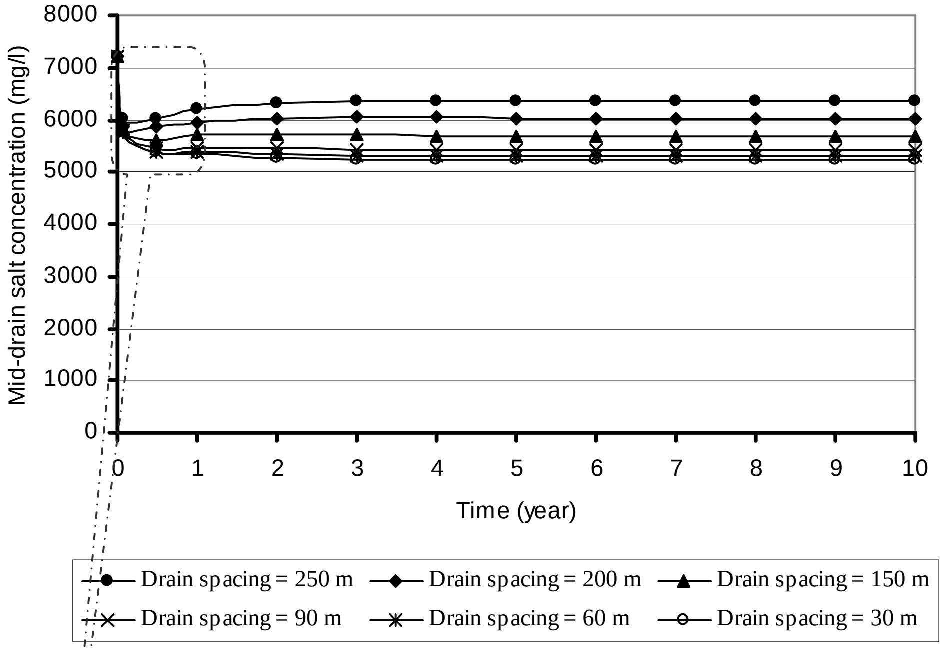


Figure 4-4(a): Mid-drain salt concentration at 1.75 m below soil surface for applied recharge of 8 mm/d with concentration of 1500 mg/l

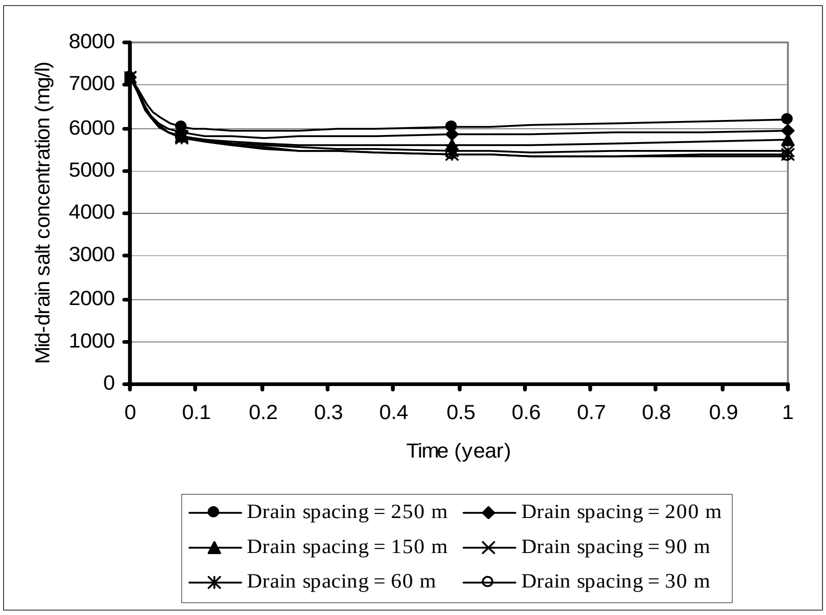


Figure 4-4(b): Mid-drain salt concentration pattern 1.75 m below soil surface for recharge concentration of 1500 mg/l at drainage between 0 and 1 year spacings could retain salt concentrations but different concentration levels and at different water table depths.

At 250 m drain spacing, notwithstanding the recharge concentration, the salt concentration retained at the base of the root zone was about 14 % lower than the initial aquifer concentration. The 200 m and 150 m spacings followed similar patterns and retained concentration levels less than the initial aquifer concentration by about 16 % and about 22 % respectively. The 90 m spacing retained concentration of about 25 % lower than the initial aquifer concentration. The concentration for spacings 60 and 30 m retained salt concentration levels of 27 % and 28 % respectively lower than the initial aquifer concentration by year 2, indicating that spacings 60 and 30 m retained almost similar concentrations at the base of the root zone.

It was however noted that after 3 years of drainage, the drain discharge concentrations for all spacings were over 99 % of the respective ‘leachable’ concentrations. The leachable concentrations for spacings 30, 60, 90, 150, 200 and 250 m were 1983, 1914, 1843, 1619, 1170 and 982 mg/l respectively.

Figure 4-5 shows the mid-drain concentration levels at 1.5 m depth from soil surface and water table depths for different spacings when a recharge water of 8 mm/d with salt concentration of 1500 mg/l was applied. Different spacing yielded different water table depths and salt concentration level at the base of the root zone indicating spacing influence on concentration at the base of the root zone due to evapotranspiration. For example, with a recharge concentration of 1500 mg/l, the salt concentration at the base of the root zone could be changed from about 6037 mg/l to about 5311 mg/l whilst the water table depth increased from 0.77 m to 1.61 m below the soil surface when spacing was reduced from 200 m to 90 m (Figure 4-4). In general there was lower water table depth and subsequent decrease of concentration at the base of the root zone with decrease in spacing as noted by Ali et al (2000). This was because at the deeper water table, less water was lost through evapotranspiration resulting to a greater net recharge and consequently greater drain discharge rate and therefore less concentration within the root zone.

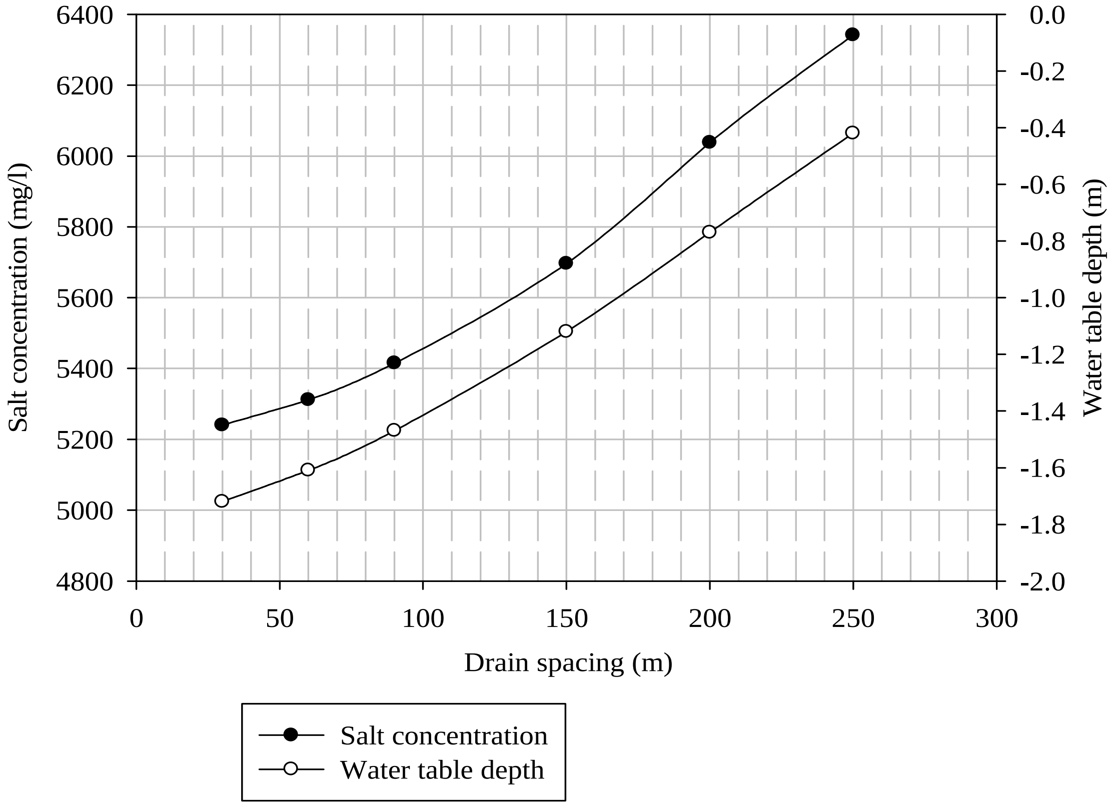


Figure 4-5: Varying spacings controlling different levels salt concentration at different water table depths for 8mm/d applied recharge of 1500 mg/l concentration at year 5

4.4.4 Salt dynamics within rooting zone for applied recharge concentrations of 1000 mg/l and 700 mg/l.

To check the model for consistency of performance, two runs of the model were made using the applied recharge rate of 8 mm/d with different concentrations of 1000 and 700 mg/l. The groundwater contribution to the evapotranspiration, the drain discharge rate and the water table depths obtained for all spacings remained the same as the corresponding drain spacing as in the run when the applied recharge concentration was

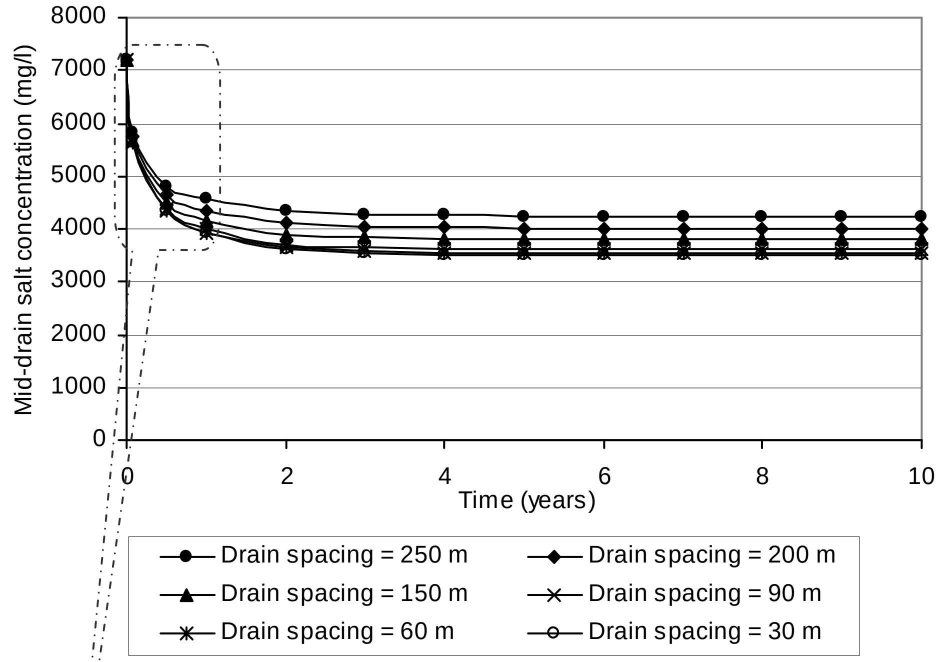


Figure 4-6(a): Mid-drain salt concentration at 1.75 m depth for applied recharge concentration of 1000 mg/l

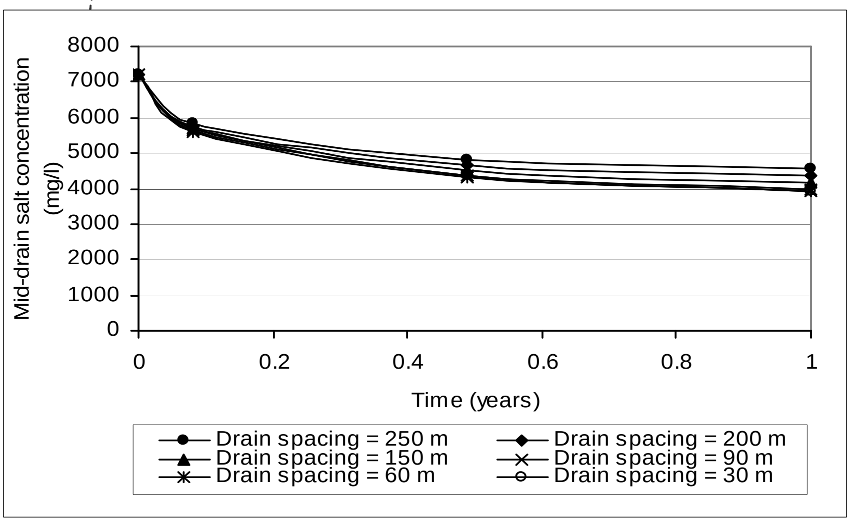


Figure 4-6b: Mid-drain salt concentration at 1.75 m depth for applied recharge concentration of 1000 mg/l at drainage between 0 and 1 year

1500 mg/l. The amount of aquifer salt leached increased with decreasing recharge concentration for all spacings. When the applied recharge concentration was 1000 mg/l, the leached aquifer salt ranged from over 6 to 8 % of the initial aquifer salt in 1 year, about 23 to 29 % of the initial aquifer salt in 5 years, and about 30 to 40 % of the initial aquifer salt in 10 years for drain spacings 250 to 30 m respectively (Table IIA in Appendix II). When the applied recharge concentration was 700 mg/l, the leached aquifer salt ranged from about 9 to 11 % of the initial aquifer salt in 1 year, about 32 to 37 % of the initial aquifer salt in 5 years, and about 44 to 50 % of the initial aquifer salt in 10 years for drain spacings 250 to 30 m respectively (Table IIC in Appendix II). The results of the two simulations showed that more salt is leached when the applied recharge is less saline (FAO, 1994). However, for all the drain spacings in both simulations, the leached aquifer salt were over 15, 50, and 70 % of their respective 'leachable' aquifer salts in 1, 5, and 10 years respectively, same percentage as were observed when the concentration of the applied recharge water was 1500 mg/l. This clearly demonstrates that the model was working correctly.

Figures 4-6 and 4-7 show the mid-drain salt concentrations at a depth of 1.75 m from the soil surface for recharge concentration of 1000 mg/l and 700 mg/l respectively after 10 years of drainage. Even though in both cases, the salt concentration became stable after year 3, for the same spacing, the salt concentration retained at the base of the root zone is less for applied recharge concentration of 700 mg/l than for the applied recharge concentration of 1000 mg/l. This indicates that the quality of recharge has effect on the salt concentration at the base of the root zone during drainage.

In the case of an applied recharge concentration of 1000 mg/l, the 250 m drain spacing had a salt concentration of about 41 % lower than the initial aquifer salt concentration (7200 mg/l) whilst the 200 m and 150 m drain spacings had 44 % and 47 % respectively lower than the initial. The 90 m, 60 m and 30 m drain spacings all had salt concentration levels of over 50 % lower than the initial aquifer salt concentration.

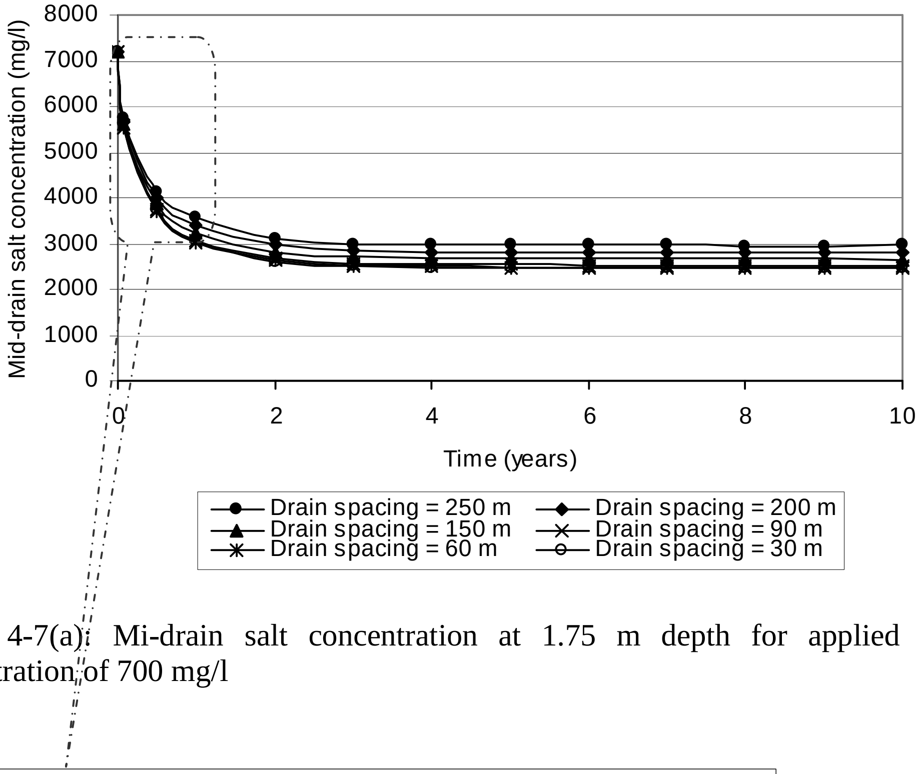


Figure 4-7(a): Mi-drain salt concentration at 1.75 m depth for applied recharge concentration of 700 mg/l

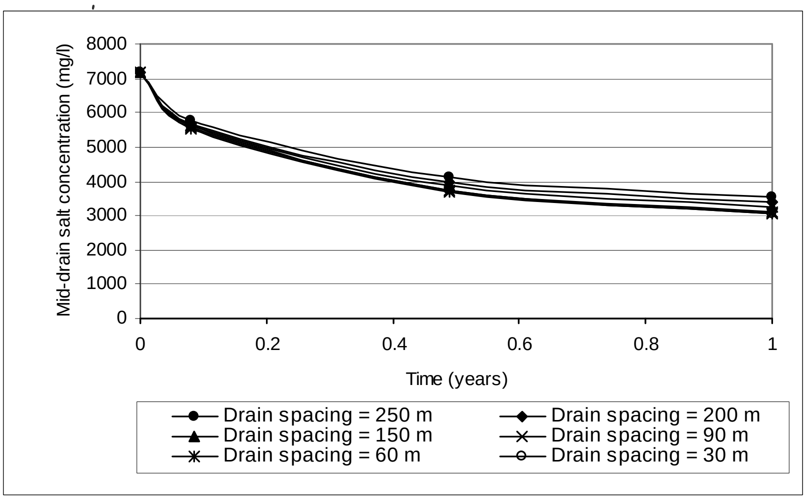


Figure 4-7(b): Mid-drain salt concentration at 1.75 m depth for applied recharge concentration of 700 mg/l at drainage between 0 and 1 year

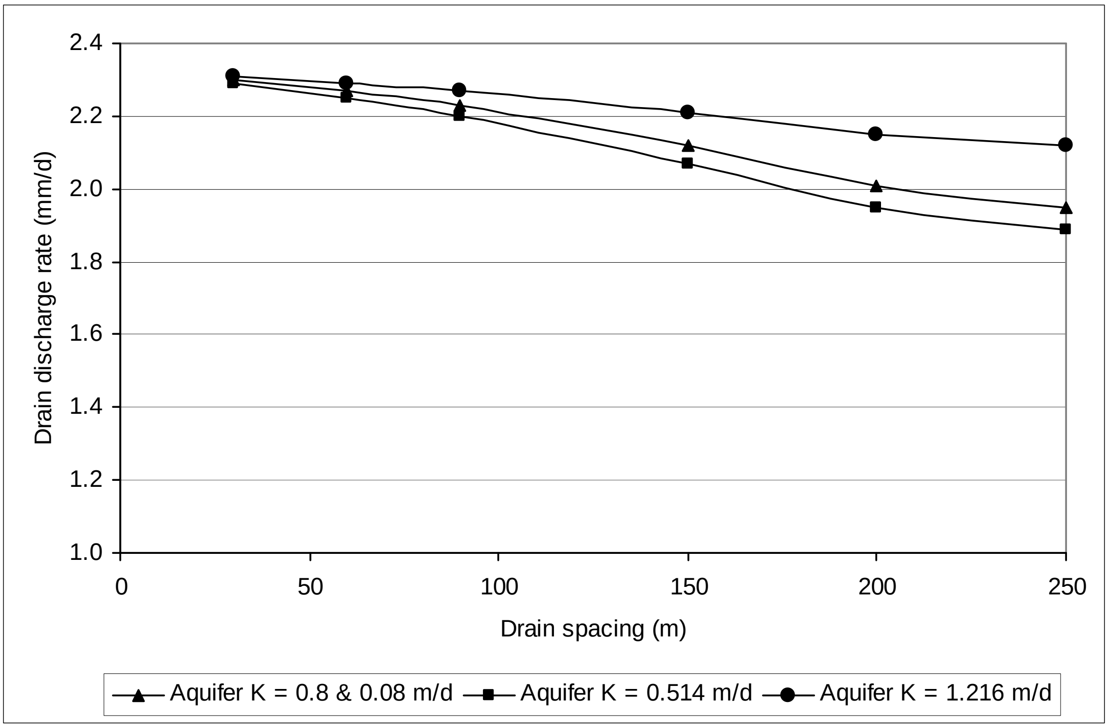
With the applied recharge concentration of 700 mg/l, the concentration at the base of the root zone reduced even further. The concentrations levels at the base of the root zone for all the spacings were over 60 % lower than the original concentration level of the aquifer, and drain spacings 30, 60 and 90 m yielded the same concentration at the base of the root zone. This indicates that the influence of drain spacing on salt concentration at the base of the root zone reduced when the applied recharge is of lower salinity.

The greater reduction of the initial aquifer salt concentration could be attributed to the larger difference between the aquifer salt concentration and the net recharge concentration.

In general, a drain spacing of 250 m is over 8 times wider than drain spacing 30 m but in terms of concentration at the base of the root zone, the drain spacing of 250 m retained salt concentration of only 1.2 times more than that for drain spacing of 30 m irrespective of the applied recharge concentration. This indicates that for any of the applied recharge concentration, the salt concentration retained at the base of the root zone was no highly dictated by the drain spacings. This was because the evpotranspiration rate of 6.24 mm/d used was not large enough to make the salt concentration at base of the root zone more sensitive to the drain spacings. This suggests, salt concentration retain at the base of the root zone is a function of not only drain spacing, but also evapotranspiration rate and salt concentration in applied recharge.

4.4.5 Performance of the model in response to different aquifer hydraulic conductivities

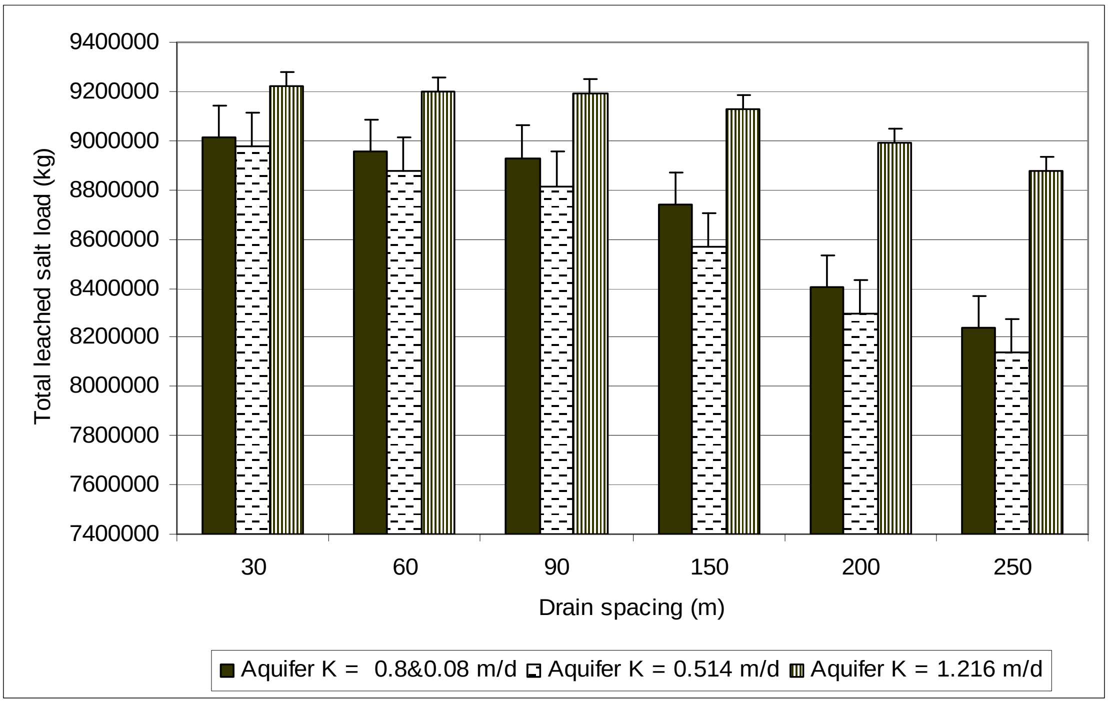
In order to evaluate the performance of the model in simulating drainage flow and leaching in different aquifer permeabilities, the model was applied to two homogeneous aquifers with hydraulic conductivities, K, of 0.514 and 1.214 m/d and one non-homogeneous aquifer with hydraulic conductivity, K of 0.8 m/d for the upper 10 m section and 0.08 m/d for the lower 10 m section. The drain discharge rates, the leached salt, and the concentration at the base of the root zone for the aquifers were then compared with prevailing evapotranspiration rate of 6.24 mm/d.



Aquifer K = 0.514 m/d is homogeneous aquifer with hydraulic conductivity of 0.514 m/d
Aquifer K = 1.216 m/d is homogeneous aquifer with hydraulic conductivity of 1.216 m/d
Aquifer K = 0.8 & 0.08 m/d is non-homogeneous aquifer with hydraulic conductivities of 0.8 m/d for the upper 10 m section and 0.08 m/d for the lower 10 m section

Figure 4-8: Drain discharges at varying spacings from aquifers of different values of hydraulic conductivities for applied recharge of 8 mm/d after 10 years of drainage.

Figure 4-8 shows drain discharges from aquifers of different hydraulic conductivity values for varying spacings after 10 years of drainage with applied recharge rate of 8 mm/ and potential evapotranspiration rate of 6.24 mm/d. There were small differences between drain discharge rates when the drain spacing was narrow but differences became more apparent with widely spaced drains (Figure 4-8). The aquifer hydraulic conductivity only had an effect on the drain discharge rate for spacings in excess of 50 m. As expected, aquifer with K =1.216 yielded the highest drain discharge rates. The drain



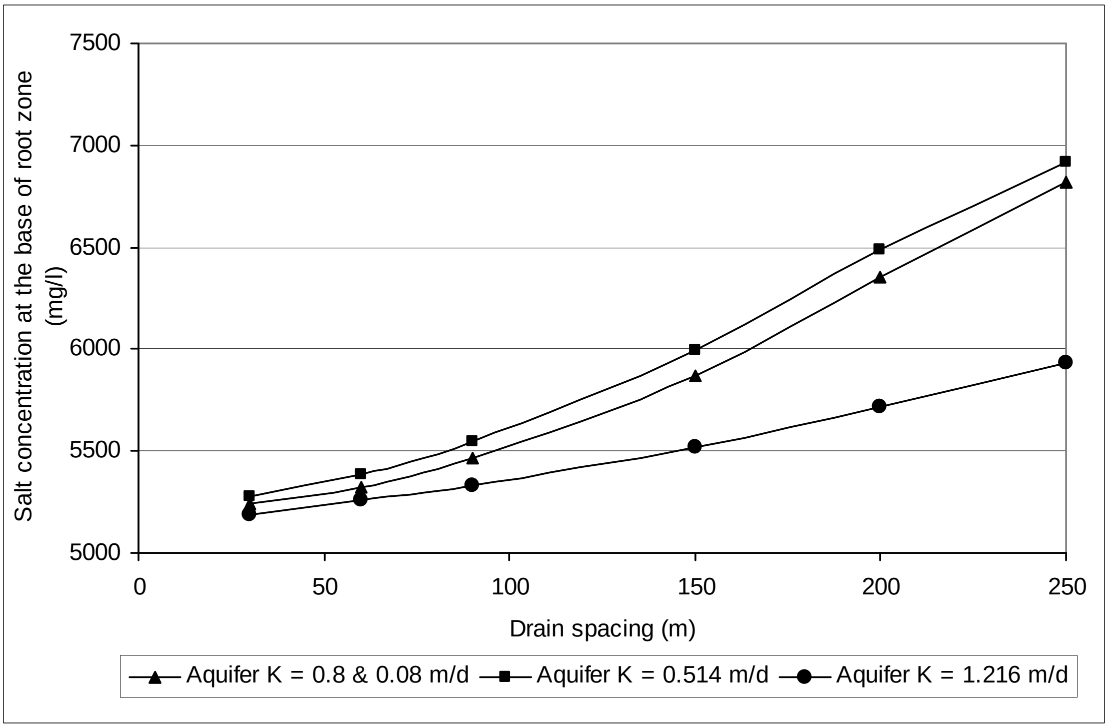
Aquifer K = 0.514 m/d is homogeneous aquifer with hydraulic conductivity of 0.514 m/d

Aquifer K = 1.216 m/d is homogeneous aquifer with hydraulic conductivity of 1.216 m/d

Aquifer K = 0.8 & 0.08 m/d is non-homogeneous aquifer with hydraulic conductivities of 0.8 m/d for the upper 10 m section and 0.08 m/d for the lower 10 m section

Figure 4-9: Comparison of total salt leached from aquifers of different hydraulic conductivities for 8mm/d applied recharge of 1500 mg/l concentration after 10 years of drainage

discharge rates for the aquifer with K = 0.514 m/d was less than the aquifer with K = 0.8 & 0.08 m/d even though the lower half of aquifer with K = 0.8 &0.08 m/d had a very small hydraulic conductivity. This emphasises the importance of flow through the more permeable upper layers. This indicates that the thickness of the upper permeable layers is sufficiently large to reduce the impact of the low hydraulic conductivity in the lower section of the aquifer.



Aquifer K = 0.514 m/d is homogeneous aquifer with hydraulic conductivity of 0.514 m/d
Aquifer K = 1.216 m/d is homogeneous aquifer with hydraulic conductivity of 1.216 m/d
Aquifer K = 0.8 & 0.08 m/d is non-homogeneous aquifer with hydraulic conductivities of 0.8 m/d for the upper 10 m section and 0.08 m/d for the lower 10 m section

Figure 4-10: Salt concentration at the base of the root zone at mid drain spacing for aquifers of different hydraulic conductivity values for 8 mm/d applied recharge of 1500 mg/l concentration and evapotranspiration of 6.24 mm/d after 10 years drainage

Salt leaching followed similar trends as the drain discharge rates. Leaching values from aquifer with K = 1.216 m/d was the highest, followed by aquifer with K = 0.8 & 008 m/d and the aquifer with K = 0.514 m/d being the least for all drain spacings (Figure 4-9). The concentration retained at the base of the root zone was, however, lowest for the aquifer with K = 1.216 m/d, followed by the aquifer with K = 0.8 & 0.08 m/d and the aquifer with K = 0.514 m/d providing the greatest concentration for all spacings (Figure 4-10).

The differences in concentrations at the base of the root zone for aquifers with K = 0.514 m/d and K = 0.8 & 0.08 m/d remained the same for all spacings, whilst the root zone concentration differences between the aquifer with K = 1.216 m/d and the other two aquifers widened with increasing spacings when spacing exceeded 50 m (Figure 4-10). This shows that the impact of aquifer hydraulic conductivity on concentration at the base of the root zone is more effective when drains are widely spaced.

4.5 Discussion and conclusions

Drain spacing equations have been traditionally used to design subsurface drainage systems to maintain water table depths in irrigated land low enough to prevent salinization in the root zone by capillary rise. However, these design systems directly do not consider salt concentration control within the rooting zone.

Correct choice of drain spacing can be a major contributor to resolving the problem of salt concentration at the base the root zone. Salt accumulation in the root zone is influenced not only by spacing but also by the quality of the applied recharge, the prevailing evapotranspiration rate, the quality of the ground water, and the aquifer characteristics. These effects and their interrelationships were analyzed by using SEAWAT model, a variable-density numerical groundwater model.

The SEAWAT model simulation showed that when there was no evapotranspiration, both closely and widely spaced drains retained the same salt concentrations that were identical to the concentration in the applied recharge, at the base of the root zone. This same concentration at the base of the root zone for all spacings was because the volume of discharges for the spacings were the same and therefore same amount of leached salt since discharge volume directly relates to the amount of leached salt (Christen and Ayars 2001). This suggests that the concentrations at the base of the root zone depended on only the concentration in the applied recharge but not necessarily on the drain spacing.

When evapotranspiration was included, the drain discharge decreased with increasing spacing with an associated rise in the water table level. This was because as the drain spacing widens, the water table rises, enhancing more water loss through evapotranspiration thereby reducing the applied water that reaches the water table which in turn is drained out as discharge. The salt concentration control at the base of the root zone however increased with spacing. Since discharge volume relates to amount of leached salt, with increasing spacing water was discharged and subsequently less leached salt thereby relatively higher salt left in the aquifer resulting to higher concentration at the base of the root zone with increasing spacing (Figure 4-4). Different spacings had differing effects on water table depths and concentration levels at the base of the root zone identical to the net recharge concentrations. The difference was because different spacings resulted in different evapotranspirational water losses, necessitating different water of different salt concentrations percolating to the water table as observed by Cooper et al (2006). Though the salt concentration at the root zone increased with spacing, the concentration increase is less marked for spacings less than 90 m. Thus spacings of 30, 60 and 90 m retained relatively the same salt concentration at the base of the root zone. This was because there was less marked difference in evapotranspirational water losses for these spacings and therefore same drained out concentration. The water table depths were relatively greater for all spacing than the corresponding spacings when evapotranspiration was not included as noted by Heuperman *et al*. (2002) that evapotranspiration is capable of lowering water table.

The amount of salt concentrations at the base of the root zone for aquifers with K =1.216, 0.514 and 0.8&0.08 m/d were similar when the spacings were less than 50 m, indicating that the impact of aquifer hydraulic conductivity on the root zone concentration was more marked when the drain spacings exceeded 50 m (Figure 4-10). The inter hydraulic conductivity differences in concentrations at the base of the root zone increased with increasing drain spacing when spacings exceeded 50 m.

The foregoing illustrates that the model is capable of simulating both drainage flow and leaching in irrigated field for different spacings. It can be concluded that variable density numerical groundwater models such as SEAWAT used in this study can be effectively used to develop effective subsurface drainage designs that could maintain long lasting concentration at predetermined levels.

CHAPTER FIVE

EFFECTIVENESS OF NUMERICAL MODELLING IN IMPROVING DRAINAGE SYSTEM DESIGNED FOR SALT CONCENTRATION CONTROL

5.1 Introduction

Chapter 3 showed that, the SEAWAT model can be used to predict concentration at the base of the root zone for varying drain spacings. This chapter seeks to establish if the SEAWAT model can be used for designing effective drainage system for concentration control in the root zone with less water application.

5.2 Methodology

The SEAWAT model was used to simulate drain spacings to maintain salt concentration of 6000 mg/l at the base of the root zone and a water table depth of 0.8 m below the land surface for 4 aquifers of different hydraulic conductivities and under different rates of groundwater contribution to evapotranspiration. The aquifers were 20 m deep. The first 3 uniform aquifers had hydraulic conductivities (K) of 1.216, 0.8 and 0.514 m/d (representing fine crumb, medium and fine soils respectively). The fourth aquifer had hydraulic conductivity of 0.8 m/d in the top 10 m and 0.08 m/d in the lower 10 m section (representing medium soil depth). The hydraulic conductivities were selected to represent a range of soil types found in irrigated fields. The groundwater contribution to evapotranspiration rates were:- 8, 7, 6, 5, 4, 3, 2 and 1 mm/d. The 0.8 m water table depth was maintained to provide a healthy crop growing environment. Also simulated were drain spacings to maintain salt concentration of 5000 and 4000 mg/l at the base of the root zone.

The water in the aquifer(s) initial concentration was 7200 mg/l with a water table depth 0.5 m below the soil surface. All other aquifer parameters, model input data and methodology are as described in Chapter 3.

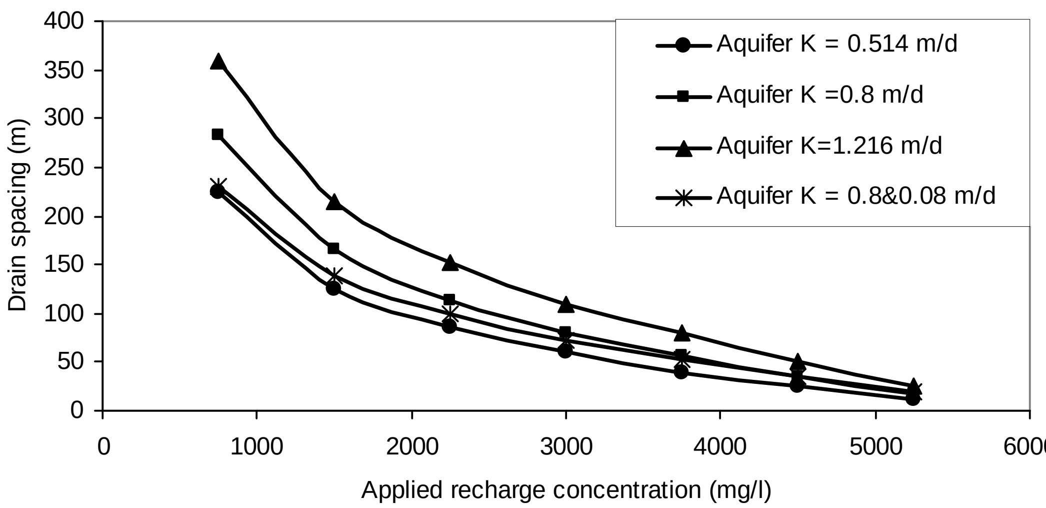
The SEAWAT models the contribution of the saturated zone water to evapotranspiration by a sliding scale from full extraction when the water table is at the soil surface, falling to a certain percentage when the water table falls below the surface. A computational adjustment was needed to enable the model to produce the desired groundwater contribution to evapotranspiration rates to meet crop water demand. This was achieved by varying the amount of water that must be applied to account for the leaching fraction and total evapotranspiration that would be required to give a water quality at the base of the root zone (0.8 m depth from soil surface) of 6000 mg/l.

The drain spacings for maintaining salt concentration of 6000 mg/l at the base of root zone and a water table depth of 0.8 m were obtained by running the model and varying the spacing until the simulated water table depth and salt concentration at the base of the root zone reached 0.8 m and 6000 mg/l respectively for all the aquifers. A similar approach was used for the other salt concentration desiring at the base of the root zone.

5.3 Results and discussion

5.3.1 Drain spacings to maintain desired salt concentration at the base of the root zone

In Figure 5-1, the simulated drain spacing is plotted against the applied recharge concentration for groundwater contribution to evapotranspiration rates of 8 mm/d for the 4 aquifers. It was found that the polynomials (Equation 5-1) fit the corresponding curves in Figure 5-1:



Aquifer K = 0.514 m/d is a uniform aquifer having hydraulic conductivity of 0.514 m/d
Aquifer K = 0.8 m/d is a uniform aquifer having hydraulic conductivity of 0.8 m/d
Aquifer K = 1.26 m/d is a uniform aquifer having hydraulic conductivity of 1.216 m/d
Aquifer K = 0.8 & 0.08 m/d is an aquifer having hydraulic conductivities of 0.8 m/d in the upper 10 m and 0.08 m/d in the lower 10 m sections.

Figure 5-1: Drain spacing versus applied recharge concentration for groundwater contribution to evapotranspiration rate of 8 mm/d.

$$DSP = A + B(RCN) + C(RCN)^2 + D(RCN)^3 + E(RCN)^4 \quad 5\text{-}1$$

where,

DSP is the drain spacing; RCN is the applied recharge concentration and A, B, C, D and E are constants. The values of the constants are given in Table 5-1.

Table 5-1: Constants contained in Equation 5-3

Type of aquifer	A	B	C	D	E
Aquifer K = 0.514 m/d	420	-0.35	10^{-4}	-3×10^{-8}	2×10^{-12}
Aquifer K = 0.8 m/d	502.4	-0.3902	10^{-4}	-3×10^{-8}	2×10^{-12}
Aquifer K= 1.216 m/d	639.3	-0.4978	2×10^{-4}	-4×10^{-8}	2×10^{-12}
Aquifer K = 0.8 &0.08 m/d	402.7	-0.3074	10^{-4}	-2×10^{-8}	1×10^{-12}

In general, differences between curves of Figure 5-1 and the corresponding polynomial were found to be less than ± 0.05 %.

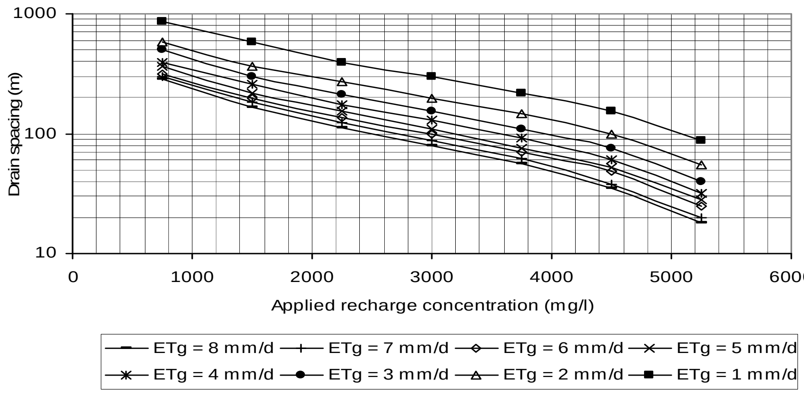
Tables IIIA, IIIB, IIIC and IIID (Appendix III) present drain spacings and the corresponding drain discharges that maintained the desired salt concentrations of 6000 mg/l at the base of the root zone and a water table depth of 0.8 m for different groundwater contribution to evpotranspiration rates. It was found that the concentration of the applied recharge could be increased with decreased drain spacing and increasing applied recharge (and drain discharge) to maintain the desired concentration of 6000 mg/l at the base of the root zone. Further decreasing drain spacing and more applied recharge (and more drain discharge) was necessary when the evapotranspiration rate is higher. For example, for the aquifer having hydraulic conductivity of 0.8 m/d, applied recharge concentrations of 750 mg/l and 3000mg/l necessitated drain spacings of 395 m and 128 m respectively with corresponding applied recharges of 4.6 mm/d (and drain discharge of 0.6 mm/d) and 7.6 mm/d (and drain discharge of 3.6 mm/d) to maintain concentration of 6000 mg/l at the base of the root zone when the groundwater contribution to evapotranspiration rate was 4 mm/d. For the same aquifer type, the same applied concentrations correspondingly necessitated drain spacings of 282 m and 80 m with applied recharges of 9.0 mm/d and 15.1 mm/d respectively to maintain concentration of 6000 mg/l at the base of the root zone when groundwater contribution rate was 8 mm/d. This emphasises the need not to use lower quality water for irrigation in areas of high evapotranspiration rate.

5.3.2 Drain spacing design

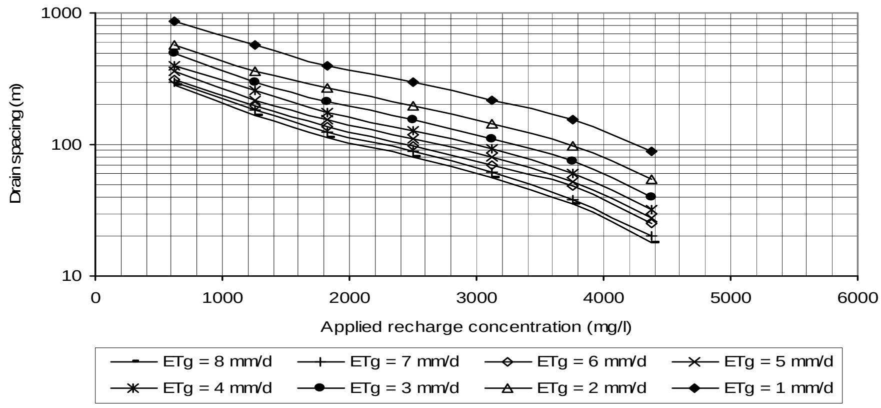
The design drain spacings need to maintain the desired concentration at the base of the root zone for a range applied recharge concentrations. It is of importance to establish a relationship between the drain spacings and the applied recharge concentrations to maintain the desired concentrations at the base of the root zone. However, the concentration at the base of the root zone is influenced by not only the drain spacing and concentration of the applied recharge but also evapotranspiration rate and aquifer hydraulic conductivity. Figures 5-2, 5-3, 5-4 and 5-5 show the relationship between design drain spacing, evapotranspiration rate and applied recharge concentration to maintain the desired concentrations at the root zone for different aquifer hydraulic conductivities.

In each Figure, the spacing is plotted against the applied recharge concentration. Groups of curves are presented such that each corresponds to the desired concentration that was maintained at the base of the root zone. Within each group, curves are plotted for groundwater evapotranspiration rates of 8, 7, 6, 5, 4, 3, 2 and 1 mm/d.

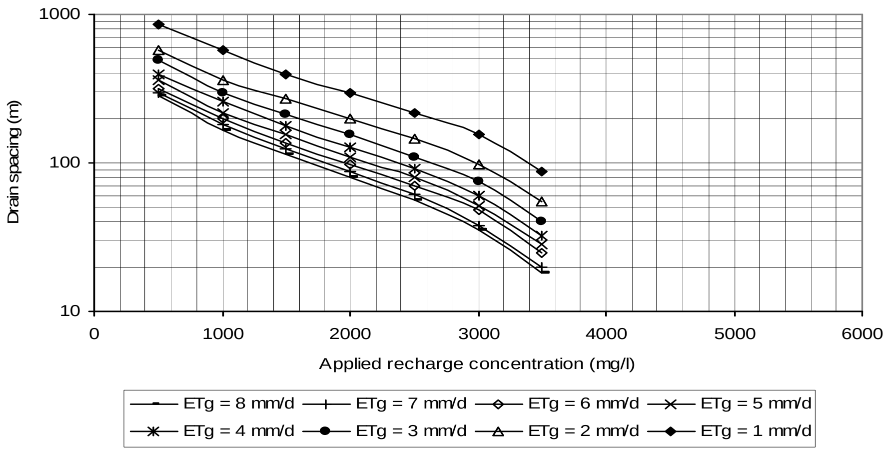
It was noted that the desired concentrations were maintained at the base of the root zone with the drain spacings yielding different drain discharges irrespective of the evapotranspiration rates for all the aquifers. Thus no two drain spacings yielded the same drain discharge either for a given evapotranspiration rate or applied recharge concentration. The drain spacings for all the evapotranspiration rates were ranked and plotted against the corresponding drain discharges. Figure 5-6 shows the relationship of the ranked drain spacing and the corresponding drain discharges for the different aquifer hydraulic conductivities.



(a): Root zone base salt concentration of 6000 mg/l for different evapotranspiration rates

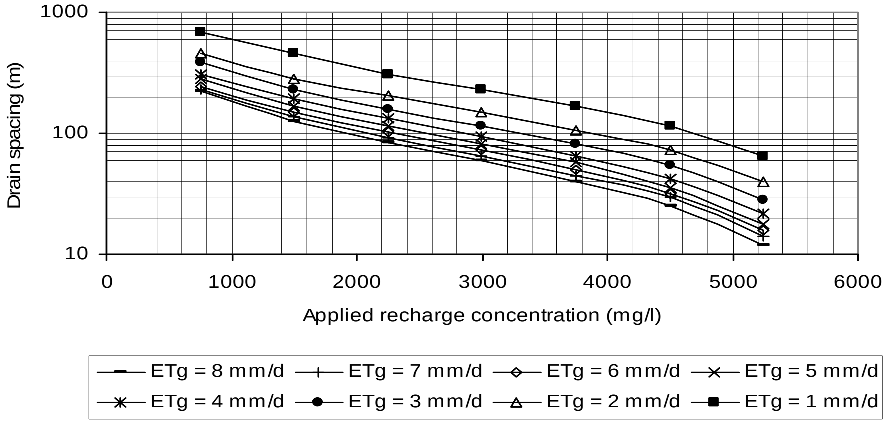


(b): Root zone base salt concentration of 5000 mg/l for different evapotranspiration rates

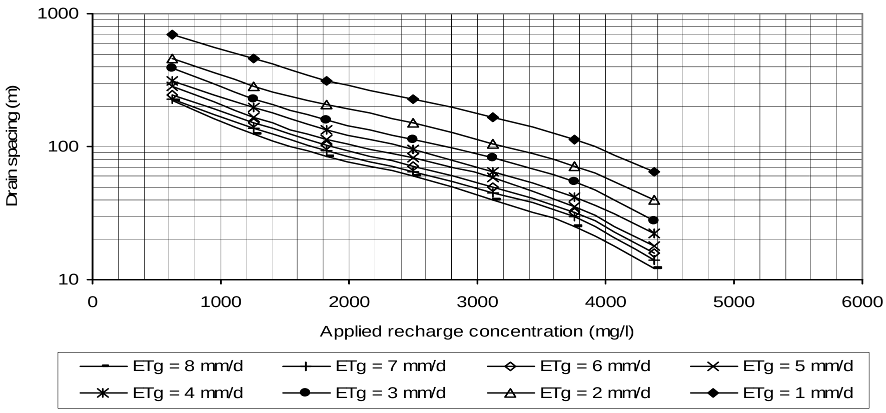


(c): Root zone base salt concentration of 4000 mg/l for different evapotranspiration rates

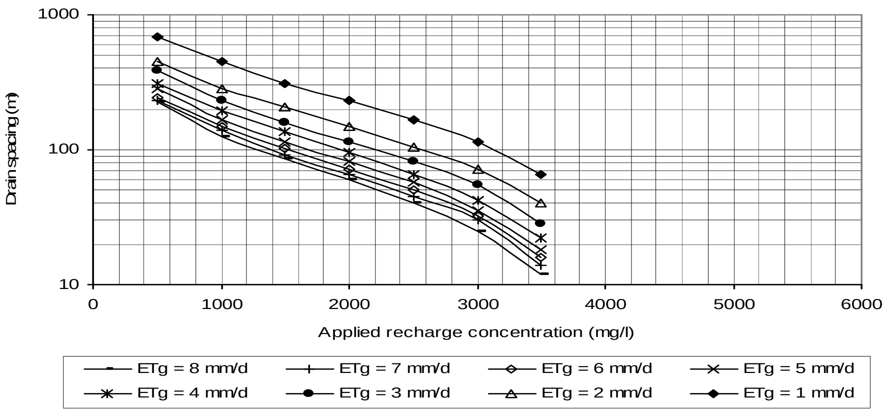
Figure 5-2: Design drain spacing for Aquifer K = 0.8 m/d to maintain the desired concentration at the base of the root zone.



(a): Root zone base salt concentration of 6000 m/g/l for different evapotranspiration rates

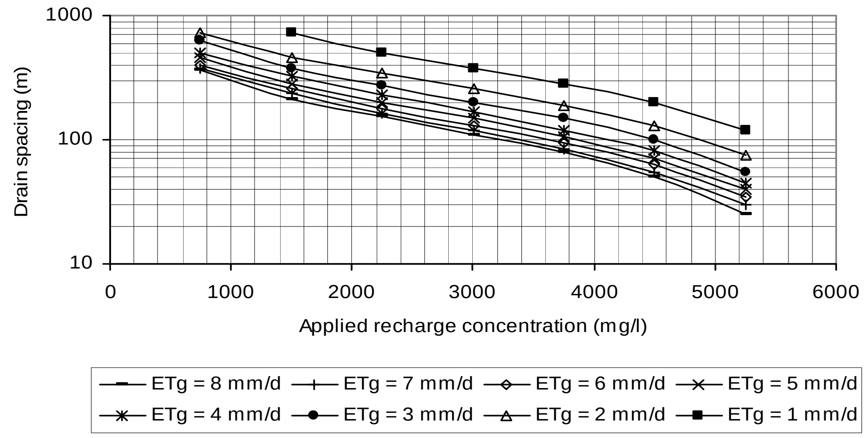


(b): Root zone base salt concentration of 5000 m/g/l for different evapotranspiration rates

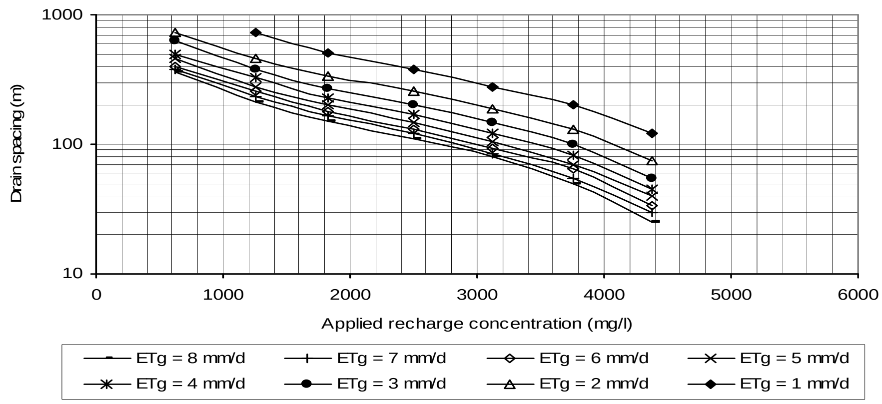


(c): Root zone base salt concentration of 4000 m/g/l for different evapotranspiration rates

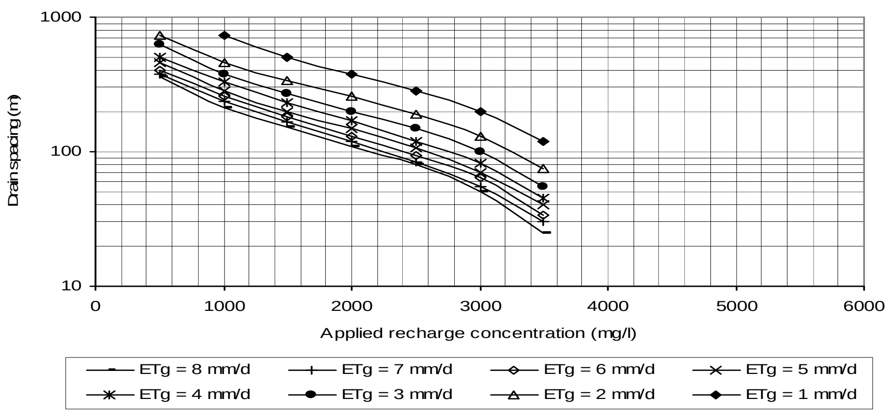
Figure 5-3: Design drain spacing for Aquifer K = 0.514 m/d to maintain the desired concentration at the base of the root zone.



(a): Root zone base salt concentration of 6000 m/g/l for different evapotranspiration rates

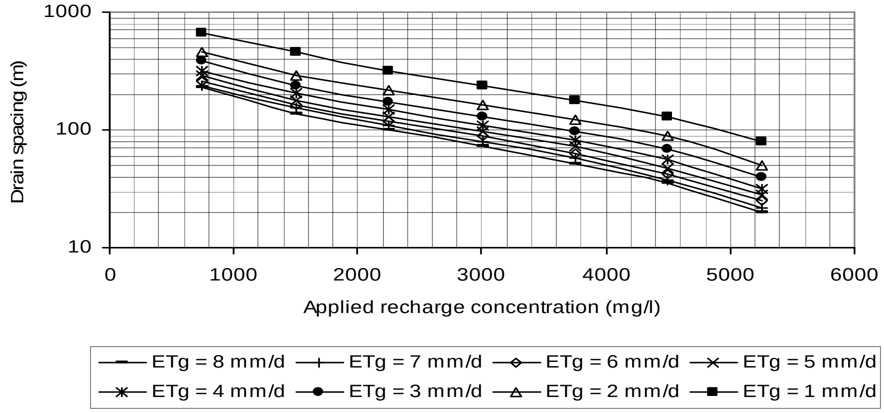


(b): Root zone base salt concentration of 5000 m/g/l for different evapotranspiration rates

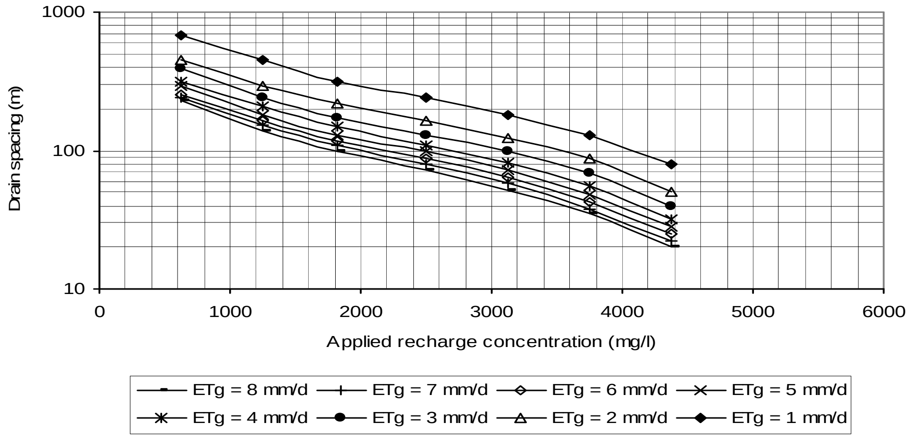


(c): Root zone base salt concentration of 4000 m/g/l for different evapotranspiration rates

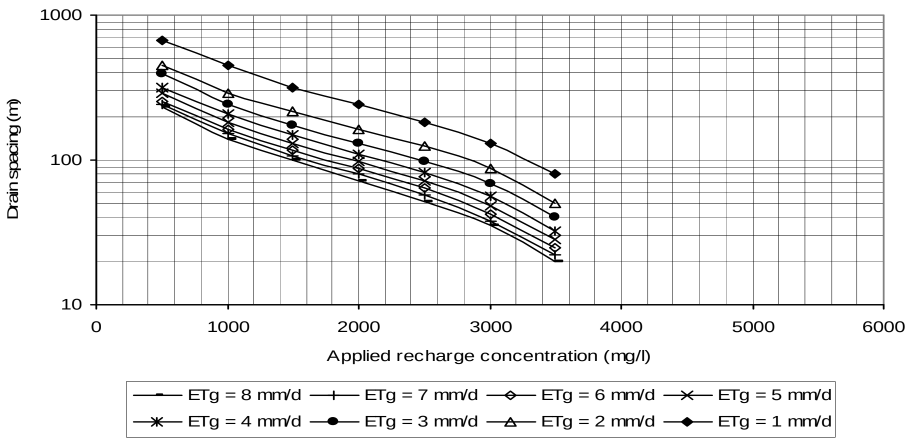
Figure 5-4: Design drain spacing for Aquifer K = 1.216 m/d to maintain the desired concentration at the base of the root zone.



(a): Root zone base salt concentration of 6000 m/g/l for different evapotranspiration rates



(b): Root zone base salt concentration of 5000 m/g/l for different evapotranspiration rates



(c): Root zone base salt concentration of 4000 m/g/l for different evapotranspiration rates

Figure 5-5: Design drain spacing for Aquifer K = 0.8 & 0.08 m/d to maintain the desired concentration at the base of the root zone.

Figures 5-2, 5-3, 5-4 and 5-5 can be used as 'salt concentration control' design spacing graphs and Figure 5-6 can be said to be a 'drain discharge' spacing design graph. It must be stated though that in view of great spatial variability of hydraulic conductivity; sloping surface and less than 20 m deep for real irrigated fields with water moving between different areas by gravity, the design graphs should be used with prudence.

The following procedure however is recommended:

a) The evapotranspiration rate, applied recharge (or its concentration) and the hydraulic conductivity of the aquifer should be known.
b) Using the 'salt concentration control' design spacing graph corresponding to the aquifer type and the desired salt concentration at the base of the root zone group, locate the value of the applied recharge concentration on the horizontal axis and draw a vertical line upwards to intersect the curve on.
c) At the intersection point of the ET_g value, draw a horizontal line to cut the vertical axis, this point corresponds to the drain spacing value.
d) Locate the drain spacing on the horizontal axis of the 'drain discharge' spacing design graph (corresponding to the aquifer type) and draw a vertical line upwards to intersect the curve.
e) The intersection of the vertical line with the curve corresponds to the drainage intensity.
f) With the drain discharge rate value established, the applied recharge may be evaluated.

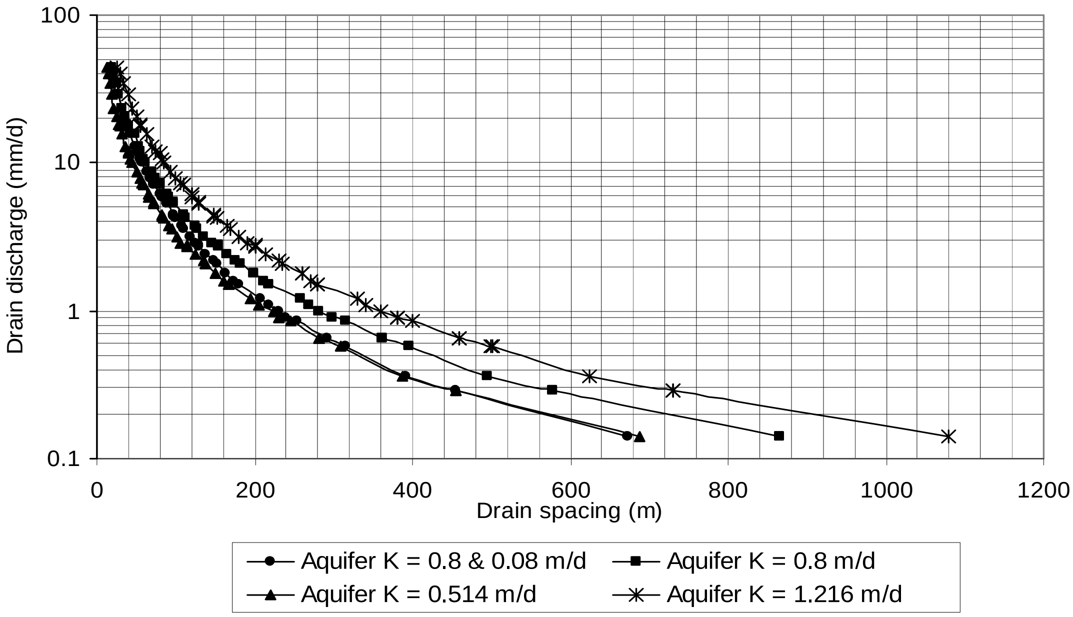


Figure 5-6: Relationship between design drain spacing and drain discharge for different aquifers

Numerical example

In an aquifer of K = 0.5 m/d in a semiarid region with ET_g = 5 mm/d, drains are to be installed 2 m below the ground surface. It is required to design the spacing to maintain salt concentration of 5000 mg/l at the water table depth of 0.8 m below the surface with an applied water concentration of 1000 mg/l. Evaluate the applied recharge needed. Compare the values obtain with that of conventional values.

Solution

Using Figures 5-3 and 5-6, for a K approximately = 0.5 m/d.

Using Figure 5-3(b) with a applied recharge concentration = 1000 mg/l to maintain salt concentration of 5000 mg/l with ET_g = 5 mm/d,

Drain spacing, DSP = 200 m.

From Figure 5-6 for a DSP = 200 m, drain discharge rate, q = 1.1 mm/d.

Then applied recharge (RCH) = ET_g + q = 5 mm/d + 1.1 mm/d = 6.1 mm/d.

Therefore, with applied recharge concentration of 1000 mg/l in an area of groundwater contribution to evapotranspiration rate of 5 mm/d, design spacing of 200 m and applied recharge of 6.1 mm/d will maintain a salt concentration of 5000 mg/l at base of the root zone and a drain discharge rate of 1.1 mm/d for a water table depth of 0.8 m.

To determine the extent that the applied recharge and spacing may differ from the conventional spacing, the following equations were solved:

$$LF = \frac{C_i}{C_n} \quad \text{(van Hoorn and van Alphen, 1994)} \qquad 5\text{-}2$$

where, LF is the leaching fraction, C_r is the irrigation (applied recharge) concentration = 1000 mg/l (in the question) and C_n is the salt concentration at the base of the root zone = 5000 mg/l (in the question)

Solving Equation 5-2, we obtained, LF = 0.2

and

$$AW = \frac{ET}{1 - LF} \quad \text{(FAO, 1985)} \qquad 5\text{-}3$$

where, AW is applied irrigation (applied recharge) water, ET is evapotranspiration rate = 5 mm/d (in the question) and LF = 0.2, we obtain applied recharge = 6.25 mm/d.

This gave a reduction of applied recharge by 3 % (drain discharge by 14 %) relative to the design spacing.

And, using the Hooghoudt's equation (Equation 2-2), the following is obtained:

$$(DSP_c)^2 = 1600 + 3200d_e \qquad 5\text{-}4$$

where, DSP_c is conventional drain spacing and d_e is given by Equation 3-6.

Solving Equations 5-4 and 3-6 with a r_o = 0.1 m yields a L_{drc} = 172 m. It is evident that the model design spacing is wider than the conventional spacing by 16 %. Therefore the model design drainage system is more economic effective than the conventional drainage system.

5.3.3 Comparison of simulated and conventional design spacing and drain discharges.

Tables 5-2, 5-3, 5-4 and 5-5 show simulated and conventional design drain spacings, and percentage differences between the simulated and the conventional spacings required to maintain concentration of 6000 mg/l at the base of the root zone for 3 uniform aquifers of K = 0.8, 0.514, 1.216 m/d and a non-uniform aquifer of K = 0.8 & 0.08 m/d respectively.

Table 5-2: Simulated and calculated spacing, and % difference between the spacings for aquifer K = 0.8 m/d

*ETg rate:	8 mm/d			7 mm/d			6 mm/d			5 mm/d			4 mm/d			3 mm/d			2 mm/d			1 mm/d		
Applied recharge conc. (mg/l)	Drain spacing (m)			Drain spacing (m)			Drain spacing (m)			Drain spacing (m)			Drain spacing (m)			Drain spacing (m)			Drain spacing (m)			Drain spacing (m)		
	Sim	Cal	% diff	Sim	Cal	% diff	Sim	calc	% diff	Sim	Cal	% diff	Sim	Cal	% diff	Sim	Cal	% diff	Sim	Cal	% diff	Sim	Cal	% diff
750	282	254	+11	298	270	+10	315	288	+9	362	335	+8	395	368	+7	496	466	+6	578	550	+5	865	839	+3
1500	165	142	+16	182	158	+15	198	173	+14	218	193	+13	258	229	+13	298	270	+10	362	335	+8	578	550	+5
2250	113	93	+22	124	103	+20	136	115	+18	155	131	+24	176	153	+15	212	186	+14	268	241	+11	395	368	+7
3000	80	64	+40	88	71	+24	98	80	+23	110	91	+21	128	106	+21	155	131	+18	198	184	+8	298	270	+10
3750	56	42	+33	62	47	+32	70	54	+30	76	62	+23	92	73	+26	110	91	+21	145	122	+19	218	193	+13
4500	35	26	+35	38	29	+31	48	32	+50	52	38	+37	60	46	+30	75	59	+27	98	80	+23	155	131	+18
5250	18	12	+50	20	14	+43	25	16	+56	28	19	+47	32	23	+39	40	29	+38	55	40	+38	88	71	+24

Sim is simulated spacing. Cal is calculated spacing

Table 5-3: Simulated and calculated spacings, and % difference between the spacings for aquifer K = 0.514 m/d

ET_g rate:	8 mm/d			7 mm/d			6 mm/d			5 mm/d			4 mm/d			3 mm/d			2 mm/d			1 mm/d		
Applied recharge conc. (mg/l)	Drain spacing (m)			Drain spacing (m)			Drain spacing (m)			Drain spacing (m)			Drain spacing (m)			Drain spacing (m)			Drain spacing (m)			Drain spacing (m)		
	Sim	Cal	% diff	Sim	Cal	% diff	Sim	Cal	% diff	Sim	Cal	% diff	Sim	Cal	% diff	Sim	Cal	% diff	Sim	Cal	% diff	Sim	Cal	% diff
750	225	192	+17	230	204	+13	245	218	+12	282	256	+10	310	282	+10	388	360	+8	455	427	+7	688	650	+6
1500	125	103	+21	138	115	+20	150	127	+18	168	143	+17	195	171	+14	230	204	+13	282	256	+10	455	427	+7
2250	85	68	+25	92	75	+23	102	84	+21	114	95	+20	135	111	+22	160	138	+16	206	181	+14	310	282	+10
3000	60	45	+33	65	50	+30	72	57	+26	82	65	+26	95	77	+23	114	95	+20	150	127	+18	230	204	+13
3750	40	29	+38	45	32	+40	50	36	+39	58	45	+29	65	52	+25	82	65	+26	105	89	+18	168	143	+17
4500	25	18	+39	30	20	+50	32	23	+39	35	27	+30	42	31	+35	55	40	+38	72	57	+26	114	95	+20
5250	12	9	+33	14	10	+40	16	11	+45	18	13	+38	22	15	+47	28	20	+40	40	28	+43	65	50	+30

*ET_g is groundwater contribution to evapotranspiration

Table 5-4: Simulated and calculated spacings, and % difference between the spacings for aquifer K = 1.216 m/d

*ET$_g$ rate:	8 mm/d			7 mm/d			6 mm/d			5 mm/d			4 mm/d			3 mm/d			2 mm/d			1 mm/d		
Applied recharge	Drain spacing (m)			Drain spacing (m)			Drain spacing (m)			Drain spacing (m)			Drain spacing (m)			Drain spacing (m)			Drain spacing (m)			Drain spacing (m)		
conc. (mg/l)	Sim	Cal	% diff	Sim	Cal	% diff	Sim	Cal	% diff	Sim	Cal	% diff	Sim	Cal	% diff	Sim	Cal	% diff	Sim	Cal	% diff	Sim	Calc	% diff
750	360	329	+9	380	348	+9	400	371	+8	460	430	+7	500	470	+6	624	592	+5	730	694	+5	1080	1051	+3
1500	214	187	+14	235	208	+13	260	227	+15	280	252	+11	330	298	+11	380	348	+9	460	430	+7	730	694	+5
2250	152	126	+21	165	139	+19	180	155	+16	200	174	+15	230	202	+14	270	243	+11	340	312	+9	502	470	+7
3000	110	88	+25	120	96	+25	130	107	+21	148	122	+21	170	144	+18	200	174	+15	260	227	+15	380	348	+9
3750	80	60	+33	84	66	+27	94	74	+27	106	85	+25	120	99	+21	148	122	+21	190	164	+16	280	252	+11
4500	50	36	+39	55	40	+38	64	46	+39	70	54	+30	82	65	+26	100	80	+25	130	107	+21	200	174	+15
5250	25	18	+39	30	20	+50	33	22	+50	40	27	+48	45	32	+41	55	40	+38	75	58	+29	120	96	+25

Table 5-5: Simulated and calculated spacings, and % difference between the spacings for aquifer K = 0.8 & 0.08 m/d

ET$_g$ rate:	8 mm/d			7 mm/d			6 mm/d			5 mm/d			4 mm/d			3 mm/d			2 mm/d			1 mm/d		
Applied	Drain spacing (m)			Drain spacing (m)			Drain spacing (m)			Drain spacing (m)			Drain spacing (m)			Drain spacing (m)			Drain spacing (m)			Drain spacing (m)		
recharge conc. (mg/l)	Sim	calc	% diff	Sim	calc	% diff	Sim	calc	% diff	Sim	calc	% diff	Sim	calc	% diff	Sim	calc	% diff	Sim	calc	% diff	Sim	calc	% diff
750	230	195	+18	240	206	+17	255	218	+17	292	251	+16	315	274	+15	392	342	+15	454	400	+14	674	596	+13
1500	138	116	+19	152	127	+20	164	138	+19	180	152	+18	208	177	+18	240	206	+17	292	251	+16	454	400	+14
2250	100	82	+22	108	89	+21	118	98	+20	130	109	+19	148	124	+19	173	148	+17	218	186	+17	315	276	+14
3000	72	59	+22	80	64	+25	88	70	+26	98	80	+23	110	92	+20	130	109	+19	164	138	+19	240	206	+17
3750	52	41	+27	58	45	+29	64	50	+28	72	57	+26	82	66	+24	98	80	+23	124	103	+20	180	152	+18
4500	35	28	+25	38	30	+27	42	33	+27	48	38	+26	56	44	+27	68	54	+26	88	70	+26	130	109	+19
5250	20	14	+43	22	15	+47	25	18	+39	28	21	+33	32	25	+28	40	30	+33	50	40	+25	80	64	+25

*ET$_g$ is groundwater contribution to evapotranspiration

Table 5-6: Simulated and calculated drain discharges, and % difference between the discharges

ET_g rate:	8 mm/d			7 mm/d			6 mm/d			5 mm/d			4 mm/d			3 mm/d			2 mm/d			1 mm/d		
Applied recharge conc. (mg/l)	Drain discharge (mm/d)			Drain discharge (mm/d)			Drain discharge (mm/d)			Drain discharge (mm/d)			Drain discharge (mm/d)			Drain discharge (mm/d)			Drain discharge (mm/d)			Drain discharge (mm/d)		
	Sim	Cal	% diff	Sim	Cal	% diff	Sim	Cal	% diff	Sim	Cal	% diff	Sim	Cal	% diff	Sim	Cal	% diff	Sim	Cal	% diff	Sim	Cal	% diff
750	1.0	1.1	-10	0.9	1	-11	0.86	0.9	-5	0.66	0.7	-6	0.57	0.6	-5	0.36	0.4	-11	0.29	0.3	-3	0.14	0.14	0
1500	2.4	2.7	-13	2.1	2.3	-10	1.8	2	-11	1.5	1.7	-13	1.2	1.3	-8	0.9	1	-11	0.66	0.7	-6	0.29	0.3	-3
2250	4.3	4.8	-12	3.8	4.2	-11	3.2	3.6	-13	2.8	3	-11	2.2	2.4	-9	1.6	1.8	-13	1.1	1.2	-9	0.57	0.6	-5
3000	7.1	8	-14	6.2	7	-13	5.3	6	-13	4.5	5	-11	3.6	4	-11	2.7	3	-11	1.8	2	-11	0.9	1	-11
3750	11.7	13.3	-14	10.2	11.7	-15	8.8	10	-14	7.3	8.3	-14	5.9	6.7	-14	4.4	5	-14	2.9	3.3	-14	1.5	1.7	-13
4500	20.2	24	-19	18.2	21	-15	15.6	18	-15	13	15	-15	10.5	12	-14	7.8	9	-15	5.4	6	-11	2.7	3	-11
5250	44	56	-27	40	49	-23	34.5	42	-22	29	35	-21	23.4	28	-20	18	21	-17	12	14	-17	6.1	7	-15

Sim. is simulated drain discharge. Cal is calculated drain discharge
ET_g is groundwater contribution to evapotranspiration

The 'positive percentage difference' means that the simulated spacing was wider than the conventional spacing. It was noted that drain discharges from the aquifers were the same for a given evapotranspiration rate and a given concentration of the applied recharges. Table 5-6 presents the simulated drain discharges, conventional drain discharges and percentage differences between the simulated and conventional drain drains discharges for all the aquifer hydraulic conductivities. The 'negative percentage difference' means the simulated drain discharge is less than the conventional drain discharge.

The conventional drain discharges and design drain spacings were obtained by the solutions of Equations 5-2, 5-3 and the Hooghoudt's steady state equation (Equation 2-2) with $r_o = 0.1$ m.

In comparing the simulated and the conventional design drain spacing, it was found that in all situations, the simulated design spacings are wider than the conventional spacings ranging from 3 % to over 50 %. This means more economic savings when the model is used as a design tool for drain spacing. Generally, the savings are much more when the evapotranspiration rate is high than when the evapotranspiration rate is low.

Comparing the simulated and the conventional drain discharges, differences in drain discharges were all negative indicating that the simulated drain discharges were less than the conventional drain discharges (Table 5-6). This means there was drained water savings which ranged from 1 to 27 % in maintaining the desired concentration at the base of the root zone. In general the percentage differences were higher in areas of high evapotranspiration than areas of low evapotranspiration. Similarly, the differences were larger when the concentration in the applied recharges were great than when the concentration in the recharges were low (Table 5-6). This means more drainage water (and irrigation water) will be saved in areas of high evapotranspiration when the model is used as a tool for subsurface drainage system than the conventional drainage system and much more water savings could be achieved when the concentration in the applied recharge is high.

5.4 Discussions and conclusion

Conventional subsurface drainage system procedures for salt concentration control in the root zone rely on lowering the water table low enough to prevent capillary rise of salt into the root zone. Christen and Ayars (2001), however, noted that this approach does not consider long term salt balance in the root zone associated with the depth and spacing of drains in a particular hydrologic setting. This study used the SEAWAT model to directly target salt concentration control at the base of the root zone with lower drain discharge (and applied water) for different climatic and aquifer conditions.

It is evident from the results that it is possible to use the SEAWAT model to design drain spacings to maintain the desired salt concentrations at the base of the root zone. As expected it was found that the design drain spacings are narrower in areas of high evapotranspiration rates for all aquifer types modelled. This could be because at high evapotranspiration rate, more water is evapotranspired leaving greater concentration in percolation into the groundwater. Therefore closely-spaced drains could remove the excess salt in order to bring the concentration at base of the root zone at the desired level. Similarly drain spacings are narrower when the concentration in the applied recharge is high than when the concentration in the applied recharge is low. As expected the narrower drain spacing resulted in greater drain discharges and in turn greater applied recharges. This conforms to the observation by Christen and Ayars (2001) that with increasing irrigation water concentration, leaching requirement is increased and this often required high drain discharge.

The comparison of the simulated design drain spacing to the conventional design drain spacings to maintain a concentration of 6000 mg/l at the base of the root zone shows that great economic savings can be achieved when the SEAWAT is used as a tool. This is because the simulated drain spacings (for all evapotranspiration rates and all aquifer hydraulic conductivities) are larger than the corresponding conventional drain spacing, providing percentage differences ranging from 3 to over 50 between the simulated and the conventional drain spacings. This is comparable to those obtained by other numerical approaches that considered evapotranspiration from the water table (Hammad, 1962; Hathoot, 1980; Hathoot et al. 1992).

Again, comparing the simulated drain discharges to the conventional drain discharges, all the percentage differences were negative indicating that the simulated discharges were less than the corresponding conventional drain discharges. This provided drain discharge savings ranging in the order of 3 to over 20 %.

It must be stated that in view great spatial variability of hydraulic conductivity, the use homogeneous hydraulic conductivity was likely to have uncertainty and a source of error; and the fact that the flat field surface and higher aquifer thickness (20 m) were assumed, do not realistically represent the flow conditions occurring in the aquifer, the design chart and the results should not be taken as absolute.

However, the numerical modelling technique clearly provides more effective designs on flat land which when extended onto sloping larger tracts of land where water is moving by gravity towards the low lying land, the SEAWAT will be much more effective than the conventional design. This is because SEAWAT is able to model lateral flow of water and salt, with drain spacing widening on higher ground where lateral outflow reduces the need for drainage, while in lower lying areas where there is expected to be a net inflow of water and salts into the root zone from higher ground, it will model higher flow densities to remove excess salinity. This is of importance in hot and dry climates because using the SEAWAT as a tool for subsurface drainage design can result in drain discharges (and in turn applied water) savings that can exceed 20 % compared with conventional design.

The results indicate that the SEAWAT model is a valuable alternative to conventional design procedure for subsurface drainage design, especially in hot and dry regions to maintain salt concentration at the base of the root zone with lower applied water.

CHAPTER SIX

6. GENERAL DISCUSSIONS AND CONCLUSIONS

6.1 Introduction

The review in Chapter 2 highlighted the detrimental effects of waterlogging and salinization on crop production and the need to maintain low levels of salt in the root zone if effective irrigation farming is to continue (Hoffman, 1985).

Pioneering researchers like Skaggs (1980), van Dam *et al.* (1997), El-Sadek et al. (2001) and many others, working on waterlogging and salinization, developed models using conventional drainage equations to design subsurface drainage systems to maintain water table levels as a means of lowering salt within the root zone (Moustafa and Yomota, 1998). Subsurface drainage design, however, needs to target salt control more than water table control since evapotranspiration could feasibly control the water table levels in arid and semiarid regions (Heuperman *et al*., 2002). In this study, a numerical variable density groundwater model called SEAWAT was used to evaluate the design of a drainage system to maintained salt concentration levels at the base of the root zone using relatively less water than with conventional design drainage system

As discussed in Chapter 2, the SEAWAT code is a computer programme that simulates three-dimensional variable density groundwater flow through porous media. SEAWAT combines modified MODFLOW (Mcdonald and Harbaugh, 1988) and MT3DMS (Zhen, 1990) codes into a single programme to solve the coupled groundwater flow and solute (salt) **–** transport equations. The model contains solution techniques that reduce numerical dispersion which is usually associated with solute transport simulation and therefore the model is capable of producing acceptable transport solutions (Langevin, 2001). The model includes boundary conditions that contain variable density source waters and is capable of simulating temporally and spatially varying salt concentrations in order to predict both groundwater flow and leaching.

SEAWAT like all numerical groundwater models is limited in its representation of the physical system because it is based on simplifications and assumptions that may or may not be valid. Inherent in the SEAWAT code are several assumptions that could introduce a degree of uncertainty into the results.

The model assumes isothermal conditions and this may influence the results. Thermal gradients can affect flow density and thus groundwater flow patterns. However, Langevin (2001), noted that thermal gradients seemed to have minimal effect on groundwater flow.

The model does not account for variations in viscosity. Studies indicate that such variations are not important unless the flow densities exceed 1,200 kg/m^3 (Langevin *et al*, 2003). In this study, flow densities remained below 1,005 kg/m^3 suggesting that variations in flow viscosity probably did not affect groundwater flow.

The processes of irrigation, runoff, recharge and evapotranspiration were represented by simplifications. The model simulates only the evapotranspiration from the saturated zone (the water table). Though the quantity of unsaturated zone evapotranspiration is probably indirectly included in the evapotranspiration from the water table, the unsaturated zone evapotranspiration may be an important process in irrigated land where unsaturated zones can be relatively thick. In this study the initial water table was assigned to be close to the soil surface (0.5 m below the surface) suggesting a reduction of the effect of the unsaturated zone evapotranspiration.

6.2 General discussions

It is clear from the results that the SEAWAT program for Simulation of Three-Dimensional Variable-Density Ground-Water Flow (USGS - US Geological Survey Office of Groundwater) can be effectively used for design of subsurface drainage systems for controlling salt concentration in the root zone on salt affected irrigated land. The programme has the advantage over conventional drain spacing equations in that it can be used to optimize drainage design to ensure that the salt concentration of the groundwater at the base of the root zone does not exceed pre determined levels whereas conventional drain spacing equations are based on maintaining the groundwater at a predetermined level.

This study was carried out on a conceptual uniform homogenous block of flat field of initial salt concentration of 7200 mg/l and water table depth of 0.5 m from the surface with an impermeable layer at 20 m deep and impermeable field boundaries. The discussions here focus on the verification of model's suitability as a drainage model on irrigated field, the simulation of drainage flow and leaching, and finally improvement of subsurface drainage intended for salt concentration control at the base of the root zone.

Verification of the model's applicability on irrigated land

Comparison between the simulated mid-drain water table heads with the mid-drain heads derived by solution of the Hooghoudt's steady state equation (Hooghoudt mid-drain head) indicated good correlation (Chapter 3).

Comparison of the mid-drain heads (Chapter 3) revealed that when the drain cell size was 0.1 m, the mid-drain water table head matched well with Hooghoudt's mid-drain head for a drain diameter of 0.1 m. Similarly the simulated mid-drain heads for drain cell sizes of 0.2 and 0.5 m compared well with the Hooghoudt's values for drain diameters of 0.2 and 0.4 m using aquifer hydraulic conductivities ranging from 0.2 m/d to 1.2 m/d (Tables 3-4a, 3-4b and 3-4c).

Another important aspect identified was that using drain cell dimension of 0.1 m per side, the head in the drains rose above the drain elevation, yielding misleading results, and indicating that drain cell dimensions must be greater than 0.1 m for accurate simulation.

The results (Chapter 3) of simulated equipotentials in the aquifer also confirmed the existence of vertical, horizontal and radial component of flow usually associated with flow to subsurface drains (Ritzema, 1994; Smedema *et al*., 2004). The equipotentials confirmed the existence of a curved water table reflecting a typical shape for drains subject to uniform applied recharge (Ritzema, 1994). This indicates that the hydrologic factors or aquifer parameters probably do not introduce too much error.

The results in Chapter 3 again showed cones of salt concentration beneath the drains even after 20 years of drainage (Figure 3-5b) similar to salt concentration patterns described by Masterson and Portnoy (2006). This indicates that sufficient groundwater had been removed by the drains causing the interface between the incoming dilute net recharge and the saline groundwater to move upwards from the underlying more concentrated zone as described by Masterson and Portnoy (2006). The leaching patterns in Chapter 3 generally appear both realistic and reasonable, and allow the model to be used to identify the leaching response within the aquifer.

The simulated mid-drain salt concentrations in the layers increased with depth (Chapter 3) reflecting a well known phenomenon relatively fresh water penetrations and seeps through saline aquifer. There was an initial exponential leaching which eventually declined to a stable level suggesting a salt balance condition. At this point, the concentration in the aquifer became identical to the concentration in the irrigation water (applied recharge) as noted by Johnston (1993) and Christen and Skehan (2001).

The foregoing demonstrates the applicability of the model to simulate drainage on irrigated land.

Simulation of drainage flow and leaching in irrigated field

The model's simulations of drainage and leaching using an applied recharge of 8 mm/d with a salt concentration of 1500 mg/l were evaluated by assessing the response of the simulated drainage flow and leaching to drain spacings (30, 60, 90, 150, 200 and 250 m) either when there no evapotranspiration or a rate of 6.24 mm/d.

Case (a): The no evapotranspiration case

The results in Chapter 4 indicated that the water table depths differed for different drain spacings. The drain discharge rates were identical to the applied recharge (8 mm/d) for all the spacing confirming that spacing had no effect on drain discharge. Water table depths for spacings in excess of 90 m reached the surface, indicating that for water table control, drain spacings should not exceed 90 m. All the spacings, leached a similar quantity of salt from the aquifer. Over 30 % of the initial aquifer salt was removed by year 1 and over 75 % by year 10 for all the drain spacings. This clearly demonstrates that, drain spacing *per se* does not influence leaching (Table 4-2). Similarly both closely and widely spaced drains maintained the similar mid-drain salt concentrations at the base of the root zone which was identical to the recharge concentration. This shows that the value of salt concentration at the base of the root zone depends only on the concentration of the recharge but not spacing.

Case (b): Evapotranspiration included

The results in Chapter 4 revealed that the drain discharge decreased with increasing spacing. This was because increasing spacing caused the water table to rise and thus in turn increased groundwater water contribution to the evapotranspiration, ET_g, leaving less water available for discharge. Raising the water table depth from 1.72 m for drain spacing of 30 m to 0.42 m for drain spacing of 250 m increased the ET_g from 5.7 to 6.01 mm/d, an increase of over 5% corroborating the general observed positive correlation between evapotranspiration rates and water table depths (Cooper et al., 2006). The drain discharge rate fell from 2.3 mm/d (for a spacing of 30 m) to 1.93 mm/d (for a spacing of 250 m), a decrease of 16 % suggesting that spacing had effect on the drain discharge and the effect could be much more if the evapotranspiration was greater. The water table depths for all spacings were deeper than for the corresponding no evapotranspiration case demonstrating the capability of evapotranspiration to lower water tables (Heuperman *et al.* 2002).

The leaching for all spacings, was less than when there was no evapotranspiration because there was less water available to percolate and drain away. Just over 4 % of the initial salt was leached by 1 year and over 20 % by 5 years for spacings of 30, 60, 90 and 150 m; only about 2 % was leached year 1 and about 10 % by year 5 for a spacing of 250 m (Table 4-5 in Chapter 4). However, the leached salts for all the drain spacings were over 15 %, 50 % and 70 % of their respective ‘leachable’ salts for 1 year, 5 years and 10 years respectively of drainage, suggesting that leachable aquifer salts generally were low. Leachable salts are the salts that are removed from aquifer when the salt balance in the aquifer is identical to the salt in the net recharge.

The results (Figure 4-5 in Chapter 4) revealed that the mid-drain salt concentration at the base of the root zone became stable at different levels for the different spacings after 3 years. This indicates that almost all the root zone leachable salt had been removed and that root zone concentration equaled the concentration of the net recharge (deep percolation). The different levels of the root zone concentration indicated that different spacing had varying achievable leachable salt concentrations because of the differing groundwater contributions to the evapotranspiration, ET_g, and differing net recharge concentrations (Table 4-4). Spacings of 30 m and 250 m achieved salt concentration at the base of the root zone of respectively about 5,200 mg/land 6,200 mg/l, a difference of only 20 % indicating that concentration at the base of the root zone is not highly sensitive to spacing.

The results (Chapter 4) when recharge concentration was changed from 1500 mg/l to 1000 mg/l and further to 700 mg/l revealed that much more salt was leached from the aquifer by decreasing the concentration in the applied recharge for all drain spacings. This could be because the less saline water resulted in greater mobilization of the salt in the groundwater to be leached. Similarly the mid-drain concentrations at the base of the root zone decreased for all spacings as applied recharge concentration. Figures 4-6a and 4-7a showed among spacings, closer levels of salt concentration at the base of the root zone with decreasing applied recharge concentration suggesting that the effect of spacing on concentration at the base of the root zone diminished with decreasing applied recharge concentration and this reinforces the effect of quality applied recharge has on salt concentration at the base of the root zone (FAO, 1985).

Improving drainage systems for salt concentration control

Chapter 5 described the use of the SEAWAT model to determine drain spacings to maintain concentrations of 6,000 or 5000 or 4000 mg/l at the base of the root zone for varying groundwater contribution to evapotranspiration rate, ET_g, and different aquifer hydraulic conductivities.

The results of the studies (Chapter 5) showed that over a wide range of irrigation water concentrations and aquifer hydraulic conductivities, the optimum drain spacing using SEAWAT was, depending on modeled water quality and aquifer hydraulic conductivities, wider by between 3 and 50 % and the amount of drain discharge reduced by between 2 and 27 % than would be recommended using conventional design equations.

However the above potential reduction in drain discharge is the maximum but this level of saving is only likely to be achieved on land close to the mid drain spacing where over irrigation will only result in water-logging, yet there is still potential for farmers closer to the drain to over irrigate and hence increase drain discharge. Nevertheless there is expected to be an overall reduction in drain discharge if subsurface drainage is installed based on SEAWAT designs and not conventional designs.

To allow easy comparison of the performance of the SEAWAT and conventional drain spacing equations a conceptual uniform flat field with impermeable boundaries was created and hence there was no topographic driven gradients effecting groundwater flow from higher to lower lying ground. Since in real irrigation schemes topographic driven flow is a major factor affecting salinity levels in the land, the above increase in efficiency will be an underestimate of the potential increases in drainage designs based on SEAWAT. This is because SEAWAT is able to model lateral flow of water and salt throughout the aquifer, with drain spacing widening on higher ground, where lateral outflow reduces the need for drainage, while in lower lying areas where there is expected to be a net inflow of water and salts into the root zone from higher ground, SEAWAT will model higher drain densities to remove excess salinity. The overall performance of variable density numerical groundwater models for designing cost effective drainage systems must therefore be appreciably more effective than conventional drainage designs which model very restricted boundary conditions between two drains.

6.3 Conclusions

The conclusions outlined below are meant to offer a better appreciation of the use of SEAWAT programme, a variable-density numerical model, for subsurface design for controlling both water table and concentration at the base of the root zone as an alternative to conventional subsurface drainage procedure that target mainly water table control.

The main aim of this research was to use a variable-density numerical groundwater model as a tool to design drain spacings that maintain salt concentration at the base of the root zone with reduced drain discharge.

Specific objectives performed were:

(i) To assess the applicability of the numerical groundwater model to irrigated field as a subsurface drainage design model.

(ii) To assess the capability of the model to simulate drainage flow and leaching in irrigated aquifers.

(iii) To use the model to design drain spacing that can maintain desired salt concentration at the base of the root zone with less discharge water compared with conventional drainage design equation.

Based on this research it is clear that evapotranspiration and recharge (applied water) concentration must be considered in designing spacing for subsurface drainage systems.

Drain spacings were designed to ensure that the salt concentration at the base of the root zone does not exceed pre determined levels instead of maintaining the water table at a predetermined level for different aquifers under different climatic conditions.

Results of this research indicate that:

1. The variable-density numerical groundwater model, SEAWAT, can be used on irrigated field as a subsurface drainage design model.
2. Different spacings maintained the same mid-drain salt concentration level identical to the applied recharge concentration at the base of the root zone when evapotranspiration was not included in the model suggesting that when there was no evapotranspiration, the concentration in the soil profile is influenced by the applied recharge concentration but not the drain spacing.

3. Different drain spacings maintained different concentration levels at the base of the root zone with different water table depths for a given applied recharge with specified concentration in areas of high evapotranspiration rate.

4. Drain spacing effect on leaching and in turn on salt concentration at the base of the root zone diminished with decreasing applied recharge concentration.

5. The design spacings designed were wider than conventional design spacing in maintaining the desired concentration in the order of 3 to about 50 % providing economic savings. The order of space widening increased in dry regions with more saline irrigation water suggesting that savings may be higher in arid and semiarid regions.

6. Based on the results, the simulated drain discharges were less in the range of 2 and 20 % than the conventional drain discharges. The savings of the discharges can exceed 20 % in regions of high evapotranspiration rate with poor quality irrigation water. This suggests that more discharge water (and applied water) savings may be obtained in dry regions with poor quality irrigation water.

Results from this study have a degree of uncertainty, which is why conclusions are reported in relative terms rather than absolute. The degree of uncertainty is primarily attributed to; (a) the assumption of flat surface and bottom of the irrigated field and (b) the assumption of homogeneous aquifer hydraulic conductivity. Attempts to use flat field surface suggests no flow from upslope to the study area and this rarely happens in real situation. The use of homogeneous hydraulic conductivity ignores the spatial variability and the strong influence of soil heterogeneity on drain flow and leaching (Maxwell et al., 2007). Although the uncertainties could limit the reliability of the design chart results estimated, the estimates probably could the best available because they were derived with numerical groundwater model that includes variable-density effects likely to influence agricultural groundwater flow.

It can therefore be concluded that the variable-density numerical groundwater model, SEAWAT, can be used a tool to design subsurface drainage system that can maintain a desired concentration at the base of the root zone with less irrigation water.

The research has contributed to the development of knowledge by:

1. developing drain spacing to control long term salt balance at the base of the root zone and water tables. The design spacings can result in saving of irrigation water by over 20 % compared to the conventional drainage design.

2. highlighting the crucial role of variable-density numerical model in designing spacing for subsurface drainage to ensure that the salt concentration of the groundwater at the base of the root zone does not exceed pre determined levels instead of maintaining the groundwater at a predetermined level.

3. demonstrating that the SEAWAT model, which was developed and mostly used for saltwater intrusion in coastal lands, can be used to design drain spacing for irrigated fields.

6.4 Recommendations

The SEAWAT model has been mostly and widely used for the intrusion of saltwater in coastal lands with little or no usage on irrigated field. Therefore it would be useful to see the SEAWAT drainage design implemented in a real project to examine how close the modeled outcomes reflect reality, and to establish what drainage water losses and drainage water salinity really would be when real farmers are brought into the equation.

The modelling work was not extended to look at its performance under variable topographic conditions due to time constraints of the project; however, it is strongly recommended that the findings of this project justify a comparative study of a design using SEAWAT and a design using conventional drain spacing equations under topographic conditions.

The study should be extended to field(s) with shallow depth. The design spacing for shallow field was not investigated and such merits further investigations since irrigated fields are not always deep.

The study could form the basis for further developing of spacing design for heterogeneous fields since irrigated fields are rarely homogeneous.

APPENDIX I

Sensitivity analysis of SEAWAT model

A sensitivity analysis was performed to evaluate the effects of some key aquifer parameters and boundary conditions on the simulated water table elevation, leached salt load, salt load remaining in the aquifer and salt concentration within the layers both for the applied recharge of 10 mm/d with zero salt concentration and/or with salt concentration of 3000 mg/l. The aquifer parameters were:- the saturated hydraulic conductivity, K; the longitudinal dispersivity, α_L; and the diffusion coefficient, D*.

The values used included saturated hydraulic conductivities, K, of 1.6, 0.8, 0.4 and 0.2 m/d; Longitudinal dispersivities, $\alpha_{L,}$of 1.0, 0.5, 0.1 and 0.01 m; and Diffusion coefficients, D*, of 0.08, 0.03, 0.015 and 10^{-5} m^2/d.

Both recharge with pure water and a concentration of 3000 mg/l produced similar effect of the selected parameters on the water table elevation, total salt and salt concentration in the aquifer. The saturated hydraulic conductivity, K, had a significant effect on the water table elevation but had no effect on the salt concentration in both the discharged water and in the aquifer. It was observed that when K $\leq$ 0.2 m/d, the water table level in the drain tended to rise above the drains and subsequently caused the water table to rise above the soil surface suggesting that SEAWAT modeling the K should be more than 0.2 m/d.

The longitudinal dispersivity, $\alpha_{L,}$ had little effect on the discharged salt load, total salt load remaining in the aquifer and water table elevation as observed by Langevin (2001). However, it had a significant effect on the salt concentration within the root zone (< 2.0 m below soil surface) though this effect diminished with time (after two years). Increasing α_L to 0.5 m or more, tended to change the shape of the salt concentration contours within the root zone layer but with a decrease in α_L values, the salt concentration contours remained unchanged with time. The programme failed to run when the α_L value exceeded 1.0 m, the length of the model domain cell. This confirmed the observation in the literature that the proportionality constant of the relation between the α_L and the distance travelled by the solute should be less than one (Gelhar, 1986). As the diffusion coefficient, D*, increased, the salt concentration remaining in the root zone also increased but the model failed to run when D* > 0.08 m^2/d. The changing shape of the salt concentration contours was clearly evident when the diffusion coefficient, D*, was 0.015 m^2/d or less.

Also investigated were drain conductance, CD,(head loss between the drain and the region of cell due to the convergent flow pattern towards the drain, flow through the openings on the wall of the drain and the material of envelope around the drain), and drain cell dimensions and it was noted that each parameter had significant effect on water table. To maintain the water tables below the soil surface for low hydraulic conductivity, the CD needed to exceed 500 m^2/d and the drain grid cell size also be greater than 0.1 m.

APPENDIX II

Model simulation of leaching with changing applied recharge qualities

Table II(A and B) and Table II(C and D) show temporal salt remaining in the aquifer and leached salts when the model was run for applied recharge of 8 mm/d with different concentrations of 1000 mg/l and 700 mg/l respectively. For each model run, the evapotranspiration rate was 6.24 mm/d. In both cases the water table depths at steady state ranged from 1.72 m to 0.42 m for spacings ranging from 30 m to 250 m respectively. It is therefore no surprise that the leached salt decreased with increasing spacing. This is because lowering water table depth with increasing spacing resulted to more evapotranspirated water thereby causing less drain discharge with less salt. This is also reflected in the leachable aquifer salts which decreased with increasing spacing in both cases (Table IIA and Table IIC).

For all spacings, the leached aquifer salts when the applied recharge concentration was 1000 mg/l were less than the leached aquifer salts for the corresponding spacing when the applied recharge concentration was 700 mg/l, and a similar pattern showing in the leachable aquifer salts (Table IIA and Table IIC). However, among the spacings in each case, the leached aquifer salts were more when the applied recharge was 1000 mg/l than when the applied was 700 mg/l. The leached aquifer salts were about 40 and about 30 % of the initial aquifer salt (280800 kg/ha) for spacings 30 and 250 m respectively (Table IIA) in 10 years of drainage, giving a leached salt difference of 10 % of the initial aquifer salt when the applied recharge salt was 1000 mg/l, whist for the same period the leached aquifer salt difference for spacing 30 and 250 m was about 5 % of the initial aquifer salt when the applied recharge was 700 mg/l (Table IIC). This suggests that the effect of drain spacing on leaching of aquifer salt becomes less significant with decreasing applied recharge concentration.

Table IIA: Salt remaining in aquifer, leached aquifer salt and 'leachable' salt for recharge concentration of 1000mg/l

Drain spacing (m)	Salt in aquifer (kg/ha)			Percentage of *initial aquifer salt leached			'Leachable' aquifer salt (kg/ha)
	1 year	5 years	10 years	1 year	5 years	10 years	
30	256,218	198,143	167,109	8.8	29.4	40.5	153,637
60	256,610	199,159	169,223	8.6	29.1	39.7	151,187
90	257,343	200,634	170,940	8.4	28.5	39.1	148,459
150	258,460	205,349	176,967	8.0	26.8	37.0	140,505
200	260,609	212,657	187,419	7.2	24.3	33.3	126,191
250	261,830	216,775	193,062	6.8	22.8	31.2	118,565

*Initial salt in the aquifer = 280,800 kg/ha

Table IIB: Relation between total leached salt and salt in the applied recharge for recharge concentration of 1000mg/l

	Drained out salt(kg/ha)			Drained out salt/*Recharge salt (dimensionless)		
Drain spacing (m)	1 year	5 years	10 years	1 year	5 years	10 years
30	51091.4	219485.6	394355.6	1.75	1.50	1.35
60	50894.2	219299.4	394238.9	1.74	1.50	1.35
90	50617.5	219113.3	393969.4	1.73	1.50	1.35
150	50038.9	218527.2	393638.9	1.71	1.50	1.35
200	48659.4	214175.6	387550.0	1.70	1.47	1.33
250	47646.7	210094.4	382083.3	1.63	1.44	1.31

*Recharge salt load = 29,200 kg/ha/year

Table IIC: Salt remaining in aquifer, leached aquifer salt and 'leachable' salt for recharge concentration of 700mg/l

Drain spacing (m)	Salt in aquifer (kg/ha)			Percentage of *initial aquifer salt leached			'Leachable' aquifer salt (kg/ha)
	1 year	5 years	10 years	1 year	5 years	10 years	
30	250,498	177,237	139,264	10.8	36.9	50.4	191,784
60	250,580	178,165	140,153	10.7	36.5	50.1	190,064
90	251,072	179,952	142,510	10.6	35.9	49.2	188,150
150	252,158	182,650	146,163	10.2	35.0	47.9	182,435
200	253,706	187,610	153,095	9.6	33.2	45.5	172,574
250	254,380	190,503	157,060	9.4	32.2	44.1	167,216

*Initial salt in the aquifer = 280,800 kg/ha

Table IID: Relation between total leached salt and salt in the applied recharge for recharge concentration of 700mg/l

	Total Drained out salt(kg/ha)			Drained out salt/*Recharge salt (dimensionless)		
Drain spacing (m)	1 year	5 years	10 years	1 year	5 years	10 years
30	49,028.9	203,284.2	344,330.6	2.40	1.99	1.68
60	48,938.3	202,491.9	343,730.6	2.39	1.98	1.68
90	48,836.9	200,843.9	343,108.3	2.39	1.97	1.68
150	48,617.2	199,838.6	341,263.9	2.38	1.96	1.67
200	47,390.3	196,630.3	336,983.3	2.32	1.92	1.65
250	46,390.3	192,662.8	331,861.1	2.27	1.89	1.62

*Recharge salt load = 20,440 kg/ha/year

Calculation of leachable salts

The leachable salts and concentrations for the various spacings were calculated as follows:

Leachable salt = V_i x C_i – V_t x C_n and **Leachable salt concentration = C_i - C_n**

Also,

$V_i = A_o \times n \times WT_{ie}$

$V_t = A_o \times n \times WT_{et}$

$C_n = (RCH \times RCN)/DD$

where,

V_i = initial volume of water in the aquifer (m^3)

V_t = volume of water in the aquifer at time t (m^3)

C_i = initial salt concentration in the aquifer (kgm^{-3})

C_n = salt concentration in the net recharge (kgm^{-3})

A_o = area of the irrigated field (m^2)

n = aquifer porosity (-)

WT_{ie} = initial water table elevation with reference to the base of the aquifer (m)

WT_{et} = water table elevation with reference to the base of the aquifer at time t (m)

RCH = applied recharge/irrigation water (md^{-1})

RCN = salt concentration in the applied recharge/irrigation water (kgm^{-3})

DD = drain discharge (md^{-1})

APPENDIX III

Supporting information to Chapter 5

Table IIIA: Design drain spacings for aquifer K = 0.8 m/d to maintain water table depth of 0.8 m and salt concentration of 6000 mg/l at the base of the root zone

RCH	ET_g = 8 mm/d		ET_g = 7 mm/d		ET_g = 6 mm/d		ET_g = 5 mm/d		ET_g = 4 mm/d		ET_g = 3 mm/d		ET_g = 2 mm/d		ET_g = 1mm/d	
conc. (mg/l)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)
750	1.0	282	0.9	298	0.86	315	0.66	362	0.57	395	0.36	496	0.29	578	0.14	865
1500	2.4	165	2.1	182	1.8	198	1.5	218	1.2	258	0.9	298	0.66	362	0.29	578
2250	4.3	113	3.8	124	3.2	136	2.8	155	2.2	176	1.6	212	1.1	268	0.57	395
3000	7.1	80	6.2	88	5.3	98	4.5	110	3.6	128	2.7	155	1.8	198	0.9	298
3750	11.7	56	10.2	62	8.8	70	7.3	76	5.9	92	4.4	110	2.9	145	1.5	218
4500	20.2	35	18.2	38	15.6	48	13	52	10.5	60	7.8	75	5.4	98	2.7	155
5250	44	18	40	20	34.5	25	29	28	23.4	32	18	40	12	55	6.1	88

RCH conc. : Applied recharge concentration. ET_g : Groundwater contribution to evapotranspiration. Disch. : drain discharge rate. DSP : design drain spacing

Table IIIB: Design drain spacings for aquifer K = 0.514 m/d to maintain water table depth of 0.8 m and salt concentration of 6000 mg/l at the base of the root zone

RCH	ET_g = 8 mm/d		ET_g = 7 mm/d		ET_g = 6 mm/d		ET_g = 5 mm/d		ET_g = 4 mm/d		ET_g = 3 mm/d		ET_g = 2 mm/d		ET_g = 1mm/d	
Conc. (mg/l)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)
750	1.0	225	0.9	230	0.86	245	0.66	282	0.57	310	0.36	388	0.29	455	0.14	688
1500	2.4	125	2.1	138	1.8	150	1.5	168	1.2	195	0.9	230	0.66	282	0.29	455
2250	4.3	85	3.8	92	3.2	102	2.8	114	2.2	135	1.6	160	1.1	206	0.57	310
3000	7.1	60	6.2	65	5.3	72	4.5	82	3.6	95	2.7	114	1.8	150	0.9	230
3750	11.7	40	10.2	45	8.8	50	7.3	58	5.9	65	4.4	82	2.9	105	1.5	168
4500	20.2	25	18.2	30	15.6	32	13	35	10.5	42	7.8	55	5.4	72	2.7	114
5250	44	12	40	14	34.5	16	29	18	23.4	22	18	28	12	40	6.1	65

RCH conc. : Applied recharge concentration. ET_g : Groundwater contribution to evapotranspiration. Disch. : drain discharge rate. DSP : design drain spacing

Table IIIC: Design drain spacings for aquifer K = 1.216 m/d to maintain water table depth of 0.8 m and salt concentration of 6000 mg/l at the base of the root zone

RCH	ET_g = 8 mm/d		ET_g = 7 mm/d		ET_g = 6 mm/d		ET_g = 5 mm/d		ET_g = 4 mm/d		ET_g = 3 mm/d		ET_g = 2 mm/d		ET_g = 1mm/d	
Conc. (mg/l)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)
750	1.0	360	0.9	380	0.86	400	0.66	460	0.57	502	0.36	624	0.29	730	0.14	-
1500	2.4	214	2.1	235	1.8	260	1.5	280	1.2	330	0.9	380	0.66	460	0.29	730
2250	4.3	152	3.8	165	3.2	180	2.8	200	2.2	230	1.6	270	1.1	340	0.57	502
3000	7.1	110	6.2	120	5.3	130	4.5	148	3.6	170	2.7	200	1.8	260	0.9	380
3750	11.7	80	10.2	84	8.8	94	7.3	106	5.9	120	4.4	148	2.9	190	1.5	280
4500	20.2	50	18.2	55	15.6	64	13	70	10.5	82	7.8	100	5.4	130	2.7	200
5250	44	25	40	30	34.5	34	29	40	23.4	45	18	55	12	75	6.1	120

RCH conc. : Applied recharge concentration. ET_g : Groundwater contribution to evapotranspiration. Disch. : drain discharge rate. DSP : design drain spacing

Table IIID: Design drain spacings for aquifer K = 0.8 & 0.08 m/d to maintain water table depth of 0.8 m and salt concentration of 6000 mg/l at the base of the root zone

RCH	ET_g = 8 mm/d		ET_g = 7 mm/d		ET_g = 6 mm/d		ET_g = 5 mm/d		ET_g = 4 mm/d		ET_g = 3 mm/d		ET_g = 2 mm/d		ET_g = 1mm/d	
Conc. (mg/l)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)	Disch. (mm/d)	DSP (m)
750	1.0	230	0.9	240	0.86	255	0.66	292	0.57	315	0.36	392	0.29	454	0.14	674
1500	2.4	140	2.1	152	1.8	164	1.5	180	1.2	208	0.9	240	0.66	292	0.29	454
2250	4.3	100	3.8	108	3.2	118	2.8	130	2.2	148	1.6	173	1.1	218	0.57	315
3000	7.1	72	6.2	80	5.3	88	4.5	98	3.6	110	2.7	130	1.8	164	0.9	240
3750	11.7	52	10.2	58	8.8	64	7.3	72	5.9	82	4.4	98	2.9	124	1.5	180
4500	20.2	35	18.2	38	15.6	42	13	48	10.5	56	7.8	68	5.4	88	2.7	130
5250	44	20	40	22	34.5	25	29	28	23.4	32	18	40	12	50	6.1	80

RCH conc. : Applied recharge concentration. ET_g : Groundwater contribution to evapotranspiration. Disch. : drain discharge rate. DSP : design drain spacing

The following numerical example calculation was to boost the use of drainage design chart developed in Chapter 5 in a different way to determine the cost saving in using the model's drainage system as compared to the conventional drainage system.

Numerical example

In a saline aquifer of K = 1.2 m/d, to provide groundwater contribution to the evapotranspiration, ET_g of 2 mm/d, drains are to be installed at a depth of 2 m. Design drain spacing that will make use of an applied recharge of 2.5 mm/d to maintain salt concentration of 4000 mg/l at water table of 0.8 m below the ground surface. Determine the recharge concentration.

Solution

Using Figures 5-4 and 5-6, for a K approximately = 1.2 m/d.

Given that applied recharge, RCH, = 2.5 mm/d and ET_g = 2 mm/d, drain discharge rate, q, is determined as:

q = RCH – ET_g =2.5 mm/d – 2 mm/d = 0.5 mm/d.

Using Figure 5-6, with q = 0.5 mm/d,

Drain spacing, DSP = 560 m.

From Figure 5-4 for drain spacing = 560 m and salt concentration control = 4000 mg/l to determine the applied recharge concentration was not easy; hence spacings 600 m and 500 m were used.

From Figure 5-4(c) for spacing = 600 m and ET_g = 2 mm/d,

Applied recharge concentration = 700 mgl.

Similarly, from Figure 5-4(c) for spacing = 500 m and ET_g = 2 mm/d,

Applied recharge concentration = 900 mg/l.

Then by interpolation, applied recharge concentration for spacing = 560 m is:

Applied recharge concentration = $700 - \frac{600-560}{600-500}(700 - 900)$ mg/l

= 780 mg/l.

Therefore, a spacing of 560 m will maintain a salt concentration of 4000 mg/l at base of the root zone and groundwater contribution to the evapotranspiration of 2 mm/d for applied recharge of 2.5 mm/d with concentration of 780 mg/l.

The extent that the spacing differed from the conventional spacing was determined by applying Hooghoudt's equation (Equation 2-2) and the following is obtained:

$$(DSP_c)^2 = 9600 + 19200d_e \qquad \text{A-1}$$

Solving Equations A-1 and 25 with an $r_o = 0.1$ m yields a $DSP_c = 518$ m.

There is therefore a space saving of about 8 % when the design spacing is used instead of the conventional spacing.

The increase in design spacings between drains compared with the conventional design is in line with observation by Hathoot, (1980) since the model takes into account of evapotranspiration that takes place from the water table.

REFERENCES

Ali, R., Elliott, R. L. and Ayars, J. E. 2000. Soil salinity over shallow water table. I: Validation of LEACHC. *J. Irrig. and Drain. Engng. ASCE,* **126(4):** 223 – 233.

Amezketa, E. 2006. An integrated methodology for assessing soil salinization, a pre-condition for land desertification. *Jourl. of Arid Environment*, 67: 291 – 302

Anderson, M. P. and Woessner, W. W. 1992. *Applied groundwater modelling simulation flow and advective transport.* University Press. Cambridge, UK

Bastiaanssen, W. G. M., El-Deen, M. S. K., Mirabile, C., Korani, M and Abdel Gawad, S. 1996. Data management related to the application of two crop-water-environment models in Argentina and Egypt. *Proc. of the 16th ICID Congress,* Cairo, Egypt: 54 – 68

Bear, J. and Verruijt, A. 1990. *Modeling groundwater flow and pollution. Theory and applications of transport in porous media*. D. Reidel Pub. Co., Dordrecht, Holland.

Bear, J. 1997. *Dynamics of fluid in porous media*. Dover Publications Inc., New York. 764p.

Belmans, C., Wasseling, J. G. and Feddes, R. A., Simulation of the waterbalance of a cropped soil: SWATRE. *Journl. of Hydrol*. **63**: 217 – 286.

Berner, R. A. 1980. *Early diagenesis: A theoretical approach*. Princeton Univ. Press. Princeton, NJ

Boring, M., Morari, F., Bonaiti, G., Paasch, M. and Skaggs, R. W. 2000. Analysis of DRAINMOD performances with different detail of soil input data in the Veneto region of Italy. *Agric. Water Manage.* **42**(3): 259 – 272.

Bos, M. G. 1994. Basics of groundwater flow. In: *Drainage Principles and Applications* (ed. by H.P. Ritzema). 2nd edn. ILRI Pub. **16**: 225 - 261

Bos, M. G. and Boers, Th. M. 1994. Land drainage: Why and How?. In: *Drainage Principles and Applications* (ed. by H.P. Ritzema). 2nd edn. ILRI Pub. **16**: 23 – 30

Carter, C. E. and Camp, C. R. 1994. Drain spacing effects on water table control and cane sugar yields. *Soil and Water Div. of ASAE. Trans. ASAE* **37(5)**: 1509 - 1513

CAST (Council for Agricultural Science Technology). 1988. Effective use of water in irrigated agriculture. Report No. 113, Amer, Iowa.

Caviero J., Farre I, Debaeke, P. and Faci, J. M. 2000. Simulation of maize yield under water stress with EPIC phase and CROPWAT models. *Agron. J*. **92**: 679 – 690.

Chhabra, R. 1996. Soil salinity and water quality. Taylor and Francis Publishers. ISBN 9054107278

Christen, E. W. and Ayars, S. E. 2001. *Subsurface Drainage System Design and Management in Irrigated Agriculture: Best Management Practices for Reducing Drainage Volume and Salt Load.* Tech. Report 38/01. CSIRO. Land and Water. Griffith, NSW, Australia.

Christen, E. W. and Hornbuckle, J. W. 2001. Subsurface drainage design and management practices in irrigated areas of Australia. Irrigation Insights No. 2. Land and Water, Australia, Canberra.

Christen, E. and Skehan, D. 2001. Design and management of subsurface horizontal drainage to reduce salt loads. *J. Irrig. and Drain. Engng., ASCE,* **127(3)**: 148 - 155.

Cooper, D. J., Sanderson, J. A., Stannard, D. L. and Groeneveld, D. P. 2006. *J. of Hydrol.,* **325** (1 - 4) pp. 21 - 34

Cosgrove, W. J. and Rijsberman, F. R. 2000. Challenge for the 21st century: Making water everybody's business. *Sustainable Devpt. Intnl.* **2**: 149 – 156.

Collis-Geirge, N. 1977. Infiltration equations for simple soil systems. *Water Resource Research,* **13**: 395 – 403.

Çullu, M. A. 2003. Estimation of the effect of soil salinity on crop yield using Remote Sensing and Geographic Information System. *Turk J. Agric.* **27**: 23 – 28

Dayem, S. A. and Ritzema, H. P. 1990. Verification of drainage design criteria in the Nile Delta, Egypt. *Irrig. and draing. Systs*. **4**: 117 – 131.

de Ridder, N. A. and Boonstra, J. 1994. Analysis of water balance. In: *Drainage Principles and Applications* (ed. by H.P. Ritzema). 2nd edn. ILRI Pub. **16**: 601 – 633.

Dixit, P., Rodriguez, D. and Chen, D. 2004. Spatial pattern of the effect of soil salinity on crop physiological parameters, soil water content and wheat yield. *Proc. 3rd Aust. New Zealand Soils Conf.* 5 – 9 dec. 2004. Univ. of Sydney, Australia.

Dong-Ju, K., Joung-Souk, K., Seong-Taek, Y. and Sang-Hoon, L. 2002. Determination of longitudinal dispersivity, $\alpha_{L,}$ in an unconfined sandy aquifer. *Hydrol. Process* **16**: 1955 - 1964

Droogers, P., van der Meer, F. B. W. and Bouma, J. 1997. Water accessibility to plant roots in different soil structures occurring in the same soil type. *Plant and Soil*. **188**: 239 – 250.

Duwig, C., Normand, B., Vauclin, M., Vachaud, G., Green, S. R. and Bacquer, T. 2003. Evaluating of the WAVE model for predicting nitrate leaching for two contrasted soil and climate conditions. *Vadose Zone Journl*. **2**: 76 - 89

El-Atfy, H. E., Abdel-Alim, M. Q. and Ritzema, H. P., 1991. A modified layout of the subsurface drainage system for rice areas in the Nile delta, Egypt. *Agric. Water Manage*., **19**: 289 – 302.

El-Sadek, A., Feyen, J. and Berlamont, J. 2001. Comparison of models for drainage discharge. *J. Irrig. and Drain. Engng.* ASCE **127(6):** 363 -369

Evans, R. O., Gilliam, J. W. and Skaggs, R. W. 1991. *Controlled Drainage Management Guidelines for Improving Water Quality*. AG-443. N.C. Agric. Extension Service, Raleigh, NC 16p

Evans, D. G. and Raffensperger, J. P. 1992. On the stream function for variable-density groundwater flow. *Water Resources Research*. **28 (8)**: 2141 – 2145.

FAO. 1980. Drainage design factors. FAO *Irrigation and Drainage Paper* **38**. FAO, Rome.

FAO. 1988. World Agriculture Toward 2000: An FAO Study. Ed. by N. Alexandratos. Bellhavens Press, London 338 pp.

FAO. 1992. The use of saline water for crop production. FAO *Irrigation and Drainage Paper* **48**. FAO, Rome.

FAO. 1994. Water quality for agriculture. FAO *Irrigation and Drainage Paper* **29** (1). FAO, Rome

FAO. 1997. Management of agricultural drainage: Water quality. *Water Reports* **13**. FAO Rome

FAO. 2002. Agricultural drainage water management in arid and semiarid areas. FAO *Irrigation and Drainage Paper* **61**. FAO, Rome.

Feddes, R. A. 1988. Effects of drainage on crops and farm management. *Agric. Water Manage.* **14**: 3 – 18.

Feddes, R. A. 1990. Proposal on non-steady state water management model for horizontal drainage design. Assistance to IWASRI, Lahore, Pakistan. Mission Report. 31pp.

Feddes, R. A., Kawalik, P. J. and Zaradny, H. 1978. Simulation of water use and crop yield. *Simulation Monogr.,* PUDOC, Wageningen. 188 pp.

Fernãndez, J. E., Slawinski, C., Moreno, F. Walczak, R. T. and Vanclooster, M. 2002. Simulating the fate of water in a soil-crop system of a semiarid Mediterranean area with the WAVE 2.1 and EURO-ACCESS-II models. *Agric. Water Manage*. **56** (2002): 113 – 129.

Fine, R. A. and Millero, F. J. 1973. Compressibility of water as a function of temperature and pressure. *Journl of Chemical Physics* **59** (10)

Franke, O. L., Reilly, T. E. and Bennett, G. D. 1987. Definition of boundary and initial conditions in the analysis of saturated ground-water flow systems – An introduction. Techniques of Water-Research Investigations of US Geological Survey, Book 3, Chapter B5

Fouss, J. L.; Bengtson, R. L. and Carter, C. E. 1987. Simulating subsurface drainage in the lower Mississippi value with DRAINMOD. *Trans. ASAE* **30**(6): 1679 – 1688.

Gates, T. K., Burkhalter, J. P., Labadie, J. W., Valliant, J. C. and Broner, I. 2002. Monitoring and modelling flow and salt transport in a salinity-threatened irrigated valley. *J. Irrig. and Drain. Engng., ASCE* **128 (2):** 87 – 99

Gayle, G. A., Skaggs, R. W. and Carter, C. E. 1985. Evaluation of a water management model for a Louisiana sugar cane field. *J. Am. Soc. Sugarcane Tech*. **4**: 18- 28

Gelhar, L. W. 1986. Scientific subsurface hydrology from theory to application. *Water Resources Research* **22**: 135s – 145s.

Ghassemi, F., Jakeman, A. and Nix, H. 1995. *Salinization of land and water resources: Human causes, extent, management, and case studies*. Univ. of New South Wales Press, Sydney, Australia.

Guitjens, J. C., Ayars, J. E., Grismer, M. E. and Willardson, L. S. 1997. Drainage design for water quality management: Overview. *J. Irrig. and Drain. Engng. ASCE* **123(3**): 148 – 153.

Guo, W. and Langevin, C. D. 2002. User's guide to SEAWAT: A computer programme for simulation of three-dimensional variable-density groundwater flow. USGS. Tallahassee, Florida.

Guo, Zh. R. and Liu, H. T. 2002. Secondary salinification of soil and dynamic control of groundwater in irrigation area of inland basin, northwestern China. *Agro-environment Protection*, **21(1)**: 45 – 48.

Gupta, S. K. 2002. A century of subsurface drainage research in India. *Irrig. and Draing. Systs.* **16:** 69 – 84.

Gutierrez B., F. H., Scheiner, J. D. and Lavado, R. S. 1993. Some effects of soil salinity on growth, development and yield of rapeseed (Brassica napus L.) *Jourl. of Agronomy and Crop Science* **172**(3): 182 – 187.

Haitjema, H. M. 1995. *Analytic Element Modelling of Groundwater Flow*. Academic Press, San Diego, CA

Hathoot, H. Y. 2002. Pipe-drainage spacing design considering subsurface evaporation. *Alexandria Engineerng Jourl*. **41** (2): 307 – 312

Hathoot, H. M. 1980. Effect of evaporation on subsurface drainage. *Bul. Fac. Engng., Alex. Univ. XIX*. **No. 5**: 65 – 75.

Hennessy, J. 1993. Water management in the 21st century. XVth ICID Congress. The Hague, Keynote address pp 1-31

Heupermann, A. F., Kapoor, A. S. and Denecke, H. W. 2002. Biodrainage: Principles, experiences and applications. *IPTRID Knowledge Synthesis Report*. No.6 FAO of UN, Rome.

Hoffman, G. J. 1985. Drainage required to manage salinity. *J. Irrigation and Drainage Div*. ASCE III (IR3): 199 – 206

Howard, K. W. F. and Lloyd, J. W. 1979. Sensitivity of parameters in the Penman evaporation equations and direct recharge balance. *Journl of Hydrlogy*, **41(3-4)**: 329 – 344.

Indo-Dutch Network Project (IDNP), 2002. *Research on the Control of Waterlogging and Salinization in Irrigated Agric. Land.* Vol. 4. Indo-Dutch Network Project, Central Soil Salinity Research Institute, India. 380pp.

Jensen, M. E., Rangeley, W. R. and Dieleman, P. J. 1990. Irrigation trends in world agriculture. In: *Irrig. of Agric. Crops.* (ed. by B. A. Stewart & D. R. Nielsen), Amer. Soc. of Agronomy, Madison, Wisconsin, USA, pp 31 – 67.

Johnson, A. I. 1967. Specific yield – Compilation of specific yields for various materials. *Water Supply Paper 1662D* USGS pp74

Johnston, W. R. 1993. Changes in subsurface drainage water salinity and boron concentrations. *Journl. of Irrig. and Drain. ASCE* **119**(1): 210 – 206.

Junior, R. S. 2000. Land degradation survey. NSW Dept of Land and water Coservn.

Kabat, P., van den Broek, B. J. and Feddes, R. A. 1992. SWACROP: A water management and crop production simulation model. *Intnl. Commission on Irrig. and Drain.*, New Delhi, Bulletin 92, **42**(2): 61 – 84.

Kabat, P. and Beekma, J. 1994. Water in the unsaturated zone. In: *Drainage Principles and Applications* (ed. by H.P. Ritzema). 2nd edn. ILRI Pub. **16**: 383 - 435

Khan, G. D., Latif, M., Khan, M. J. and Kanwar, R. S. 2002. Analysis of groundwater behaviour in a farmer controlled subsurface tile drainage system in Mardan, Pakisan. *Irrign and Drain. Sys.* Vol. **16** (4): 327 – 345.

Khan, S., Rana, T. and Yuanlai, C. 2006. Can irrigation be sustainable? *Agricultural Water Management*. **80**: 87 - 99

Kibaroglu, A. 2002. Design and management of irrigation systems: The southeastern Anatolia development sproject. In: *Modern and traditional Irrigation Technology in the Eastern Mediterranean.*(ed. by Ö. Mehmet and H. A. Biçat). IDRC. pp 155 - 172

Kroes, J. G. Beldman, J., te Beest, J. G., Boland, D. and Th. Vellinga. 2001. *Conflicting interests in a Dutch agric. Diary farming system.* Paper presented at IAHS symposium. Wagenningen, The Netherland.

Kurien, V. M., Cooke, R. A., Hirschi, M. C. and Mitchell, J. K. 1997. Estimating drain spacing of incomplete drainage systems. *Trans. of ASAE* **40** (2): 377 – 382.

Kutilek, K. and Nielsen, D. R. 1994. *Soil Hydrology*. GeoEcology Publication. Catena Velag

Langevin, C. D. 2001. Simulation of ground-water discharge to Biscayne Bay, Southeastern Florida. *Water Resources Investigations Report 00-4251*. USGS. Talla. Fl.

Langevin, C. D., Shoemaker, W. B. and Guo, W. 2003. MODFLOW-2000, the U.S. Geological survey modular groundwater model- Documentation of the SEAWAT-2000 version with the variable-density flow process (VDS) and the integrated MT3DMS transport process (IMT). *Open-File Report 03-426*. USGS. Talla. Fl.

Langevin, C. D., Swain, E. D. and Wolfert, M. A. 2004. *Simulation of integrated surface-water/ground-water flow and salinity for a coastal wetland and adjacent estuary*. US Dept. of Interior, US Geological Survey

Liu, X., Wilson, C. and Grieve, C. M. 2005. Effect of salinity on accumulation of chiro-inositol and other non-structural carbohydrates in limonium. *Proc. of the Int. Salinity Forum, Managing Saline Soils and Water: Science, Technology and Soil Issues.* April 25 – 27, 2005. Riverside, CA: 93 – 96.

Logue. K.M. and Green, R. E. 1991. Statistical and graphical methods for evaluating solute transport model. *J. Contam. Hydrol*. **7:** 51 - 73

Mahmood, K., Morris, J., Collopy, J. and Slavich, P. 2001. Groundwater uptake and sustainability of farm plantations on saline sites in Punjab Province, Pakistan. *Agric. Water Manage*., **48**: 1 – 20.

Mallants, D., Jacques, D., Vanclooster, M., Diels, J and Feyen, J. 1996. A stochastic approach to simulate water flow in a macroporous soil. Geoderma. **70**: 299 - 324

Mandavia, A. B. 1999. Modernization of irrigation system operational management by way of canal automation in India. In: *Modernization of Irrigation System Operations: Proc. of the 5th ITIS Netwaork Intnl. Meeting*, Aurangabad, 28 – 30 Oct. 1998. FAO: 21 - 52

Manguerra, H. B. and Garcia, L. A. 1997. Modelling flow and transport in drainage areas with shallow ground water. *J. Irrig. and Drain. Engng. ASCE* **123(3)**: 185 – 193.

Marinelli, F. and Durnford, D. S. 1998. Semianalytical solution to Richards' equation for layered porous media. *J. Irrig. and Drain. Engng., ASCE,* **124(6):** 290 – 299

Massoud, F. I. 1976. Basic principles for prognosis and monitoring of soil salinity and sodicity. *Managing Saline Water for Irrigation: Proc. Int. Salinity Conf.,* Texas Tech. Univ., Texas, 423 – 454

Masterson, J. P. and Portnoy, J. W. 2006. *Potential Changes in Groundwater Flow and their Effect on the Ecology and Water Resources of the Cape Cod National Seashore, Massachusetts.* USGS. 16pp

Maxwell, R. M., Welty, C. and Harvey, R. W. 2007. Revisiting the Cape Cod bacteria injection experiment using a stochastic modelling approach. *Environ. Sci. Technol*. **41**: 5548 – 5558.

McDonald, M. G. and Harbaugh, A. W. 1988 A modular three-dimensional finite-difference ground-water flow model. Techniques of water- resources investigations of the United States Geological Survey. Chapter A1, Bk. 6 USGS.

Merz, R. D. and Skaggs, R. W. 1998. Application of DRAINMOD-S to determine drainage design criteria for irrigated semiarid lands. In: *Drainage in the 21st Century: Food Production and the Environment. Proc. of the Seven International Drainage Symposium.* (ed. by L. C. Brown). March 8 – 10, 1998. Orlando, Fl. ASAE, USA.pp 347- 354.

Moustafa, M. M. and Yomota, A. 1998. Spatial modelling of soil properties for subsurface drainage projects. *Journl. of Irrig and Drain. Engng.* **124**(4): 218 - 228

Mualem, Y. 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resour. Res.* **12**(3): 513 – 521.

NRW (Natural Resources and Water) 2006. Land management. Dept of Nat. Res. and Water. The State of Queensland. Australia.

Nijland H. J., Croon, F. W. and Ritzema, H. P. 2005. Subsurface drainage practices. Guidelines for implementation, operation and maintenance of subsurface pipe drainage systems. *ILRI Publication* **60.**

Postel, S. L. 1999. *Pillar of sand: Can the irrigation miracle last?* W. W. Norton, New York.

Postel, S. L. 1993. Water and agriculture. In: *Water in Crisis: A Guide to the World's Fresh Water Resources* (ed. by P. H. Gleick). Oxford Univ. Press: pp 56 - 66

Pereira, L. S. 1988. Modernization of irrigation systems: A case of research oriented to improve management. *Irrig. and Drain. Manage.* **2(1):** 63 - 77

Qureshi, A. S., Iqbal, M., Anwar, N. A., Aslam, M and Chandhry, M. R. 1996. Benefits of shallow drainage. In *Proc. of Seminar on On-Farm Salinity, Drainage and Reclamation.* Pub. 179

Rajasthan Agric. Drainage Research Project (RAJAD). 1996. *Analysis of subsurface drainage design criteria.* Chambal Common Area Devpt. Authority. Nutech Photolithographers: New Delhi, India, 260pp

Rao, K. V. G. K., Kumbhare, P. S. and Kamra, S. K. 1988. Studies on the performance of subsurface drainage system- a case study of Sampla (India). *Annual Report*, *Central Soil Salinity Research Inst.*, *Karnal*: 64 – 65

Reilly, T. E. 2001. System and Boundary Conceptualization in Ground-Water Flow Simulation. Techniques of Water-Resources Investigations of the US Geological Survey, Book 3, Chapter B8.

Ritzema, H. P., Satyanarayana, T. V., Raman, S. and Boonstra, J. 2007. Subsurface drainage to combat waterlogging and salinity in irrigated lands in India: Lessons learned in farmers' fields. *Agric. Water Manage*.

Ritzema, H. P. 1994. *Subsurface flow to drains*. In: Drainage Principles and Applications (ed. by H. P. Ritzema) 2nd edn. ILRI Pub. 16: 263 – 305.

Robinson, M. 1990. Impact of improved land drainage on river flows. Report no. 113. *Inst. of Hydrology*, Wallingford, UK. 226pp

Rushton, K. R. 2003. *Groundwater Hydrology: Conceptual and Computational Models.* John Wiley and Sons Ltd.

Rushton, K. R. and Redshaw, S. C. 1979. *Seepage and Groundwater flow. Numerical analysis by analog and digital methods.* John Wiley & Sons.

Sadras, V., Roget, D. and O'Leary, G. 2000. On-farm assessment of environmental and management constraints to wheat yield and efficiency in the use of rainfall in the Mallee. *Aust. J. Agric. Research* **53**: 587 – 598.

Sanders, L. L. 1998. A manual of field hydrogeology. Prentce Hall Inc.

Sarwar, A., Bastiaanssen, W. G. M., Boers, Th. M. and van Dam, J. C. 2000. Evaluating drainage design parameters for the fourth drainage project, Pakistan by using SWAP model: Part I – calibration. *Irrg. and Drain. Systs.* **14**: 257 – 280.

Satyanarayana, T. V. and Boonstra, J. 2007. Subsurface drainage pilot area experience in three irrigated project commands of Andhra Pradesh in India. *Irrig. and Draing*. **56**: S245 – S252

Schilling, K. E. and Helmers, M. 2008. Effect of subsurface drainage tiles on streamflow in Iowa agricultural watersheds: Exploratory hydrograph analysis. *Hydrological Processes* **22**(23): 435-

Schultz, B., Thatte, C. D., and Labhsetwar, V. K. 2005. Irrigation and drainage – main contibutors to global food product. *Irrig. and Draing.*, **54**: 263 – 278.

Shah, N., Nachabe, M. and Ross, M. 2006. Extinction depth and evapotranspiration from groundwater under selected land covers. *Ground Water* **45**(3): 329 – 338.

Sharma, D. P. and Gupta, S. K. 2005. Subsurface drainage for reversing degradation of waterlogged saline land. *Land Degradation and Devpt*. **17(6)**: 605 – 614.

Sharma, D. P., Singh, K. and Rao, K. V. G. K. 2000. Subsurface drainage for rehabilitation of waterlogged saline lands: Example of a soil in semiarid climate. *Arid Soil Res. and Rehab.* **14**: 373 - 386

Shen, L. and Chen, Z. 2007. Critical review of the impact of tortuousity on diffusion. *Chem. Eng'g. Science*. **62** (14): 3748 - 3755

Shukla, K. N., Chauhan, H. S. and Srivastava, V. K. 1999. Transsient drainage to penetrating drains in sloping aquifers. *J. Irrig. and Drain. Engng., ASCE,* **125(5)**: 246 – 253.

Shiklomanov, I. A. 1991. The world's water resources. In *Proc. of the Intl. Symposium to Commemorate 25 years of the IHP,*: 93 - 126UNESCO/IHP

Singh, R., Helmers, M. J. and Zhiming Qi. 2006. Calibration and validation of DRAIMOD to design subsurface drainage systems for Iowa's tile landscapes. *Agric. Water Manage.* **85**(3): 221 - 232

Skaggs, R. W. 1980. Methods for design and evaluation of drainage-water management systems for soils with high water tables. *Drainmod. Reference Report.* USDA, SCS, SNTC, Texas.

Skaggs, R. W. 1982. Field evaluation of a water management simulation. *Trans. ASAE* **25**: 666 – 674.

Skaggs, R. W. 1986. Drainage modelling in research and design. In: *Proc. Intl. Seminar on Land Drainage* (ed. by J. Saavalainen and P. Vakkilainen). Helsinki Univ. of Technology: 153 – 180.

Skaggs, R. W. 1999. Drainage simulation models. In: *Agric. Drain. Agron. Monogr*. **38**. ASA, CSSA and SSSA, Madison, WI: 461 - 492

Smedema, L. K., Vlotman, W. F. and Rycroft, D. W. 2004. *Modern land drainage: Planning, design and management of agric. Drainage systems.* A.A. Balkema Publishers

Srinivasulu, A., Sujani Rao Ch., Lakshmi, G. V., Satyanarayana, T. V. and Boonstra, J. 2004. Model studies on salt and water balances at Konanki pilot area, Andhra Pradesh, India. *Irrig. Draing. Systs*. **18**: 1 – 17

Swain, E. D., Howie, B. and Dixon, J. 1996. Description and field analysis of a coupled groundwater/surface water flow model (MODFLOW/BRANCH) with modifications for structures and wetlands in southern Dade County, Florida. *Water resources investigations Report* **96** – 4118. 67p

Tanji, K. K. (ed.) 1990. Nature and extent of agricultural salinity. In: *Agricultural Salinity Assessment and Management. ASCE Manuals and Reports on Engineering Practices* No. 71 (ed. by K. K. Tanji) ASCE. New York. Pp 619

Vanclooster, M., Viane, P. Diels, J and Christiaen, K. 1994. WAVE: a mathematical model for simulating water and agrochemicals in the soil and vadose environment. *Reference and Users Manual. Inst. for Land and Water Manage.*, Katholieke Universiteit Leuven, Leuven, Belgium

Vanclooster, M., Boesten, J. J. T. I., Trevisan, M., Brown, C. D., Capri, E., Eklo, O. M., Gottesbüren, B., Gouy, V. and van der Linden, A. M. A. 2000. A European test of pesticide-leaching models: methodology and major recommendations. *Agric. Water Manage.* **44** (2000): 1- 19.

Van Dam, J. C., Huygen, J., Wesseling, J. G., Feddes, R. A., Kabat, P., van Walsum, P. E. V., Groenendijk, P. and van Diepien, C. A. 1997. Theory of SWAP version 2.0. Simulation of water flow, solute transport and plant growth in the Soil-Water-

Atmosphere-Plant environment. Report 71. Dept of Water Resources, Wageningen Univ.,The Netherlands.

Van der Ploeg, R. R., Horton, R. and Kirkham, D. 1999. *Steady flow to drains and wells.* In: Agricultural Drainage (ed. by R. W. Skaggs and J. Van Schilfgaarde). Agronomy Series no. **38**. ASA, CSSA, SSSA.: 213 - 264

Van Genuchten. M. Th. 1987. A numerical model for water and solute movement in and below the root zone. *Res. Report. US Salinity Lab.*, Riverside, CA.

Van Hoorn, J. W. and van Alphen, J. G. 1994. *Salinity control* In: Drainage Principles and Applications (ed. by H. P. Ritzema) 2nd edn. ILRI Pub. 16: 533 – 600.

Van Schilfgaarde, J. 1974. Nonsteady flow to drains. Drainage for Agric. Amer. Soc. Of Agron, Madison.: 275- 283.

Van Wijk, A. L. M. and Feddes, R. A. 1986. Simulating effects of soil type and drainage on arable crop yields. In: *Agric Water Manage*. (ed. by A. L. M. van Wijk and J. Wasseling). Proc. Symp. on Agric Water Manag., Arnhem.

Vereecken, H. M., Vanclooster, M., Swerts, M. and Diels, J. 1991. Simulating water and nitrogen behaviour in soil cropped with winter wheat. *Fert. Res*. **27**(1991): 233 – 243.

Wahba, M. A. S. and Christen, E. W. 2006. Modelling subsurface drainage for salt load management in Southeastern Australia. *Irrig. Draing. Systs*. **20**: 267 - 282

Wahba, M. A. S., Christen, E. W. and Amer, M. H. 2005. Irrigation water saving by management of existing subsurface drainage in Egypt. *Irrig. and Draing*. **54**: 205 - 215

Wallace, J. S. and Batchelor, C. H. 1997. Managing water resources for crop production. *Phil. Trans. Royal Soc. Biol. Sci*.**352**: 937 - 947

R-12

Wang, H. F. and Anderson, M. P. 1982. *Introduction to groundwater modelling – Finite difference and finite element methods*. W. H. Freeman and Co., New York, USA.

Wang, Y., Xiao, D., Li Yan and Li Xiaoyu, 2008. Soil salinity evolution and its relationship with dyanamics of groundwater in the oasis of inland river basins: case study from the Fubei region of Xinjiang Province, China. *Environ. Monit. Assess*. **140**: 594 – 606.

Wang, X., Mosley, C. T., Frankenberger, J. R., Kladivko, E. J. 2006. Subsurface drain flow and crop yield predictions for different drain spacings using DRAINMOD. *Agric. Water Manage.* **79** (2): 113 - 136

Ward, A. D. and Timble, S. W. 2004. Environmental Hydrology. 2nd edn. CRC Press. Pp.448

Willmott. C. J. 1982. Some comments on the evaluation of model performance. *Bull. Am. Meteorol. Soc.* **63**: 1309 – 1313.

Wiskow, E. and van der Ploeg, R. R. 2003. Calculation of drain spacings for optimal rainstorm flood control. *J. of Hydrology*. **272(1-4):** 163 - 174

Wisler, C. O. and Brater, E. F. 1949. *Hydrology*. Chapman and Hall, London.

Wolters, W. 2000. *Research on technical drainage issues: Lessons learned from IWASRI/NARP Project 1988-2000.* Pub no. 226. Intl. Waterlogging and Salinity Research Inst, Lakhore, Pakistan: 36pp

Write, J. and Sands, G. 2001. Planning and agric. subsurface drainage. *Agric. Drainage Pub. Series.* Univ. of Minesota Ext. Servives

Xevi, E., Gilley, J. and Feyen, J. 1996. Comparative study of two crop yield simulation models. *Agric. Water Manage*. **30**: 155 - 173

Xu, M. J. and Eckstein, Y. 1995. Use of weighted least-squares method in evaluation of the relationship between dispersivity and field-scale. *Ground Water* **33** (6): 905 – 908.

Yeo, A. R. 1999. Predicting the interaction between the effects of salinity and climate change on crop plants. *Horticultural Science*, **78**: 159 – 174.

Yurtseven, E., Kesmez, G. D. and Ünlükara, A. 2005. The effects of water salinity and potassium levels on yield, fruit quality and water consumption of a native Central Anatolian tomato species (Lycopersicum esculentum L.). *Agric. Water Mange.*,**78**: 128 – 135.

Zhang, D. F. and Wang, Sh. J. 2001. Mechanism of freeze-thaw action in the process of soil salnization in northeast China. *Environmental Geology,* **41**: 96 - 100

Zheng, C. and Wang, P. P.1999. MT3DMS: A modular three-dimensional multispecies transport model for simulation of advection, dispersion, and chemical reaction of contaminants in groundwater systems; documentation and user's guide. *Contract Report SERDP-99-1*. USACE.

Zucker, L. A. and Brown, L. C. (eds) 1998. Agric. Drainage: Water quality impacts and subsurface drainage studies in Midwest. *Ohio State Univ. Agric. Bulletin 871*.