LEACHING OF EXCESS SALTS FROM THE ROOT ZONE OF APEDAL SOILS

by

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"I am careful not to confuse excellence with perfection.

Excellence, I can reach for, perfection is God's business."

Michael J. Fox.

Dedicated to Nadia

"No one cares how much you know, until they know how much you care"

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DECLARATION

I hereby declare that this dissertation hereby submitted for the Magister Scientiae Agriculturae degree at the University of the Free State, is my own work and has not been submitted to any other University.

I also agree that the University of the Free State has the sole right to publication of this dissertation.

Signed:

Johannes Hendrikus Barnard

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ABSTRACT

In South Africa a huge amount of energy was spend on irrigation research over the past two decades, mainly to optimise water application in order to prevent crop water stress. In the quest to conserve water for transpiration, researchers tended to neglect the importance of drainage or percolation, which eventually results in the accumulation of salts in the root zone. Salts also accumulate in the root zone where shallow water tables are present. Farmers along the Lower Vaal River expressed their concern about yield losses induced by build-up of salts in the root zone. The detrimental affect of salinity on field crops are extensively reported in the literature and the only way to address the problem is through leaching. Sustainable utilization of these saline or potential saline soils depends on adequate natural drainage or artificial drainage systems, which ensures a net downward flux of water and salts below the root zone for optimum development and functioning of roots. This dissertation focuses mainly on the management of salts in the root zone of apedal soils.

The research was conducted on two soil types (Clovelly and Bainsvlei) reconstructed in 5000 litre lysimeters on the experimental farm, near Bloemfontein, of the Department of Soil, Crop and Climate Sciences (University of the Free State). A total of 30 lysimeters, 15 per soil type arranged in two parallel rows under a moveable rain shelter were used. It was assumed that the artificially prepared soil profiles are stable because more than 10 cropping cycles were completed before the commencement of this experiment.

The first aim of Chapter 3 was to address the effect of irrigation water salinity on the accumulation of salt in the root zone under shallow water table conditions. A total of 612 mm was irrigated with irrigation water salinity treatments that varied between 15 and 600 mS m^{-1}. Results showed that in the absence of drainage, salts will accumulate in the root zone at an alarming rate. In fact, salinity of the soil water almost doubled with respect to that of the irrigation water during only one growing season. These various saline profiles were used to characterise the impact of soil water salinity on the hydraulic characteristics of the two soils under investigation. After saturation of the profiles, drainage curves were *in situ* determined by allowing water to drain freely from the profiles for approximately a month. These drainage curves revealed that the initial soil water salinity did not significantly influence the hydraulic characteristics of both soils. It was possible to quantify the amount of salt removed

during a drainage cycle. Although both soils are apedal, the two soils differed markedly in their discharge rates and amounts.

Chapter 4 had focused on quantifying the pore volume of water required to leach excess salts from the profiles. It was found that piston flow can describe the leaching process, because one pore volume of drainage was sufficient to remove 100% of the excess salts, irrespective irrigation water salinity or soil water salinity. The results also showed that it is more efficient to remove 80% of excess salts in stead of 100%. On freely drained soils it is therefore possible to effectively and efficiently manage the salinity level of the root zone through controlled irrigation in excess of crop water demand, when necessary.

Complex dynamic models are helpful in understanding the nature and complexity of solute movement in soils, but unfortunately they are not widely used by irrigators and managers. The final objective (Chapter 5) was to derive a simple model capable of estimating the depth of water required to remove excess salts from the root zone. The non-linear exponential association ($y = a \{1- \exp -b\ x\}$) of the *in situ* determined leaching curves provided the best mathematical description of the fraction of excess salts removed in relation to the depth of leaching water required per unit depth of soil. Verification of the proposed model showed that it is possible to accurately estimate the leaching requirement for effective and efficient management of root zone salinity in apedal soils. It was recommended that the proposed model should be expanded to include more soil types.

OPSOMMING

In Suid Afrika is groot hoevelheid energie oor die afgelope twee dekades aan navorsing oor besproeiingskedulering spandeer, hoofsaaklik om watertoediening te optimiseer sodat waterstremming by gewasse verhoed kan word. In die strewe om meer water vir transpirasie beskikbaar te stel, het navorsers die belangrikheid van dreinering of perkolasie agterweë gelaat. Die fyn skedulering het daartoe gelei dat soute onder besproeiing in die wortelsone akkumuleer. Soutakkumulasie vind ook plaas waar vlak watertafels voorkom. Boere langs die benede Vaal Rivier het hul sorg uitgespreek oor oesverliese weens soutakkumulasie in die wortelsone. Die nadelige effek van versouting is wyd in die literatuur aangeteken en daarvolgens is die enigste wyse om die probleem op te los, loging. Die volhoubare benutting van versoute of potensieële versoute gronde, hang van die teenwoordigheid van natuurlike of kunsmatige dreinering af. Dreinering veroorsaak ‘n afwaardse beweging van water en soute verby die wortelsone wat optimale groeitoestande vir plantontwikkeling skep. Hierdie studie fokus grootliks op die bestuur van soute wat in die wortelsone van apedale gronde voorkom.

Die navorsing is op twee gronde (Clovelly en Bainsvlei) gedoen. Die gronde is geherkonstrueer in 5000 liter lisimeters wat op die proefplaas van die Departement Grond, Gewas en Klimaat Wetenskappe (Universiteit van die Vrystaat) geinstalleer is. ‘n Totaal van 30 lisimeters, twee parallele rye van 15 lisimeters elk per grond tipe, is onder ‘n bewegende reënskerm uitgelê. Dit is aanvaar dat die gronde in die lisimeters stabiel is omdat meer as 10 gewasse voor die aanvang van die experiment daarin verbou is.

Die eerste doelwit (Hoofstuk 3) was om die effek van sout akkamulasie in gronde afkomstig van besproeiingswater onder toestande van vlak watertafels, te ondersoek. ‘n Totaal van 612 mm besproeiing is met soutinhoude wat vanaf 15 tot 600 mS m^{-1} wissel toegedien. Die resultate het aangetoon dat onder toestande van onvoldoende dreinering, soute in die wortelsone teen ‘n verontrustende tempo akkumuleer. Die geleivermoë van die grondwater het oor een seisoen amper verdubbel in vergelyking met die elektriese geleivermoë van die besproeiings water wat gebruik is. Hierdie soutprofiele is gebriuk om die impak van grondwater-versouting op die hidrouliese einskappe van die genoemde gronde te bestudeer. Na versadiging van die profiele is, *in situ* dreineringskurwes bepaal deur die water oor ‘n periode van ‘n maand vrylik vanuit die grond te laat dreineer. Hierdie dreineringskurwes het aangetoon dat die grondwater-versouting nie die hidrouliese einskappe van die gronde

beinvloed het nie. Dit was moontlik om die hoeveelheid soute wat tydens een dreineringsiklus geloog het, te kwantifiseer. Alhoewel beide gronde apedaal is, het die logingstempo- en hoeveelheid merklik van mekaar verskil.

In Hoofstuk 4 is daar hoofsaaklik gekonsentreer op die kwantifisering van die porievolume water wat benodig word om oortollige soute vanuit die profiele te loog. Daar is gevind dat suiervloei die logingsproses die beste beskryf, omdat een porievolume water voldoende was om 100% van die oortollige soute te verwyder. Die resultate het ook aangetoon dat dit meer waterbesparend is om 80% van die soute, instede van 100%, te verwyder. Op goed gedreineerde gronde is dit moontlik om die soutinhoud van die wortelsone deur middel van beheerde oor-besproeiing effektief en doeltrefend te bestuur, sonder dat gewaswaterstremming voorkom.

Dinamiese modelle is nuttig om die kompleksiteit van soutbeweging in gronde te verstaan. Hierdie modelle word egter nie algemeen deur besproeiingsboere- en bestuuders gebruik nie. Die finale doelwit (Hoofstuk 5) was om ‘n eenvoudige model te ontwikkel wat die hoeveelheid water wat benodig word om oortollige soute vanuit die wortelsone te loog, te bereken. So ‘n model is afgelei vanaf *in situ* bepaalde logingskurwes. Die nie-lineêre eksponensiale funksie (y = a {1- exp –b x}) het die beste wikundige passing tussen die fraksie oortollige soute verwyder en die hoeveelheid logingswater per eenheid gronddiepte gegee. Verifikasie van die voorgestelde model het aangetoon dat dit moontlik is om die logingshoeveelheid vir effektiewe en doeltreffende bestuur van soute in apedale gronde te voorspel.

CHAPTER 1

INTRODUCTION

1.1 General

The global demand for food and agricultural produced raw materials makes the further study and optimal use of the resources, water and soil, on the earth imperative and urgent. In science and politics the opinion prevails that the soil currently being used for agriculture, can supply not only the recent demand of mankind, but must fulfill all future food requirements of an ever growing population. In order to meet those requirements, the further study and optimal utilisation of water and soil resources must be given paramount importance, especially water quality and soil forming processes that are associated with water and land degradation. One of these processes of soil degradation is the accumulation of salt (salinization), which leads to soil degradation especially in soils with an impermeable layer within or below the root zone (Szabolcs, 1989).

The importance of irrigation in the world's agriculture has rapidly increased in the past decade or two resulting in lower food prices, higher employment and more rapid agricultural and economic development. Irrigation speaks for itself in terms of increased crop production. But the question remains, how sustainable is the irrigation schemes. History showed us that irrigation failed in many regions, probable because the technology and knowledge at the time was incapable of coping with the problems created. One of the biggest problems in the past and today are salt accumulation making the soil unsuitable for crop production. Secondary salinization is predominant in arid and semi-arid regions. The countries affected by this phenomenon include; the United States of America, Argentina, Brazil, Chile, Peru, Australia, Thailand, China, India, Pakistan, Iran, Iraq, Turkey, Syria, Egypt and Spain. According to Ghassemi *et al*. (1995) 20% of the worlds irrigated lands are salt affected, with the United States, Pakistan, Iran, Egypt and Argentina having the highest share of salt-affected to irrigated land. In South Africa it was estimated that 8.9% of the irrigated area is affected by secondary salinization (Ghassemi *et al*., 1995).

Salinization of irrigated soils is mainly caused by irrigating in excess of crop water demand, leakage from canals and storage dams, irrigation of unsuitable soils and deteriorating irrigation water salinity.

Although water on earth is abundant, only 1% of all water is available for human use. The rest lies in the ocean, seas and glacial ice. Agriculture is a major user of fresh water with a world average of 71% of all water use. The growing demand for water by industrial and mining sectors makes the management and conservation of water resources therefore essential. This increasing demand (while water resources are limited) must ultimately lead to the re-use and recycling of available water resources. In many parts of the world this is already happening, where field drainage and industrial and domestic wastewaters are re-used and recycled for irrigation (Ragab, 2002). The increased use of marginal water enhances the change of salinization of irrigated soils. According to Stander (1987) (as noted by Moolman *et al.*, 1999) the salinity of South African's water resources, with specific emphasis on the total salt content, is steadily albeit slowly, increasing. This is especially true of rivers and storage dams situated in the semi-arid south-western and south-eastern parts of South Africa (Fourie, 1976). Du Preez *et al.* (2000) found a decline in water quality along the lower Vaal River and concluded that at the current rate there will be in 50 years time a significant increase in irrigation water salinity, which will in turn result in an increase in soil salinity.

Salinity is also often linked with the rise of water tables resulting from irrigating in excess of crop water demand and poor drainage. High water tables frequently results in soils from most irrigation schemes to become saline and water logged before their full potential are reached. It is estimated that 20% (260 000 ha of the 1.3 million ha irrigated) of irrigated soils in South Africa have shallow water tables in or just below the rooting depth. Shallow water tables are normally an indication that salinization is active to varying degrees in these soils (Backeberg *et al.*, 1996).

Investigations on the accumulation of salts in soil are divided into two categories. Firstly those that inhibit the toxic effect of the salt without removing them from the soil and secondly those that try to eradicate the problem by removing (leaching) the salt from the soil. It was the latter that was found to be more successful, and in the past a major effort was devoted to the latter approach (Letey, 1984). It is clear that secondary salinization is a major problem and an effort must be made to improve irrigation management on farms. Poor management of irrigated soils will inescapably lead to the build up of salts in the root zone. The effects of salinity in soils results in reduced crop growth and in severe cases even crop failure.

1.2 Motivation and objectives

The sustainable utilization of saline soils depends heavily on adequate natural or artificial drainage, to ensure a net downward flux of water and salts for optimum development and functioning of roots.

On-farm drainage strategies are influenced by many processes related to water and solute movement. Basic knowledge of the processes as well as the factors that influence it is important for formulating strategies on salt removal and disposal. The objective of Chapter 2 will be to review literature on the processes involved in solute transport and the factors affecting salt removal from the root zone.

The main aim of this study is to focus on removal of excess salts from the root zone of saline apedal soils. Although sodic soils are excluded from the scope of this study, it is still regarded as an important component, mainly due to the structural breakdown of soils and a corresponding loss in hydraulic conductivity (Van der Merwe, 1973). The two soils that will be studied represent a deep Clovelly and Bainsvlei soil types (Soil Classification Working Group, 1991) which occur abundantly in the irrigated Orange and Vaal River systems which is one of the largest irrigation systems in South Africa. These soils also tend to form water tables in lower lying landscapes, where irrigation in excess of crop water demand is practised. Chapter 3 will therefore address the effect of irrigation water salinity on soil salinity in the absence of freely drained conditions, and its impact on the drainage characteristics of apedal soils.

Irrigating scheduled to meet the crop water demand leads to the accumulation of salts, especially with saline irrigation water in conjunction with overhead irrigation systems, such as centre pivots and linear irrigation systems. In Chapter 4 an attempt will be made to quantify the pore volume of water required to leach excess salts from various saline soils with water of a constant salinity under unsaturated conditions. Removing all of the excess salts will not be entirely rational in terms of managing root zone salinity.

Ultimately a proper salinity management model should address all the different factors affecting salinity, it's effect on crop growth and the depth of leaching required with the purpose of controlling groundwater, stream flow and farmland salinization. Chapter 5 will focus on the development of an easy applicable empirical model capable of estimating salt removal from various saline apedal soils, irrigated with water of various salinities in order to effectively and efficiently manage root zone salinity.

The main purpose of this study was to supply additional information in order to contribute towards the understanding and application of the leaching component of the Water Research Commission funded project 1359/1/06, "Effect of irrigation water and water table salinity on the growth and water use of selected crops".

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The simultaneous transport and interaction of solutes and water is essential for soil fertility, through the supply of nutrients in the root zone, and the prevention of soil salinity and alkalinity (Hillel, 1998). In the past processes involving solutes were considered to belong to soil chemistry alone and outside the treatise of soil physics. Modern research however came to recognize the importance of disciplines that are in fact complimentary and overlapping, which should allow a better understanding of the interactive phenomena in the environment. Salinization of irrigated soils is closely related the movement of water which is responsible for the movement of salts. The flow processes can be divided into the unsaturated root zone, overland flow and water table or groundwater movement (Connell *et al.*, 1999). The aim of this chapter is to review literature on the processes involved in solute transport, and the factors affecting salt removal from the unsaturated root zone.

2.2 Water and salt balance

The unsaturated root zone is the most important region for agriculture because it contains the majority of roots and all the soil components necessary for plant growth. The hydrological processes that influence crop growth, yield and deterioration of soil and water resources can be described in terms of the soil water balance. The water balance (Equation 2.1) of the unsaturated root zone, for a given time interval, is the following:

$$\Delta W = (I+P) + G - ET - D \pm R \qquad (2.1)$$

where $I + P$ = amount of irrigation (I) and precipitation (p) measured in a rain gauge (mm)
G = capillary rise from the water table (mm)
ET = actual crop evapotranspiration (mm)
D = drainage or deep percolation below the deepest roots (mm)
ΔW = variation of water stored in the root zone (mm)
R = runoff (-) or runon (+) of surface flow water (mm).

Each of the components of the water balance can be multiplied by its salt concentration to give the salt balance of the root zone. A simple salt balance is obtained if salts added by fertilizers, precipitation, dilution and uptake by plants are considered negligible (Beltran, 1999):

$$\Delta S = Ic_i + Gc_g - Dc_d \pm Rc_r \tag{2.2}$$

where c_i = salt concentration of the irrigation water (mg L^{-1})

c_g = salt concentration in the capillary water (mg L^{-1})

c_d = salt concentration of the drainage water (mg L^{-1})

c_r = salt concentration of the surface flow (mg L^{-1})

ΔS = variation of salt content in the root zone (mg L^{-1}).

From the water balance it is clear that when the contribution of salts due to irrigation, surface flow and capillary water exceeds the loss of salt that is leached by percolation water, the salt content in the root zone will increase. The amount of water applied for leaching must be optimized to allow for leaching without raising the water table. In irrigated soils this optimization can seldom be achieved and maintained in the long run, in the absence of artificial drainage systems. Leaching of salts from the root zone without adequate drainage is doomed to fail. As obvious as it seems, this principle is often ignored in irrigation areas, which makes it impossible to sustain irrigation in the long run. Such areas will sooner or later be abandoned. Hillel (2000) emphasized that this is already happening in great and small river valleys from the Indus in Pakistan to the Murray-Darling in Australia and the San Joaquin in California, to mention just a few.

Water movement and retention within the soil is an important component of agricultural and environmental processes such as drainage (Zeleke, 2003). The rate at which water flows through the soil depends on fundamental soil hydraulic properties. The relationship between volumetric soil water content and matrix potential describes soil water retention and hydraulic conductivity. Solute transport in the unsaturated root zone depends on the hydraulic conductivity which is strongly influenced by the geometry of the water filled pores.

2.3 Processes of solute movement

The classical theory of solute transport processes are described in most of the soil physics handbooks (Jury *et al*., 1991; Marshall *et al*., 1996; Hillel, 1998; Jury & Horton, 2004). According to the miscible displacement theory the primary transport of salt in soil is through the flux of a dissolved solute and occurs in response to two processes, convection and diffusion. Convection is where salts are transported during the mass flow of water through fluxes from wet to drier soil. Occurring simultaneously is diffusion defined as salt movement in response to a gradient in the salt concentration of the soil solution. The relative importance of each of these processes will vary as the magnitude of the water flux varies. When the two processes of solute movement is added it gives the total solute flux J_l.

2.3.1 Convection

According to Jury & Norton (2004) the bulk flow or convective transport of a solute (J_{lc}) may be written as:

$$J_{lc} = Jw\ Cl \tag{2.3}$$

where Jw = the water flux
Cl = the solute concentration.

Equation 2.3 is based on a macroscopic approach and does only take into consideration the mean pore water velocity over many soil pores (Hillel, 1998). It does not represent the actual flow paths, which curve around solid particles and air space. The flow velocity along the different flow paths differs and salt ions can diffuse from higher concentrations in slow moving streams into the faster flowing less concentrated soil solution. This process is called hydrodynamic dispersion. Solute convection can then be described by Equation 2.4:

$$J_{lc} = Jw\ Cl + Jlh \tag{2.4}$$

where Jlh = the hydrodynamic dispersion flux.

When the soil is near saturation, convective velocity will be high which means that hydrodynamic dispersion will exceed the diffusion component of solute movement. During unsaturated conditions, hydrodynamic flow ceases and diffusion becomes the dominant mechanism in solute movement (Herald, 1999).

2.3.2 Diffusion

Diffusion results from the random thermal motion of ions, atoms or molecules. It is well known that all molecules will move from a high to a low concentration until the solution is uniform. The speed with which equilibrium is reached will depend on the concentration gradient (Herald, 1999).

The one-dimensional process of solute diffusion can be calculated from Fick's first law, Equation 2.5 (Jury *et al*., 1991; Nye & Tinker, 1977).

$$J_{ld} = - dif_w \, dCl / dx \qquad (2.5)$$

where J_{ld} = the liquid diffusion flux or transport of solutes
dif_w = the diffusion coefficient of a solute in water
dCl / dx = the concentration gradient across the section.

It only accounts for saturated steady state conditions where the salt concentration remains constant with time. The diffusion coefficient is the slope of the relationship between, J_{ld} and dCl / dx, which can be measured experimentally. Rewriting Equation 2.5 for unsaturated conditions gives Equation 2.6:

$$J_{ld} = -dif_s \, \Theta \, dCl / d\,x \qquad (2.6)$$

where Θ = volumetric soil water content
$-dif_s$ = diffusion coefficient of a solute in soil.

During unsaturated conditions the volume of water (θ) available through which diffusion can take place is reduced, so Ds will be smaller than Dw. With drying there will be less water for salt to travel through so the actual value of Ds will reduce further. Mahtab *et al*., (1971) (as cited by Herald, 1999) concluded that Ds would increase linearly with an increase in the water content of the soil. Since air as well as solid particles forms barriers to liquid diffusion, a liquid tortuosity factor must be included to account for the increased path length of the diffusing solute in soil. The liquid diffusion flux is then formally written as Equation 2.7:

$$J_{ld} = -Dw\ f\ \Theta\ dCl / dx$$
$$= -dif_s\ dCl / dx \qquad (2.7)$$

where f = tortuosity factor.
dif_s = $Dw\ f\ \theta$

2.3.3 The convection-dispersion equation

These two processes of solute transport through soil are often called convective-dispersive transport and occur under the following conditions: (i) the soil is homogeneous through the volume in which solute transport occurs and (ii) the time for solutes in stream tubes of different velocity to mix is short compared to the time required for solutes to move through the soil by means of convection (Jury *et al.*, 1991). For this reason the hydrodynamic dispersion flux can be described with an equation that is mathematical identical to the diffusion flux (Equation 2.8):

$$Jlh = -Dlh\ dCl / dx \qquad (2.8)$$

where Dlh = the hydrodynamic dispersion coefficient.

It has been observed that the hydrodynamic dispersion flux is proportional to the pore water velocity. The total flux of dissolved solute in the convection-dispersion model (J_l) can then be written as Equation 2.9:

$$J_l = Jw\ Cl - Dlh\ dCl / dx - dif_s\ dCl / dx$$
$$= -De\ dCl / dx + JwCl \qquad (2.9)$$

where De = the effective diffusion-dispersion coefficient.

When the one dimensional solute conservation equation (Jury *et al*., 1991) is combined with Equation 2.9, and where the solute vapor (Jg) phase is taken as negligible, the solute transport equation may be written as Equation 2.10:

$$d/dt\,(p_b C_a + \Theta Cl) = d/dx\,(De\ dCl/dx) - d/dx\,(JwCl) - r_s \qquad (2.10)$$

where dt = the change in time

p_b = the soil bulk density

C_a = the absorbed solute concentration

Θ = the volumetric water content

Cl = the dissolved solute concentration

r_s = the reaction rate per volume.

2.3.4 Transport of chemicals through soil

The processes of solute movement in the soil describe extremely soluble, inert ions like chloride, best. In reality the soil water contains many ions that contribute to the osmotic potential of the soil solution, and reactions such as precipitation, dissolution and cation exchange can affect the overall chemical concentration of the soil solution. Some salts such as calcium carbonate are not especially soluble in water and when significant quantities of these salts are concentrated around plant roots, the salts precipitates out of the solution. Cation exchange can also alter the amount of calcium in solution and change the extent of precipitation or dissolution (Jury *et al*., 1991). Marshall *et al*., (1996) explained the importance of these various chemical processes by means of simple breakthrough curves, as described in Figure 2.1.

Line B in Figure 2.1 indicates the transport of an inert non-sorbet solute of constant concentration Co, flowing through a saturated column of a nonaggregated soil. When a liquid varying in composition and concentration is introduced into a soil column and the outflow's composition is changing over time, as the existing soil solution is displaced and replaced by the new one, it is called miscible displacement. Figure 2.1 express the number of pore volumes of drainage fluid which passed through the plane of measurement of the concentration of solute C. For example, in a saturated soil, line B indicates that a solute fraction of 0.5 or 50% (C / Co = 0.5) will be displaced at a cumulative flow of one pore volume. In the absence of dispersion an abrupt change will occur at the outlet end as the previous solution is pushed out by the arrival of the new solution, which is described as Piston flow which is indicated by the vertical line P in Figure 2.1.

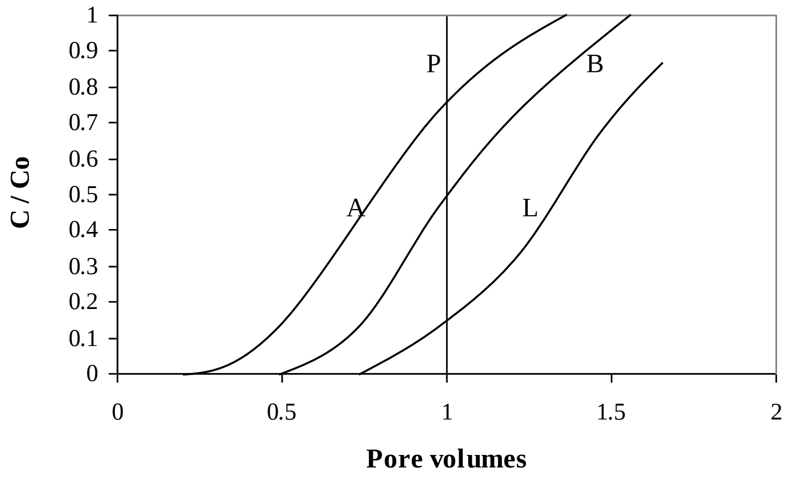


Figure 2.1 Miscible displacement or breakthrough curves.

When an anion is repelled from a colloid surface, as indicated be line A, it will result in the anion leaching faster than would be the case for an inert nonionic solute. In contrast, line L indicates the effect of adsorption when cations are adsorbed which delay the arrival of a change in solute concentration, compared to a non-adsorbed solute.

There are a number of other aspects of chemical transport that can be important. During transport chemicals in the leaching solution may react with exchangeable ions in the soil to from other products with different solubilities and adsorption characteristics. Some chemicals are volatile and transport in the gaseous and liquid phases may be influenced significantly (Marshall *et al*., 1996).

Chemicals can also flow through larger pores or cracks that commonly exist in field soils which are called macropores. These large pores have a profound effect on water and solute transport through soils. The amount of solute that may be transported in macropores and how deeply such transport may continue depends on the continuity and geometry of water-filled macropores. Results by Allaire-Leung *et al*. (2000) illustrated that macropore continuity is an important variable and should be included in modelling chemical transport through macropore soils. The importance of macropore continuity seems to increase with an increase in the adsorption characteristics of the solute. The presence of another macropore can lead to interactions between macropores and in turn enhance the importance of macropores.

Different hydraulic characteristics of soil layers are a major cause of wetting front instability which causes a substantial change in the speed and depth of solute transport (Marshall *et al*., 1996). The acceleration of flow due to any type of heterogeneity in the soil is referred to as preferential flow. In reality laboratory results of solute transport in soil columns are not totally representative of field conditions because of the heterogeneity of natural soils. Schoen *et al*. (1999) investigated solute movement in a large almost undisturbed soil lysimeter where the observed spatial variability in concentration and water content suggested that preferential flow occurred.

This very limited survey, of the complex processes involved in solute movement, it is obvious that there are many factors that will influence salt removal from the root zone.

2.4 Factors affecting salt removal from the root zone

2.4.1 Effect of soil salinity on hydraulic conductivity

Irrigation water varies greatly in salinity and has an immense influence on soil salinity. The quality of irrigation water can be classified according to the sum of the total dissolved salts and the sodium adsorption ratio (SAR). The electrical conductivity (EC, mS m^{-1}) is a measure of the ability of water to conduct an electrical current, due to the presence of ions carrying a charge. The EC is therefore directly proportional to the total dissolved salts (TDS, mg L^{-1}) in water since the total as well as the relative salt concentration influence the EC of water. The EC of natural water is related to TDS by a conversion factor ranging from 5.5 to 7.7. The exact value however depends on the ionic composition of the water (Du Preez *et al.*, 2000). According to Richards (1954) a conversion factor of 6.4 can be used. The SAR is calculated from the sodium, calcium and magnesium concentrations in the water.

A common feature of soils irrigated with low quality water is an increase in the total dissolved salts or for that matter salinity (Singh *et al*., 1992; Tedeschi & Dell' Aquila, 2005). The major solutes comprising dissolved salts are the cations Na, Ca, Mg and K and the anions Cl, SO_4, HCO_3, CO_3 and NO_3. For saline soils the electrical conductivity of the saturated extract

(EC_e) must be greater than 400 mS m^{-1} and the SAR ratios smaller than 15. Saline-sodic soils has an EC_e > 400 mS m^{-1} and a SAR < 15 and sodic soils an EC_e < 400 mS m^{-1} and a SAR > 15 (Gupta & Abrol, 1990). De Villiers (2003) classified salt-affected soils in South Africa as non-saline when the EC was lower than 200 mS m^{-1}, slightly saline when the EC was between 200 and 400 mS m^{-1} and moderately saline when EC was between 400 and 800 mS m^{-1}. Sodic soils was classified as soils with EC lower than 400 mS m^{-1}, ESP (exchangeable sodium percentage) higher than 15 and a pH higher than 8.5. Saline-sodic soils have an EC of more than 400 mS m^{-1} and an ESP of more than 15. When pH is higher than 8.5, the soil is classified as alkaline saline-sodic and when the pH is lower than 8.5, as non-alkaline saline-sodic.

Sodicity is a condition caused by sodium ions adsorbed on the electrostatically charged clay particles. Soils with high exchangeable sodium levels tend to swell and disperse excessively (Bohn *et al*., 1985), especially when combined with low electrolyte concentrations in the soil solution (Mace & Amrhein, 2001). Widely accepted indices for characterizing sodicity are the ESP of the exchange complex and the SAR of the soil solution. The SAR is the ratio of the sodium ion concentration to the square root of the average concentration of the divalent calcium and magnesium ions. Richards (1954) established a relationship between SAR of the soil solution and ESP of the exchange complex from numerous soil samples in the Western states of America to be:

$$ESP = 100[-a + b\,(SAR)]/\{1+[-a+b(SAR)]\} \qquad (2.11)$$

where a = 0.0126

b = 0.01475.

When the ambient soil solution is highly concentrated the tendency of adsorbed cations (Na) to diffuse outwards is suppressed. This is because there is a weaker osmotic gradient between the region of adsorption ions close to the particles and the ambient solution further from the particles. Various chemical, physical and biological processes in soils can cause changes in hydraulic conductivity. The primary decline in hydraulic conductivity in soils is generally attributed to aggregate swelling and clay dispersion (Sumner, 1993).

The threshold salt concentration concept was introduced by Quirk & Schofield (1955) in an effort to quantify the affects of various exchangeable sodium percentages and total electrolyte concentration of the soil solution on hydraulic conductivity. It is defined as the level to which the salt concentration of the soil solution must be decreased to give a 10 to 15% reduction in hydraulic conductivity at various ESP levels. From the work of McNeal & Coleman (1966), presented in Figure 2.2, it is obvious that a decrease in salt concentration will cause a decrease in hydraulic conductivity, which is also correlated to the ESP of the soil solution. It is therefore possible to maintain the permeability of a soil, irrespective of the ESP, by using a sufficiently strong electrolyte concentration.

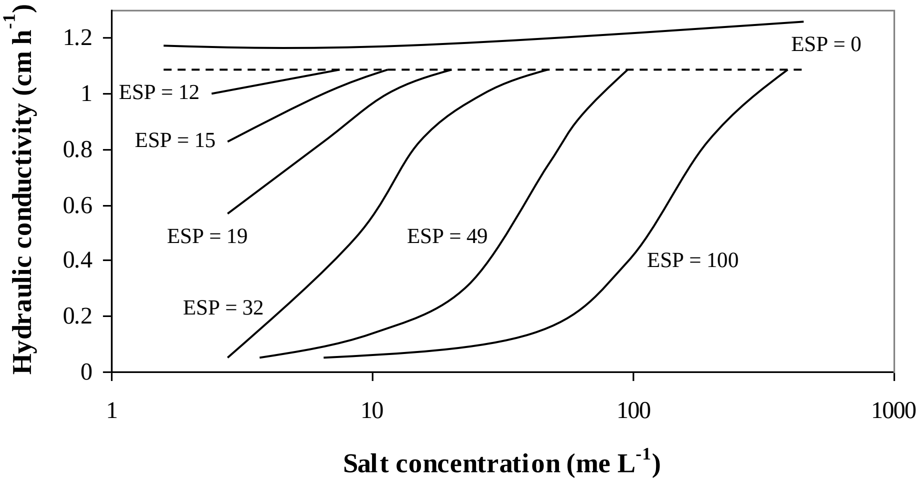


Figure 2.2 Hydraulic conductivity of a sandy loam soil as related to total salt concentration of the soil solution and to the soil's exchangeable sodium percentage (McNeal & Coleman, 1966).

Van der Merwe (1973) covered the effect of electrolyte concentration and exchangeable cations on hydraulic conductivity of soils in an excellent review. He concluded that clay mineralogy provided a quantitative explanation for a decrease in the hydraulic conductivity of soils to be anticipated under low salt, high sodium conditions. Soils that are high in either kaolinite and sesquioxides or in amorphous minerals are quite stable under such conditions whereas soil containing high percentages of montmorillonite, and especially soils containing a clay fraction dominated by 2:1 layer silicates, appeared to be most labile with respect to its hydraulic conductivity.

Clay type and content in the soil is therefore probably the most important aspects to consider when assessing sodium affected soils. For a 2:1 clay type the relative hydraulic conductivity will decrease markedly with an increase in clay content, particular at low salt concentrations. It was found that the degree of saturation of Ca, Mg and Na on the exchange complex has also a profound affect on the physical condition of clayey saline – alkali soils (Van der Merwe & Burger, 1969). The single effects of Ca and Mg saturation on the physical condition of these soils were almost identical to each other, whereas the Na saturated soils exhibited an extremely poor physical condition. This is obviously true when it is considered that it is primary Na on the exchange complex that causes swelling and dispersion of clay particles. Combinations of Ca-Na and Mg-Na solutions affected the physical properties differently. The Mg-Na soil was in a poorer physical condition than the Ca-Na saturated soil.

2.4.2 Soil type

Generally control of salinity is accomplished easier in permeable soils. Coarse textured soils are more permeable than fine textured soils. The processes involved in the transport of chemicals through soils illustrate that water movement through coarse and medium textured soils, to be rather uniform with the displacement of a resident soil solution by miscible displacement. Unfortunately the same do not apply to clayey soils. In clayey soils whether saline, saline-sodic or sodic, macropore flow is of vital importance because most of the water movement takes place through these pores. Indirect evidence of macropore flow was found where leaching of salt from heavy clay subsoil occurred even though the soils remained unsaturated (Tanton *et al*., 1995).

Results from Armstrong *et al*. (1998) showed that in saline-sodic clay topsoils, aggregate size, storm duration and storm frequency directly influence the rate of leaching from the topsoil under conditions of minimum tillage. Aggregate size was found to be the most important factor influencing the rate of leaching. When 200 mm of drainage occurred 71.5, 61.5 and 51.5% of the soluble salts had been leached from 7.5, 25 and 45 mm mean diameter aggregates respectively. As the aggregate size decreased rainfall depth and frequency had less of an effect on leaching.

Nielson & Biggar (1961) suggested that leaching soils at water contents below saturation (intermitted sprinkle) can produce more efficient leaching than under continuous flooding. At a high water application rate, a large proportion of the water falling on an unsaturated clay layer is drained before the soil becomes saturated. With a lower application rate drainage did not begin until the aggregates had become fully saturated due to the mobile water in the macropores being continuously absorbed into the micropores (Tanton *et al*., 1996). This is important because in saline clay soils virtually all of the soluble salts are contained in micropores within aggregates, and are practically impermeable in terms of gravitational induced drainage flow. Removal of salts from the aggregates will depend on the degree of salts diffusing from the interior of the aggregates to the macropores outside the aggregates. Under unsaturated flow there is more time for the salts to diffuse out of the aggregates, allowing for leaching to be more efficient.

Obviously soil characteristics are important in determining the amount of water needed for leaching. It is well known that the quantity of good quality water for irrigation in the world is limited (Oster, 1994). Much attention has therefore been devoted to the optimal quantity of water that must be applied to cause leaching. Excessive leaching will not only waste water, and cause the water table to rise but also leach essential nutrients from the root zone (Cartagena *et al.*, 1995).

2.4.3 Quantity and salinity of water for leaching

Leaching curves: A useful rule of thump is that a unit depth of water will remove 80% of salts from a unit soil depth. This is however a simplification of the leaching process because different soil characteristics and leaching practices can have a huge influence on the amount of water needed. For more reliable estimates it will be useful to conduct leaching tests on a limited area and prepare leaching curves (Abrol *et al*., 1988). Leaching curves relate the ratio of actual (C) salt content to the initial (Co) salt content in the soil to the depth of water (Dw) per unit depth of soil (Ds). Figure 2.3 shows leaching curves as influenced by different leaching practices such as continuous ponding and intermitted ponding (Hoffman, 1980).

Khosla *et al*., (1979) explained that the validity of the empirical relationship of a leaching curve is likely restricted to experimental conditions and soil salinity characteristics. They showed that one pore volume displacement resulted in 75% salt removal from a saline-sodic soil.

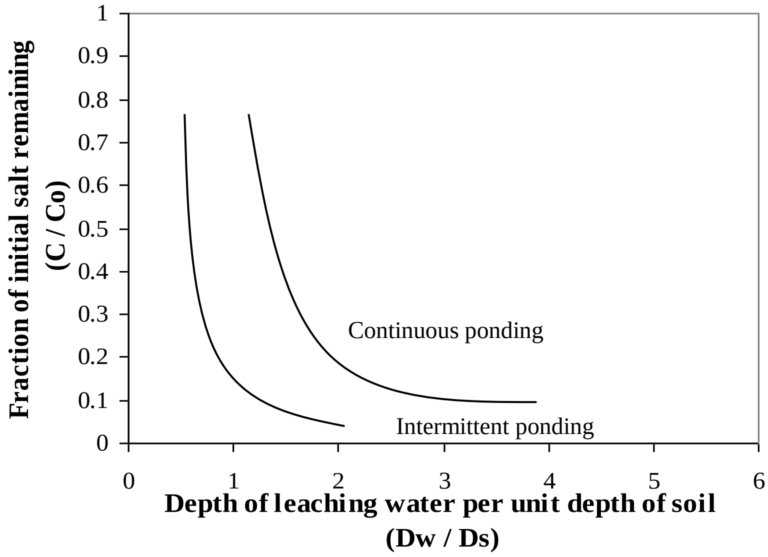


Figure 2.3 Depth of water per unit soil depth required to leach a saline soil by continuous and intermitted ponding (Hoffman, 1980).

Van der Molen (1956) removed 50% of chloride with one pore volume; while Gardner and Brooks (1957) reported a value of 1.5 pore volumes for 80% salt removal. The experimental data for the desalinization curve of Sharma & Khosla (1984) showed that 1 and 1.4 units of good and poor quality water per unit soil depth respectively were required to remove 80% of the salts from a sandy loam, saline-sodic soil. For comparable soil textural and experimental conditions much smaller quantities of water (Dw / Ds = 0.5) were found to be required by Leffelaar & Sharma (1977) (as cited by Sharma & Khosla, 1984). The lower leaching efficiency observed by Sharma & Khosla (1984) can be attributed to swelling and clay dispersion. This soil had been irrigated with highly sodic water for the last 15 to 20 years.

Leaching curves can adequately describe the amount of water required to remove salts in the soil to a predetermined level. It will however depend very much on soil characteristics and leaching conditions and should therefore be determined *in situ*.

Leaching requirement (LR): The U.S Salinity Laboratory (Richards, 1954) defined it as the fraction of irrigation water that must pass through the root zone in order to prevent mean soil salinity from rising above some specified limit. Assuming steady-state conditions of flow through, and no appreciable dissolution or precipitation of salts from the soil, and no significant removal of salts by the crop or capillary rise of salt bearing water from the water table, Equation 2.12, (Hillel, 2000) can be used to calculate a simple salt balance:

$$LR = EC_i / EC_d = D_d / D_i \quad (2.12)$$

where EC_i and EC_d = the irrigation and drainage water salinity respectively (mS m^{-1})
D_d and D_i = the depth of drainage and irrigation water respectively (mm).

The LR will depend on the salinity of the irrigation water, amount of water extracted from the root zone by the crop, and the salt tolerance of the specific crop planted. For example over the long term, the leaching requirement can be calculated with Equation 2.13 (Van Hoorn & Alphen, 1994):

$$LR_{lt} = [(ET – P)] / [(1 – f_i (1\text{-}LF)) / (f_i (1 – LF))] \quad (2.13)$$

where LR_{lt} = long-term leaching requirement (mm)
ET = crop evapotranspiration demand in the considered period (mm)
P = precipitation (mm)
f_i = leaching efficiency coefficient as a function of the irrigation water applied
LF = leaching fraction.

Leaching fraction: The equilibrium between soil salinity and the salinity of the irrigation water is a function of the ratios between the amount of water percolating beneath the root zone and the amount of irrigation water applied which mixes with the soil solution (Beltran, 1999). This ratio is called the leaching fraction:

$$LF = f_r R / f_i I \quad (2.14)$$

where f_r and f_i = the efficiency coefficient as a function of the percolating water depth R (mm) and the irrigation water I (mm).

The LF will depend on the threshold salinity level of the crop under cultivation. Different methods can be used to calculate the LF. Figure 2.4 shows the approach used by Van Hoorn & Alphen (1994). It is based on the equilibrium between the water and salt balances where water intake by roots is represented in the Figure 2.4. Water extraction decreases with depth within the root zone from 40 % of the total uptake occurring in the top quarter to 10% present in the deepest quarter. This means that the crop will receive 40% of its ET from the upper quarter of the root zone, 30% from the next quarter, 20% from the next and 10% from the lowest quarter. However, this pattern depends on rooting characteristics of crops, and its interaction with the environment.

From Figure 2.4 it is evident that an increase in irrigation water salinity (EC_i dS m^{-1}) will have to be met by a higher LF to maintain soil salinity (EC_e, dS m^{-1}) at the threshold level for the crop under cultivation (Beltran, 1999). This is in accordance with the results found by El-Haddad & Noaman (2001), who concluded that, a leaching fraction of 0.25 at high saline irrigation water was inadequate to attain the steady-state salt balance during the growth period of halophytes, although there was an increase in drainage salinity. When the LF was increased to 0.50 the situation was reversed.

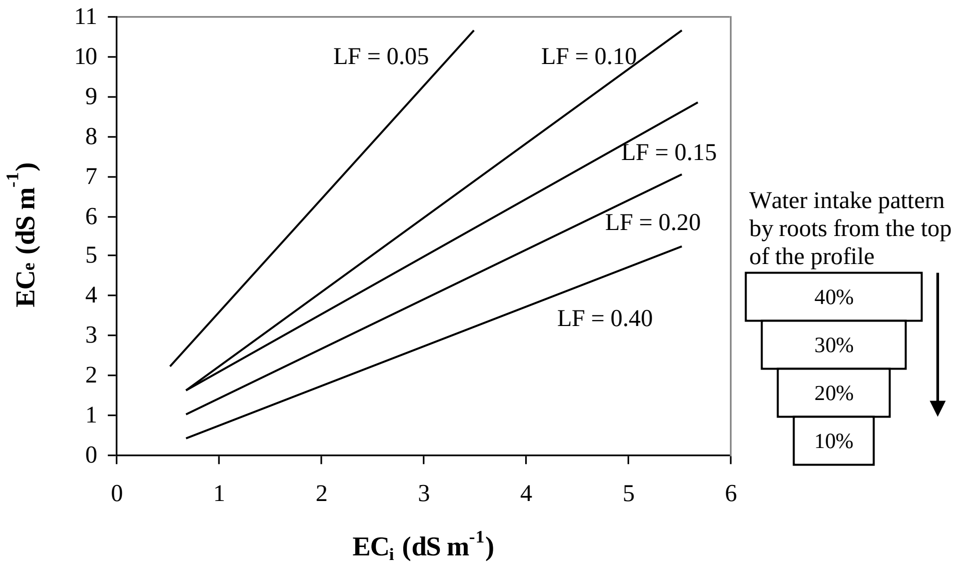


Figure 2.4 Relationship between EC_e and EC_i for different leaching fractions (Van Hoorn & Alphen, 1994).

In the presence of a high sodium concentration in the irrigation water an increase in LF will not be advisable because of the sodification hazard of the soil. Infiltration in these soils are poor and for this reason, instead of increasing leaching, it is more advisable to decrease the sodium adsorption ratio by increasing the calcium content of the irrigation water. This increase in the salt concentration will help maintain permeability of the soil and prevents dispersion of clay. When this initial stage of leaching with saline water is finished, the salinity of the irrigation water can gradually be decreased to assure that the soil is brought to the desired salinity level (Hillel, 2000).

Crop water requirements: Equation 2.13 illustrates the importance of crop water demand when calculating the leaching requirement. Calculations of water application depth for leaching should not be based on the pre-irrigation soil water content deficit and field capacity. Experiments conducted with sunflower plants by Meiri *et al*. (1977) showed that where saline and non-saline waters were used for leaching, drainage was doubled when plants were covered by plastic bags to suppress transpiration, illustrating the negative effect of transpiration on leaching fractions.

Water uptake during leaching reduced the intended leaching fraction by 51% and 42% in non-saline and saline treatments respectively. This was found to be particular true for high frequency irrigations and high transpiration rates. It is apparent that for leaching to occur successfully in the presence of crops, crop water requirements (ET) cannot be ignored. There will be an accumulation of salt if an ET smaller than 100% instead of greater than 100% is applied during the growing season of crops (Nightingale *et al.*, 1991; Garcia-Sanches *et al.*, 2003).

Soil depth and salinity: Leaching will always be effective because salt accumulation will always decrease with an increase in the LF under free drainage conditions. It was established by Rawlins & Raats, (1975) (as noted by Hillel, 2000) that the quality of irrigation water is important for effective leaching of salts from the root zone since leaching brings the salinity of the soil close to that of the irrigation water. This is true for the top of the soil profile, but as water infiltrates and moves deeper into the soil profile the leaching fraction decreases thus increasing soil salinity (Ayers & Westcot, 1985).

Although leaching will always be effective, its efficiency will greatly increase from a low to high soil salinity content. Monteleone *et al*., (2004) therefore suggested that periodic leaching should only be applied when soil salinity has reached the threshold salinity level, capable of interfering with crop yield. Saline irrigation water will therefore be effective in leaching soil with high soil salinity contents, but care will have to be taken for the fact that at the top of the soil profile soil salinity will be close to that of the irrigation water.

2.4.4 Irrigation management

2.4.4.1 Type of irrigation systems

When poor quality irrigation water is used the suitability of the irrigation method depends on the capabilities of the specific method to minimise/avoid the risks associated with the use of those waters. In what concerns salinity, risks refer to the following (Pereira *et al*., 2002):

(i) soil salinization, which relate to the easiness to leach the salts in the root zone, in relation to the capability to apply the leaching requirement evenly;
(ii) plant toxicity related to direct contact of the water with the plant leaves;
(iii) difficulties in infiltrating the applied water without excessive runoff; and
(iv) crop stress and yield reduction, due to inability to maintain adequate water availability in the soil.

The type of irrigation system used is important in applying the water needed for leaching, uniformly and effectively over the field. Sprinkle irrigation is an ideal method for irrigating frequently and with small quantities of water at a time. Leaching of salts is also accomplished more efficiently when the water application rate is lower than the infiltration capacity of the soil (Abrol *et al*., 1988). Careful consideration however will have to be taken for modern mobile sprinkle irrigation systems (centre pivots). In arid and semi-arid areas leaching of excess salts with centre pivots from the root zone is almost impossible. The reason is probable because of the high application rates at the far end of the circular fields that are required for irrigations of more than 30 mm at a time (Du Preez *et al*, 2000). These high application rates can exceed the infiltration rate of the soil which will result in runoff. Most of the modern centre pivots can also not apply that amount of water at a time especially because these systems are adapted to be more efficient for water conservation.

Drip irrigation systems cannot apply water uniformly over the field but will leach the soil under the emitter frequently. Long term use of drip irrigations may result in salt accumulation because salts tend to accumulate over the periphery of the wetted volume of soil if rainfall is insufficient to leach out such accumulations (Hillel, 2000). When subsurface drip irrigation is used the same trend also applies, salt will accumulate close to the soil surface if rainfall is not sufficient for leaching of salt to occur. Very high soil salinity levels close to the surface were recorded with dripper lines at 300 and 600 mm depths (Oron *et al*., 2002). In arid and semi-arid regions of the world like South Africa where rainfall is very low these two irrigation practices can cause salinization problems. Soil salinity under drip irrigation affect crop yield less compared to other irrigation methods (Hanson & May, 2004). This is probably because of the regular and frequent supply of water that maintains a constantly higher matric potential in the soil. It seems that drip irrigation systems is the best method of saline water application as it avoids leaf injury to plants, and maintains optimum conditions for water uptake by roots (Minhas, 1996). Drip irrigation is not widely used in South Africa for various reasons which makes flood and sprinkler irrigation that more important (Backeberg *et al.*, 1996). With these irrigation methods, irrigation management through scheduling will be of vital importance in preventing and controlling salinization of irrigated soils.

2.4.4.2 Irrigation scheduling

In traditional irrigation scheduling in semi-arid areas the water was applied in excess relative to crop requirements. Modern irrigation scheduling approaches was adjusted to meet only the seasonal crop water requirements, with the purpose of improving water conservation. This meant that there was not enough extra water for drainage discharge through leaching of salt to occur. Caballero *et al*. (2001) indicated that soil salinization will be a problem under modern irrigation scheduling, based water conservation, if occasional episodes of drainage discharge, induced by heavy rainfall do not occur. This will be difficult in low rainfall regions, necessitating leaching through the application of water in excess of crop water requirements, as has already been discussed, as an important component in irrigation scheduling. Consideration will have to be taken for shallow water tables, already mentioned, when excess salts have to be leached.

It is generally accepted that an increase in irrigation water salinity, decreases the ET of the specific crop irrigated with those waters. On the other hand, Yang *et al*. (2002) concluded that when saline irrigation water were used for irrigation, a higher irrigation frequency resulted in an higher ET which in turn resulted in higher yields. Under low-intensity sprinkling the soil never becomes saturated so a greater portion of the applied water moves through the soil matrix, producing more efficient leaching per unit volume of water infiltrated. This is very time consuming and can cause problems. The interval between irrigations will determine the water content of the soil. When poor quality irrigation water was used to irrigate barley, the weekly irrigation had a soil matrix potential between 25 and 30 cbar, whereas the biweekly irrigation ranged from 40 to 50 cbar (Al-Tahir *et al*., 1997). Poor quality irrigation water reduced the germination of barley with 6 and 16% for weekly and biweekly irrigation frequencies, respectively. This was probably due to the fact that frequent irrigations increase the total water potential which reduces the impact of water stress. Ibrahim & Willardson, (2004) emphasized that because most irrigated soils have shallow water tables, salt will accumulate in the upper profile when the irrigation interval is long. A high water table and short irrigation intervals increased the water content in the upper soil layers, lowering therefore the matrix-suction gradient between the unsaturated soil and the water table.

2.5 Conclusions

Solute movement in soil follows the basic saturated and unsaturated flow processes as described in the classical soil physics handbooks. According to the miscible displacement theory the primary transport of a solute in soil is through the flux of a dissolved solute and occurs in response to two processes, convection and dispersion. The relative importance of each of these processes will vary as the magnitude of the water flux varies. The only reliable way for removing excess salts from the root zone is through a flux of water percolating below the root zone (leaching). Soil characteristic, irrigation water salinity, irrigation systems and management practices are some of the most important factors influencing leaching of excess salts from the root zone. Basic knowledge on the movement and the factors that influence it, is important in formulating strategies on salt removal from soils and disposal. A proper management strategy is therefore needed when it comes to removing excess salts from the root zone. In order to come up with such strategies future research is needed. This research needs can be addressed according to the objectives of this study (Chapter 1).

CHAPTER 3

DRAINAGE OF SATURATED SOILS WITH DECREASING SOIL WATER SALINITIES

3.1 Introduction

The soil water balance contains drainage as one of the components determining the fate of soil water in the root zone. Capillary rise from a shallow water table may, contribute significantly towards the irrigation requirements of crops (Wallender *et al.*, 1979). It is reported that 20 to 40% of the evapotranspiration demand of different crops can be met by capillary rise from water tables at depths of 0.7 to 1.5 m (Gharmarnia *et al.*, 2004). A corresponding 30 to 65% reduction in irrigation requirements of crops was found under conditions where shallow root accessible water tables are present (Ehlers *et al.*, 2003). Drainage could also be regarded as a net loss of water for crop production. Water that percolates deeper than the root zone does not make a contribution to production for that specific season. In semi-arid regions of South Africa 1 to 36% of the annual rainfall can be lost through deep percolation depending on soil type, water content of the soil and total rainfall (Bennie *et al.*, 1994).

Managing percolation in irrigation is an important aspect which determines the sustainability of any irrigation scheme. Under low salinity conditions percolation should be minimized as uncontrolled irrigation eventually lead to waterlogging, depending on the depth of the impermeable soil layer beneath the root zone. It is estimated that 20% of irrigated soils in South Africa have shallow water tables in or just below the rooting depth of annual crops (Backeberg *et al.*, 1996), and are associated with salinization of irrigated soils (Ehlers *et al.*, 2006). These water losses can truly be regarded as unproductive. The field water capacity concept, namely the wetness of an initially wetted zone, two days after infiltration, was introduced for managing percolation as a common working definition. Hillel (1980) criticised the general use of the concept because the redistribution process is in fact continuous and exhibits no abrupt breaks or static levels. Although the drainage rate decreases constantly the process continues and equilibrium is approached, if at all, only after long periods. Ratliff *et al.* (1983) therefore introduced the drained upper limit (DUL) which is the *in situ* water content of the rooting depth at a constant slow drainage rate following thorough wetting, and depends solely on the properties of the soil profile. Bennie (1995) emphasized that wetting of the maximum rooting zone beyond the DUL will result in unproductive water drainage losses. Sometimes it is however necessary to remove salts from the root zone with percolating waters, a process known as leaching. In this case percolation can be regarded as productive as it prevents future potential yield losses due to the build up of hazardous salinity levels in the soil. This nett downward flux of salty water through the root zone can have a profound effect on the hydraulic conductivity of soils (Van der Merwe, 1973). Aggregate slaking and clay dispersion, which lead to pore plugging was established as the primary loss of hydraulic conductivity (Van der Merwe, 1973; Sumner, 1993) and are narrowly correlated to the exchangeable sodium percentage in the soil (Bohn *et al.*, 1985). A loss in hydraulic conductivity will impede with the drainage required for salinity control.

Removing salts out of the root zone, through drainage water, is probable the single most important factor that must be considered in order to achieve short and long-term salt balances for optimum crop production and in reclaiming salt-affected soils (Beltran, 1999). An investigation on irrigated soils along the lower Vaal River indicated that an un-drained clay soil contained 84750 kg salts ha^{-1} m^{-1} soil depth as compared to its drained equivalent with only 22844 kg salts ha^{-1} m^{-1} (Du Preez *et al.*, 2000).

This chapter will firstly address the effect of irrigation water salinity on soil salinity in the absence of freely drained conditions, secondly its impact on the drainage characteristics of apedal soils and thirdly determine how much salts will be removed during a single drainage cycle, from a saturated soil profile.

3.2 Materials and methods

3.2.1 Description of experimental site

The research were conducted at the Lysimeter Research Facility of the Department of Soil, Crop and Climate Science (University of the Free State) near Bloemfontein (29˚01’00’’S,26˚08’50’’E), South Africa (Figure 3.1). The research facility is described in detail by Ehlers *et al.* (2003). Basically the experimental area consist of a 70 m by 35 m area, including the fringes, with 30 round lysimeters (1.8 m diameter and 2 m deep) arranged in two parallel rows of 15 each, with their rims 0.05 m above the bordering soil surface.

Figure 3.1 Photo of experimental site and moveable rain shelter.

A 100 mm layer of gravel (10 mm in diameter) was placed in the bottom of each lysimeter and covered with a plastic mesh. The one row of lysimeters was filled with a Clovelly Setlagole soil (Soil Classification Working Group, 1991) from the Sand-Vet region and the other row with a Bainsvlei Amalia soil (Soil Classification Working Group, 1991) from the experimental site. Particle size analysis was carried out on both soils using the pipette method of Day (1965). The results of the 300 mm depth intervals are summarised in Table 3.1.

An underground access chamber (1.8 m wide, 2 m deep and 30 m long), allowed access to the inner walls of the lysimeters. The bottom of each lysimeter was connected to a manometer and a bucket that was used to recharge and regulate the height of the water table. A moveable rain shelter (Figure 3.1) that can be moved into place when a rainfall event occurs was constructed to prevent any dilution of the soil solutions in the lysimeters by rainwater.

Table 3.1 Particle size distribution of both soils for the different depths at which it was packed in the lysimeters

Soil Form	Family	Depth (mm)	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Silt (%)	Clay (%)
Clovelly	Setlagole	0-300	1.34	10.66	79.00	4.00	5.00
		300-600	1.36	25.64	65.00	3.00	5.00
		600-900	1.36	25.64	65.00	3.00	5.00
		900-1200	1.36	25.64	65.00	3.00	5.00
		1200-1500	1.36	25.64	65.00	3.00	5.00
		1500-1800	1.36	25.64	65.00	3.00	5.00
Bainsvlei	Amalia	0-300	0.30	6.42	83.28	2.00	8.00
		300-600	0.16	4.08	77.76	4.00	14.00
		600-900	0.06	3.52	78.42	4.00	14.00
		900-1200	0.14	5.68	76.18	4.00	14.00
		1200-1500	0.12	5.10	70.78	4.00	20.00
		1500-1800	0.16	5.16	70.68	4.00	20.00

3.2.2 Experimental layout and treatments

It can be assumed that the artificially packed soil profiles were stable because more than 10 cropping cycles were completed since the establishment of the facility. The last trail was maize irrigated with five different irrigation water salinity treatments, replicated three times per soil type *viz.* $EC_{i\ 15}$ = 15 mS m^{-1} (control), $EC_{i\ 150}$ = 150 mS m^{-1}, $EC_{i\ 300}$ = 300 mS m^{-1}, $EC_{i\ 450}$ = 450 mS m^{-1} and $EC_{i\ 600}$ = 600 mS m^{-1}. A water table was kept at a constant depth of 1.2 m from the soil surface by applying water of the same salinity as the irrigation water (Ehlers *et al.*, 2006). Irrigation scheduling of the different treatments were based on the principle of (i) weekly applications of surface irrigation and (ii) by recharging the water table daily to a constant depth. The surface irrigation amount was calculated from the deficit between the *in situ* determined drained upper limit of the first 600 mm soil depth and the actual soil water content measured with a neutron soil water neutron meter. The mean total crop water use of all the treatments was 612 mm of which, 300 mm was applied through surface irrigation and 312 mm through subsurface recharge of the water tables. It implies that leaching was effectively zero.

Irrigation water salinity: The amount of the different salts (mg L^{-1}) used to prepare the irrigation water, the total dissolved salts (TDS, mg L^{-1}), the sodium adsorption ratio (SAR) and the electrical conductivity (EC_i, mS m^{-1}) for the different irrigation water salinity treatments are presented in Table 3.2. Sodium chloride (NaCl), calcium chloride ($CaCl_2$), magnesium sulphate ($MgSO_4$), sodium sulphate (Na_2SO_4), potassium chloride (KCl) and magnesium chloride ($MgCl_2$) were used to make up the different irrigation water salinity treatments. Calcium (Ca^{2+}) and magnesium (Mg^{2+}) was used in a ratio ranging between 1.2 and 1.6, whereas for sulfate (SO_4^{2-}) and chloride (Cl^-) ranged from 1.3 to 1.4. These ratios are based on the mean long-term values of the Lower Vaal and Riet Rivers (Du Preez *et al.*, 2000). After dissolving the mentioned salts in distilled water, samples were taken analized and the concentration of the mentioned cations and anions were determined using standard procedures (The Non Affiliated Soil Analysis Work Committee, 1990). Results from the analysis were used to calculate the SAR and the total dissolved salts TDS with Equations 3.1 and 3.2, respectively. The results of both the SAR and TDS for the various EC_i treatments are summarised in Table 3.2.

$$SAR = Na^+ / [(Ca^{2+} + Mg^{2+})/2]^{0.5} \tag{3.1}$$

$$TDS = \sum (Ca^{2+}\ Mg^{2+}\ Na^+\ K^+\ Cl^-\ SO_4) \tag{3.2}$$

Table 3.2 Solute concentration and composition for the various irrigation water salinities (EC_i) used as treatments

EC_i (mS m^{-1})	**150**	**300**	**450**	**600**
Salts		mg L^{-1}		
NaCl	360	790	1140	1415
$CaCl_2$	100	235	500	825
$MgSO_4$	297	620	1190	1740
Na_2SO_4	0	50	20	45
KCl	105	187	553	750
$MgCl_2$	45	40	90	250
TDS	988	2003	3554	5107
SAR	3	5	5	5

Soil water salinity: After harvesting of the maize experiment, soil water was extracted from the soils in the lysimeters with ceramic suction cups, installed at depths of 300, 500, 700, 900, 1100 and 1500 mm from the soil surface. The electrical conductivity of the soil water (EC_{sw}, mS m^{-1}) from the suction cups was measured with an Ecoscan Electrical Conductivity Meter.

These water samples were further analyzed for dissolved cations (Ca, Mg, Na and K) and anions (Cl, SO_4) using standard procedures (The Non Affiliated Soil Analysis Work Committee, 1990). The soils in the lysimeters were then saturated over a period of two days with the same salinity irrigation water that was used in the maize experiment. The mean amount of water applied to saturate the soils in the lysimeters was 267 mm for the Clovelly soil and 211 mm for the Bainsvlei soil, as the soil was already saturated to a depth of 1200 mm from the soil surface because of the presence of a water table.

3.2.3 Measurements

Percolation: Plastic covers were placed over the soil surface of the lysimeters to prevent water loss through evaporation. The manometer and bucket connected to the bottom of the lysimeters were disconnected in order to allow the water to drain from the soil. Drainage water was collected in 10 L buckets, via the drain-outlet of each lysimeter. The number of buckets and time were recorded on a 24 hour basis throughout the entire measuring period of 27 days. The cumulative drainage volume (mm) per lysimeter was regressed against time (days), using the rational function ($y = \{a + bx\} / \{1 + cx + dx^2\}$) of the software package Curve Expert of Hyams (1995). The statistical results are summarized in Appendix 3.1 for each lysimeter of both soils. It can be assumed that this method provides an accurate description of cumulative drainage as the R^2 values are constantly higher than 0.98 for all the lysimeters. The resulting cumulative drainage curves were then used to calculate drainage rates on a daily basis. Samples from the drainage were collected daily for electrical conductivity measurements. At the end of the drainage period the EC_{sw} of the water collected from the suction cups at the various depths was measured again.

Change in soil water content: Volumetric soil water content was measured with a CPN 503 DR hydroprobe neutron soil water meter (NWM) at 300 mm intervals to a depth of 1800 mm from the soil surface. Water content measurements were done three times during the first 24 hours, two times during the second 24 hours, after which only one measurement was taken every other day until the 27th day after saturation. Drainage (D, mm) was calculated indirectly from the change in soil water content measurements (ΔW, mm) made with the NWM assuming that precipitation, evaporation, transpiration and runoff were zero (Equation 3.3):

$$D = -\Delta W = -(W_i - W_{i-1}) \quad (3.3)$$

where i = time of measurement (days).

Drainage calculated with Equation 3.3 was plotted as cumulative drainage versus cumulative time and then regressed with the mentioned rational function.

3.2.4 Neutron soil water meter calibration

It was not possible to calibrate the neutron soil water meter (NWM) with the standard procedure of gravimetric soil water and bulk density measurements. Instead an indirect method was used. In this procedure the directly measured cumulative drainage was compared with the drainage calculated indirectly using Equation 3.3. The measured and calculated drainage was plotted against each other to determine the deviation from a 1:1 fit. The slope of the original calibration function of the NWM (Equation 3.4) was adjusted with small increments, and the procedure repeated until the best fit was observed:

$$\theta = 18.68CR - 0.779 \quad (3.4)$$

where θ = the water content (mm mm^{-1})
CR = the count ratio of the NWM.

The best fit for the Clovelly (Cv) soil was obtained with a slope of 21 for $EC_{i\ 15}$ and $EC_{i\ 150}$, and 23 for $EC_{i\ 300}$, $EC_{i\ 450}$ and $EC_{i\ 600}$ treatments. In the case of the Bainsvlei (Bv) soil a slope of 21 for $EC_{i\ 15}$, and 22 for $EC_{i\ 150}$, $EC_{i\ 300}$, $EC_{i\ 450}$ and $EC_{i\ 600}$ gave the best fit. The 1:1 cumulative drainage graphs, presented in Figure 3.2 for both soils, showed a good agreement between the direct and indirect methods. The R^2 values were above 0.85 for both soils and the slopes were close to 1. In the rest of this study the indirect method for calculating drainage the adjusted slopes will be used.

3.2.5 Statistical analysis

All the analysis of variance was computed at a 95% confidence level using the NCSS software package of Hintze (1997). This software package was also used to compare treatment means with Tukey-Kramer's multiple comparison tests at a confidence level of 95%.

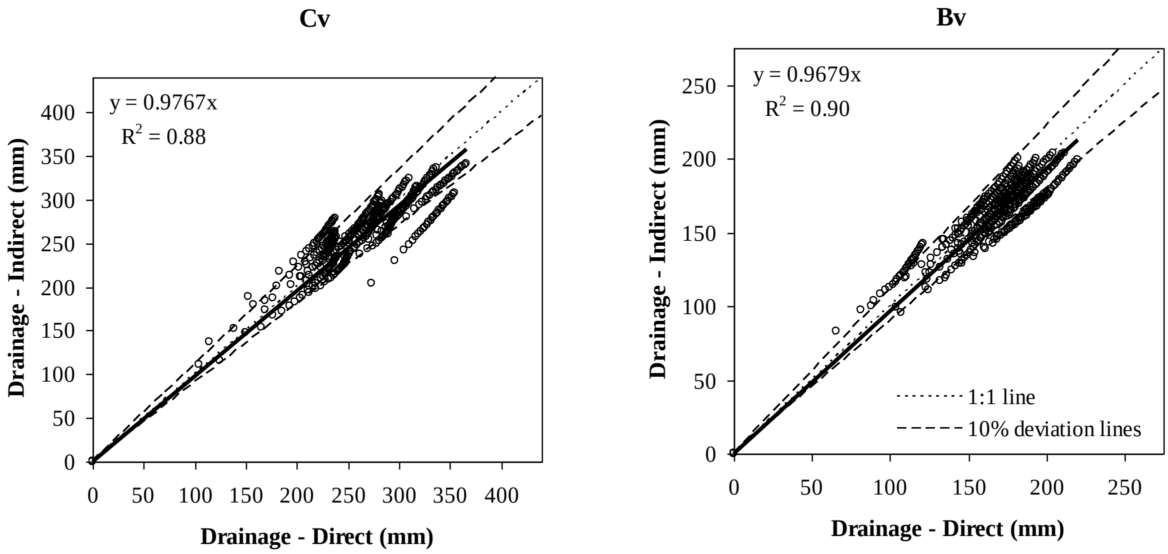


Figure 3.2 Comparison of the indirectly calculated cumulative drainage, using the calibrated CPN, with the directly measured values for all the lysimeters of both soils.

3.3 Results and discussion

3.3.1 Salinity status of the soils

This section of the study focuses on the salinity status of the profiles resulting from the application of irrigation water of various salinities during the maize growing season under zero drainage or shallow water table conditions. The mean amounts of water applied for the different treatments were 800, 727, 591, 483 and 381 mm for the $EC_{i\ 15}$, $EC_{i\ 150}$, $EC_{i\ 300}$, $EC_{i\ 450}$ and $EC_{i\ 600}$ treatments of the Cv soil, respectively and 778, 761, 639, 501 and 461 mm for the EC_i treatments of the Bv soil, respectively. After harvesting a mean of 267 and 211 mm additional water were irrigated to increase the soil water levels of the Cv and Bv soils to field saturation, respectively.

The effect of the irrigation on the salinity status of the soils can be illustrated by the analysis of the samples extracted with the various suction cups. The mean EC_{sw} and the mean SAR of the different treatments are presented in Table 3.3 (Appendix 3.2). The EC_{sw} results in Table 3.3 show that an increase in EC_i resulted in an increase in the mean EC_{sw} of the profile for both soils since the EC_{sw} at the start of the growing season were near to the EC_i treatment used. For the Clovelly (Cv) soil the mean EC_{sw} over the depth of the profile increased from 200 to 1852 mS m^{-1} with an increase in EC_i treatments ($EC_{i\ 15}$ – $EC_{i\ 600}$). The Bainsvlei (Bv) soil increased from 100 to 1523 mS m^{-1} over the various EC_i treatments. In general the mean SAR values tend to follow the same profile distribution pattern as the EC_{sw}. The mean SAR of the profile (0-1800 mm) increased slightly with an increase in EC_i treatments for both soils. This increase was however marginal probable because of the low SAR values of the higher EC_i treatments (Table 3.2). The mean SAR of the profiles increased from 4 to 13 for the various treatments of the Cv soil and from 3 to 9 for the various treatments of the Bv soil.

Table 3.3 The mean soil water salinities (EC_{sw}) and sodium adsorption ratio (SAR), at various depths through the profiles of both soils for the various irrigation water salinity treatments (EC_i)

		EC_i (mS m^{-1})									
		15		**150**		**300**		**450**		**600**	
Soil	**Depth (mm)**	**EC_{sw} (mS m^{-1})**	**SAR**	**EC_{sw} (mS m^{-1})**	**SAR**	**EC_{sw} (mS m^{-1})**	**SAR**	**EC_{sw} (mS m^{-1})**	**SAR**	**EC_{sw} (mS m^{-1})**	**SAR**
Cv	**300**	174	4	1209	12	1131	13	2138	15	2088	12
	500	578	7	1415	11	1456	13	1844	11	3314	10
	700	150	4	943	8	1864	13	1964	11	2216	14
	900	121	3	540	9	1054	12	1303	12	1512	17
	1100	101	2	293	7	683	9	931	8	1172	14
	1500	78	3	212	5	414	8	419	6	808	8
	0-1800	**200**	**4**	**769**	**9**	**1101**	**11**	**1433**	**11**	**1852**	**13**
Bv	**300**	139	3	1149	9	1970	13	2374	10	2670	9
	500	108	2	923	6	1190	10	1633	10	1883	8
	700	163	4	738	8	1110	9	1548	10	1817	12
	900	67	3	298	6	1458	15	1012	10	1311	10
	1100	70	2	223	5	443	8	696	9	794	9
	1500	50	1	223	4	356	7	558	8	664	8
	0-1800	**100**	**3**	**592**	**6**	**1088**	**10**	**1303**	**9**	**1523**	**9**

From the strong relationship (R^2 = 0.78) between the EC_i and the increase in soil water salinity (ΔEC_{sw}) during the maize season, as displayed in Figure 3.3, it can be concluded that a mean total of water application of 612 mm between the treatments almost doubled the mean EC_{sw} of the profiles over the growing season.

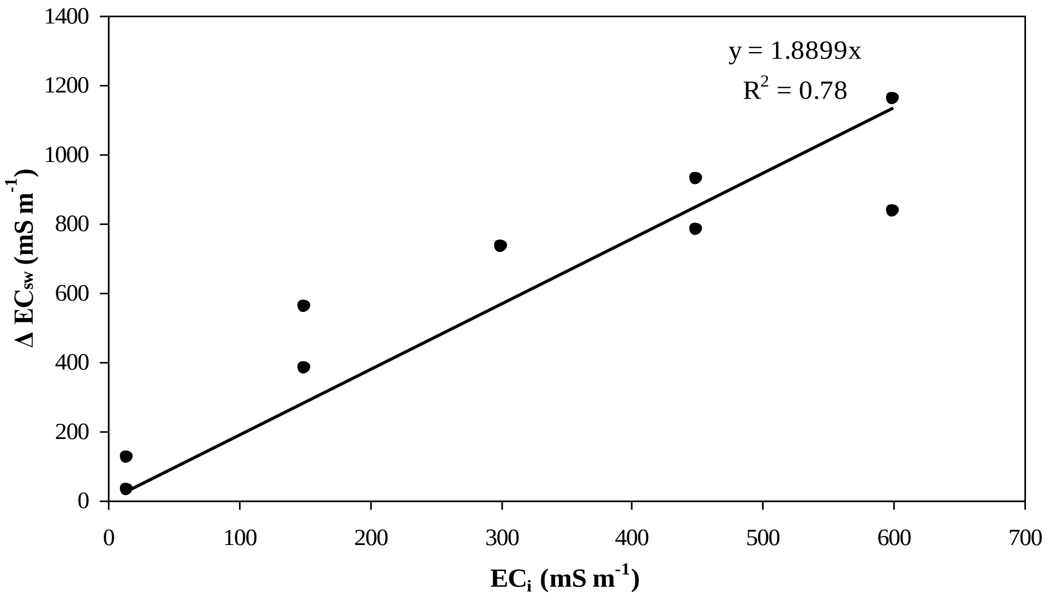


Figure 3.3 Influence of irrigation water salinity (EC_i) on the increase in the mean salinity of the profile (ΔEC_{sw}) after a mean total of 612 mm irrigation.

The mean SAR of the profile during the growing season did not increase because the SAR of the various EC_i treatments was kept as low as possible. The importance of these observations can be illustrated with the following example. Irrigating a saline water table soil, with water of which the EC is 200 mS m^{-1} will convert a non-saline soil (EC_{sw} = 225 mS m^{-1}) to saline within only one season, with an estimated EC_{sw} = 426 mS m^{-1}.

It was not possible to extract samples with the suction cups for the electrical conductivity determinations. As already mentioned the soils were saturated before extraction. It can therefore be assumed that EC_{sw}, because of the extraction from saturated soil will be comparable to EC_e. Ayers and Westcot (1976) however emphasized that in relating EC_e to EC_{sw} a general factor of two can be used (EC_{sw} = 2 EC_e), since EC_{sw} depends on the water content of the soil. Shalhevet and Reiniger (1964) reported a range of values of 1.8 and 3 depending on soil texture.

According to the United States Salinity Laboratory Staff (1969), soils where the electrical conductivity of the saturated extract (EC_e) is smaller than 400 mS m^{-1} are classified as non-saline. Saline soils have EC_e values of > 400 mS m^{-1} and SAR < 15, while sodic soils have SAR values > 15 and EC_e < 400 mS m^{-1}. Following these criteria the soil profile of the Cv soil, the $EC_{i\ 15}$ treatment can be classified as non-saline while all the other treatments are classified as saline. For the Bv soil it is also only the $EC_{i\ 15}$ treatment not classified as saline. None of the soil profiles of both soils for all the treatments was classified as sodic since the highest SAR was 13. Sodicity results in swelling and dispersion of clay particles which in turn causes a loss in hydraulic conductivity and therefore drainage (Van der Merwe, 1973). Mace & Amrhein (2001) however indicated that at SAR values of 5 to 8, a loss in hydraulic conductivity/permeability can occur when combined with low electrolyte concentrations. For some of the Free State soils the SAR of the saturation extract of soils should be less than 5 when irrigated with water that have an electrolyte concentration of 3-5 me L^{-1} (van der Merwe, 1973). In Figure 3.4 the SAR was regressed against the corresponding EC_{sw} for all the depths of both soil profiles and various EC_i treatments. The nonlinear relationship was best described (R^2 = 0.85) by a power function illustrating that with an increase in the SAR the corresponding EC_{sw} increased as well. A few data points seem not to be in relation with the function. Most of these values come from the top soil layer of the more clayey Bv soil.

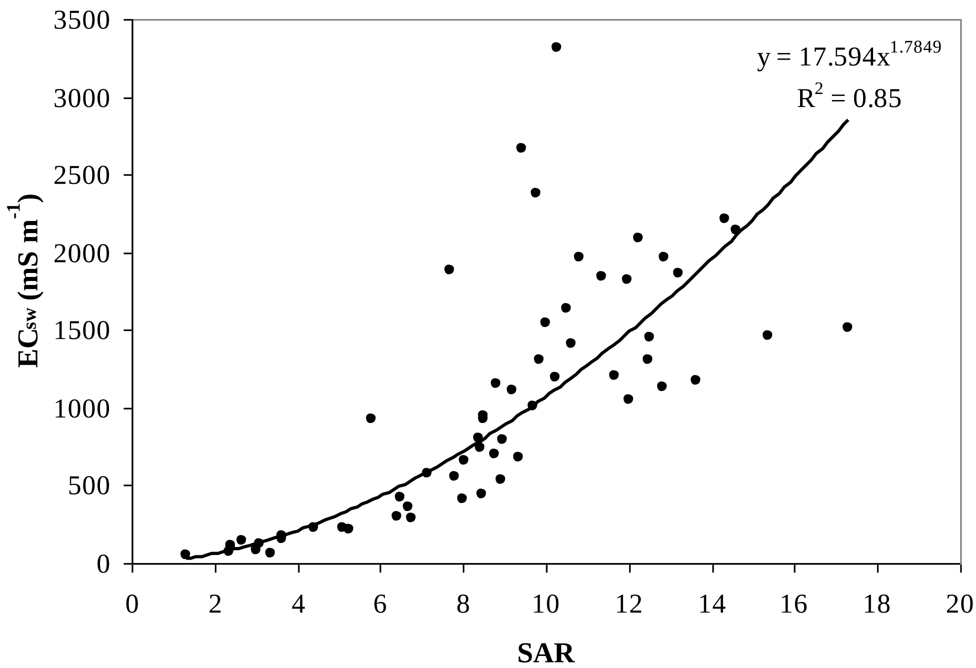


Figure 3.4 The sodium adsorption ratio (SAR) regressed against the corresponding electrolyte concentration (EC_{sw}) for all the depths of both soils and irrigation water salinities (EC_i).

Swelling and dispersion of clay particles should therefore not be a problem in the experimental soils and it should be possible to maintain the permeability of the soils, irrespective the SAR as long as it is accompanied by a sufficiently strong electrolyte concentration (more than 6 and 3 me L^{-1} for SAR values of 13 and 9 respectively (van der Merwe, 1973). Soil water salinity should therefore not have an effect on the hydraulic conductivity of these saline soils with SAR values of 9 and 13. In order to confirm this assumption a further analysis of drainage from saline apedal soils is necessary.

3.3.2 Effect of deteriorating soil water salinity on drainage

The one-dimensional drainage flux through the bottom of the root zone is equal to the hydraulic conductivity which is a logarithmic function of the mean water content (Bennie *et al.*, 1988). Unfortunately the hydraulic conductivity could not be measured directly because the soil water potential could not be measured. It was therefore decided to use the drainage flux measure at the bottom of the lysimeters to measure the mean effect of soil water salinity (EC_{sw}) on drainage. The volume of recorded drainage water was used to construct cumulative drainage versus time curves for each lysimeter (Appendix 3.1). From these drainage curves three periods were selected to represent fast, moderate and slow periods of drainage, *viz.* 0-2 days, 2-5 days and 5-27 days. The drainage rates (DR, mm day^{-1}) for a specific period were calculated by dividing drainage during that specific period with the corresponding amount of days. Table 3.4 provides the mean drainage rates and EC_{sw}-values for the various treatments.

Only the moderate drainage period of the Cv soil indicated a small decrease in drainage rate with a decrease in soil water salinity. This decrease was however not associated with an increase in EC_{sw} since a R^2 value of 0.26 was obtained when DR was plotted against EC_{sw}. The reduction in drainage occurs in sodic soils where swelling and dispersion normally block soil pores. It is highly unlikely that clay dispersion occurred because no traces of clay-sediment could be found in the drainage water.

In general Table 3.4 shows a small improvement in drainage rates associated with deteriorating soil water salinity for both soils. This could be attributed to a thinner electrical double layer resulting from higher electrolyte concentrations of the bulk soil solution (Bohn *et al.*, 1985).

Table 3.4 Mean drainage rates (DR) during the various drainage periods for the mean salinity levels of the profiles (EC_{sw}) corresponding to the various treatments (EC_i) of both soils

Soil	**EC_i (mS m^{-1})**	**15**	**150**	**300**	**450**	**600**	
Cv	Mean EC_{sw} (mS m^{-1})	200	769	1101	1433	1852	
	Drainage period			**Mean DR (mm day^{-1})**			**$LSD_{0.05}$**
	Day 0-2	85.1_a	95.2_{ab}	129.6_{ab}	112.1_{ab}	137.9_b	**46.2**
	Day 2-5	12.7	12.4	6.1	10.5	6.0	**ns**
	Day 5-27	1.6	1.4	1.6	1.5	1.8	**ns**
Bv	Mean EC_{sw} (mS m^{-1})	100	592	1088	1303	1523	
	Drainage period			**Mean DR (mm day^{-1})**			**$LSD_{0.05}$**
	Day 0-2	56.9	74.5	71.3	74.3	67.0	**ns**
	Day 2-5	5.5	5.3	5.9	5.9	6.5	**ns**
	Day 5-27	1.3	1.4	1.4	1.5	1.5	**ns**

The small improvement in drainage rates was not significantly correlated with an increase in deteriorating soil water salinity, except between the mean EC_{sw} of the profile of 200 and 1852 mS m^{-1} for the Cv soil. Bohn *et al*. (1985) also demonstrated that the changes in the thickness of the electrical double layer normally occur over small distances (nm). Following this theory the results indicate that the magnitude of compression of the double layer were probably not enough to improve the drainage of both soils. For practical reasons this improvement is assumed to be insignificant, concluding that soil water salinity will not affect the drainage rates of apedal soils as long as the SAR values of the soil water are below 15 and with high electrolyte concentration irrigation water. For SAR values of 15, van der Merwe (1973) found for several Free State, Northern Cape and North West Province soils, that the electrolyte concentration of the saturation extract in equilibrium with the irrigation water quality should be above 8 me L^{-1} to prevent a more than 15% reduction in hydraulic conductivity.

3.3.3 Soil water content versus time relationships

Drainage curves derived from *in situ* measured soil water content-time functions, as described by Ratliff *et al.* (1983), is commonly used to estimate the drainage component of the field water balance (Hensley *et al*., 1993; Bennie *et al*., 1994; Van Rensburg, 1996; Bennie *et al*., 1998; Hensley *et al*., 2000; Van Staden, 2000 and Botha *et al*., 2003). Figure 3.5 illustrates, a typical drainage curve, for the 1800 mm profiles of all the lysimeters for both soils (Data in Appendix 3.3). The semi-logarithmic regression lines were fitted through all the replications of all the treatments because EC_{sw} had no significant influence on drainage. Excellent correlations were found as indicated by the R^2 of 0.91 and 0.89, for the Cv and Bv soils, respectively.

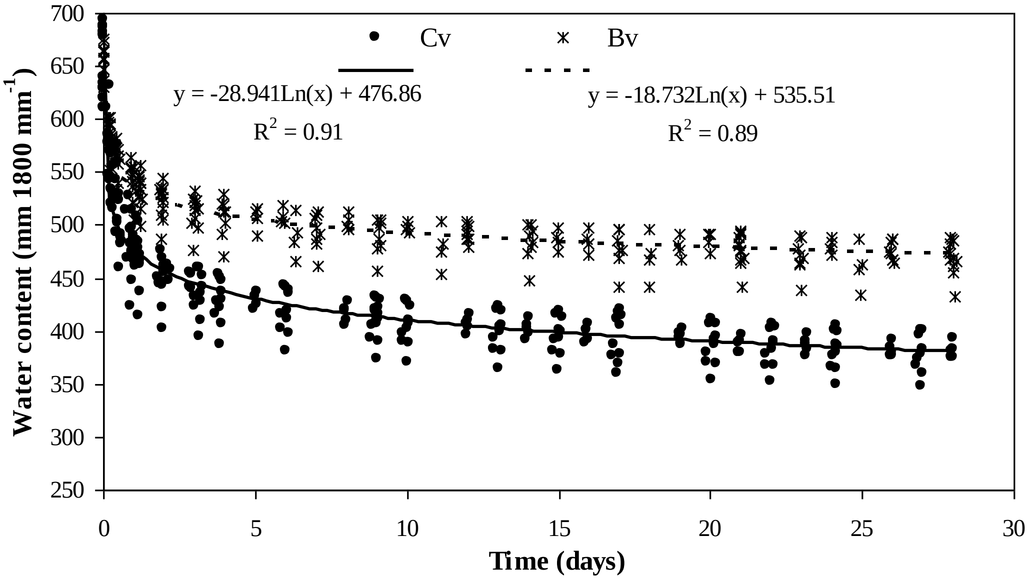


Figure 3.5 Water content versus time, for the 1800 mm profiles of both soils, for all the lysimeters.

The presumed water content two days after saturation where drainage allegedly ceases, was termed the field capacity. For the Cv and Bv soils respectively a water content of 457 and 523 mm 1800 mm^{-1} were calculated with the semi-logarithmic regression lines, corresponding to a total drainage of 212 and 135 mm for the Cv and Bv soils, respectively. Despite the fact that both soils are apedal, the drainage was almost twice as large for the Cv soil in comparison to the Bv soil, probably because of the larger proportion of macropores in the more sandy Cv soil as compared to the Bv soil. In reality a true field capacity cannot exist, because water will drain continuously under gravity as long as no impermeable layer is present (Jury *et al.*, 1991). Figure 3.5 confirmed this by illustrating a decline in water content at a gradual almost constant rate from day 2 – 27 after saturation.

The drained upper limit (DUL) was selected according to the guidelines of Ratliff *et al.*, (1983) as the water content corresponding with a slow drainage on the drainage curves. At the 27th day the water content decrease in the soil profile was about, 0.1 to 0.2% water content per day, therefore almost negligible. Following this approach mean DUL-values of 381 and 474 mm 1800 mm^{-1} were derived for the Cv and Bv soils, respectively. Jury *et al.*, (1991) emphasized that what constitutes a negligible drainage rate will depend upon the particular problem under consideration. Because the importance of drainage varies from application to application no universal criteria can be develop to decide when to neglect drainage.

The mean field saturation between the lysimeters was measured to be 668 and 658 mm 1800 mm^{-1}, for the Cv and Bv soils, respectively, which suggest that the bulk densities are also similar or closely related. Unfortunately this theory could not be tested as it was not possible to measure the bulk densities because it was decided not to disturb the soil profile in the lysimeters at this stage. An attempt was made to calculate the mean bulk density for the profile from the measured field saturated water content values, assuming that 5% of the pores contain air. The estimated values seem to be realistic and amounts to 1617 and 1633 kg m^{-3} for the Cv and Bv soils, respectively. Zeleke (2003) measured the bulk densities of the Bainsvlei soil in its cultivated state, using 200 mm depth intervals over the 1.6 m profile. The mean value amounted to 1658 kg m^{-3} and appears to be slightly higher than the estimated values of the Bainsvlei soil in the lysimeters. Zeleke (2003) also calculated the drainage of the profile to be 0.84 mm day^{-1} on the 26th day after saturation, using the internal drainage method of Hillel *et al*. (1972). The corresponding drainage estimated with the drainage curve obtained from the lysimeters amounts to 0.7 mm day^{-1} on the same day.

3.3.4 Soil water and salt distribution regime

It is general knowledge that salt movement in soil follows the basic flow pattern of soil water assuming that adsorption of chemicals to clay particles or by-pass flow is negligible (Jury *et al*., 1991; Herald, 1999; Marshall *et al*., 1996). Figure 3.6 represents the mean volumetric soil water content (mm mm^{-1}) of all the lysimeters at various depths through the profile of both soils. Steady-state conditions exit at saturation with an almost equal distributed water content through the profile. Under these conditions water drains from the soil profile at the same rate as the applied unit hydraulic gradient. The water also drains at the same rate from all depths under this unit hydraulic gradient. Following these initial saturated state, transient state conditions takes over allowing for the mean water content to decrease as water drains from the soil. This is generally experienced in the field due to the intermitted nature of evaporation, transpiration, rainfall and irrigation. From Figure 3.6 it is noticeable that water drained more rapidly from the top soil layers as compared to the deeper soil layers. At the DUL the soil water content is especially high in the deeper soil layers, which may be attributed to the increase in the suction gradient between the wetter and the drier zone of the profiles which causes a corresponding decrease in hydraulic flux.

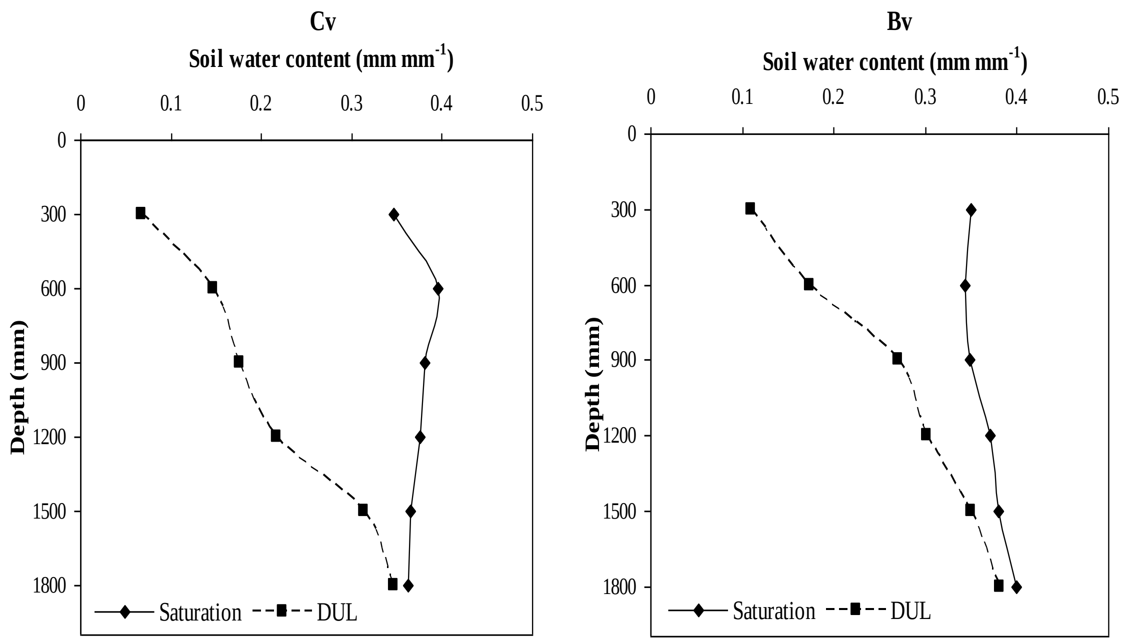


Figure 3.6 Mean volumetric soil water distribution of all the lysimeters for both soils at the start (saturation) and end (DUL) of the drainage period.

It should be kept in mind that a layer of gravel was present at the bottom of the lysimeters. Restricted flow of water occurs especially in the transition of water from a fine-textured top-layer to a coarse textured gravel layer beneath (Hillel, 1998). Despite the presence of steep hydraulic gradients flow through layers of unsaturated soil can be nearly zero under conditions over the transition to the larger empty macropores in the gravel. The sandier Cv soil also indicated a steeper decline in drainage with a decrease in soil depth than the more clayey Bv soil.

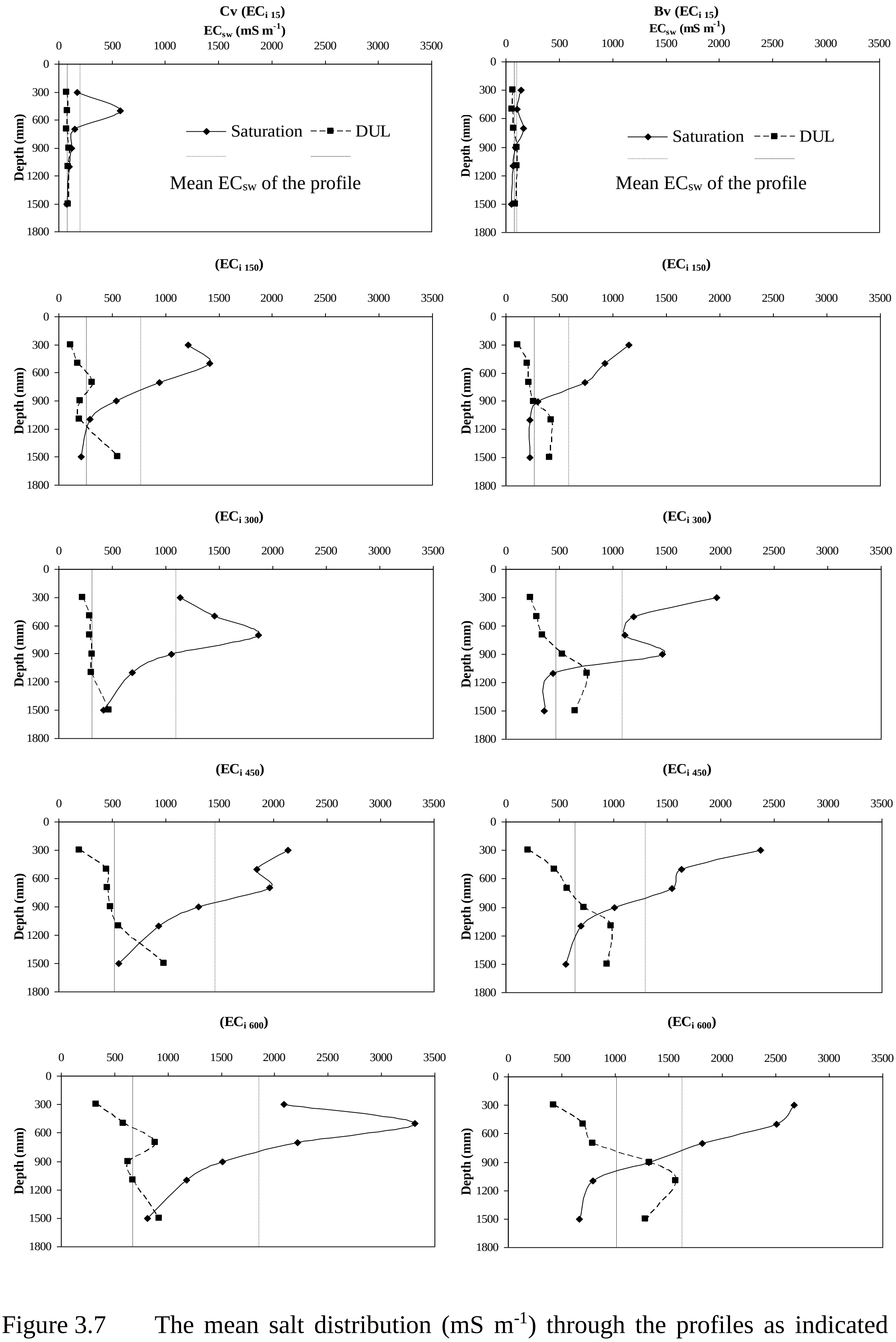


Figure 3.7 The mean salt distribution (mS m^{-1}) through the profiles as indicated by the mean electrical conductivity (EC_{sw}) of the profile for the various EC_i treatments of both soils at the start (saturation) and end (DUL) of the drainage period.

When water, either irrigation or rainfall, infiltrates into the soil its salinity will be affected. The process of salinization depends on several factors with the most important probably being the salinity of the irrigation water, the residual soil salinity due to previous irrigations and irrigation management. Figure 3.7 represents the mean salt distribution through the profile for the various soil salinities of the various EC_i treatments at the start of the drainage period (saturation) and at the end of the drainage period (DUL). The full data set can be found in Appendix 3.4.

The salt distribution through the profile changed significantly for all the EC_i treatments of both soils as water drained from the soils during the complete drainage cycle. When water moves downward into the profile, from one soil layer to the next, the residual soil solution is displaced by the incoming solution. After continuous leaching the soil solution will approach the quality of the irrigation water. The mean EC_{sw} to a depth of 900 mm at the DUL for the profiles of the $EC_{i\ 15}$ to $EC_{i\ 600}$ treatments amounted respectively to 81, 203, 280, 396 and 607 mS m^{-1} for the Cv soil and 76, 198, 348, 490 and 809 mS m^{-1} for the Bv soil, respectively. Figure 3.6 and 3.7 showed that as water drained from the top of the profile, the salt peak in the top of the profiles of all the EC_i treatments for both soils was largely pushed downward into the profiles. The difference between the salt content at field saturation and the DUL (ΔEC_{sw}) was calculated at all the depths for the various soil water salinities of the EC_i treatments to quantify the amount of salt removed by the mean 287 and 186 mm of drainage for the Cv and Bv soils, respectively. The fraction of salt removed per soil layer was expressed as a fraction of the corresponding initial EC_{sw} at the start of the drainage period and regressed against soil depth for the Cv and Bv soils, respectively. Figure 3.8 shows that approximately all of the initial EC_{sw} had been removed from the top of the profile.

The non-linear regressed lines were forced through 0.90 because 100% of the initial soil salinity cannot be removed since the soil salinity will be leached to the corresponding irrigation water salinity. With every increase in soil depth there will be a decrease in the fraction of initial EC_{sw} removed as the salts in the top of the profile is displaced deeper into the profile. For the Cv and Bv soils, respectively 287 and 186 mm of drainage were required to effectively remove salts from the top 1250 and 900 mm of these soils. Figure 3.8 illustrates that below these depths the displaced salt from the top of the profile accumulated as indicated by the negative values.

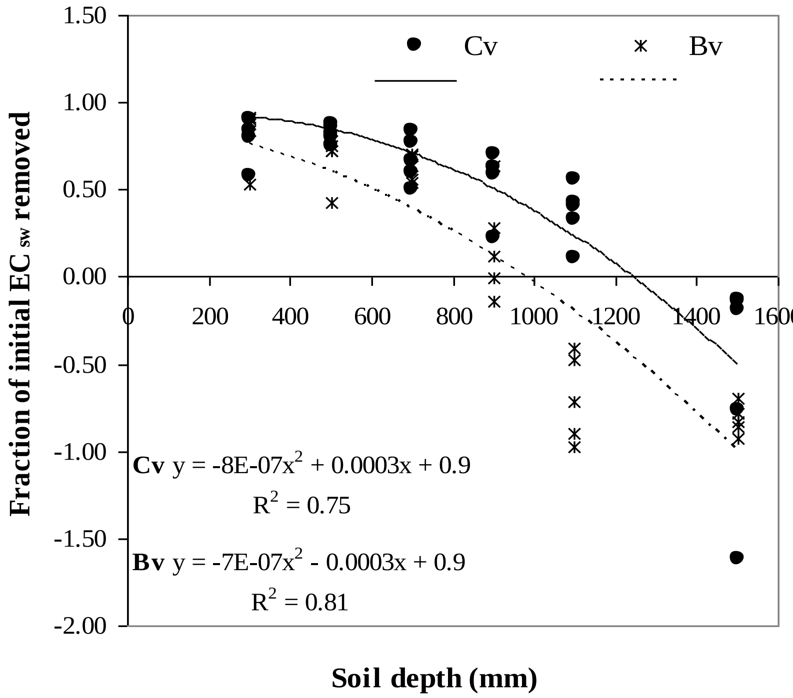


Figure 3.8 The fraction of initial EC_{sw} removed from various depths through the profiles of the Cv and Bv soils respectively.

The conditions under which this experiment was conducted namely the drainage between saturation and DUL represents the initial leaching of salts towards an artificial drainage system installed at a depth of 1800 mm. It shows that additional drainage is required for removing the rest of the salts. According to the difference between the mean EC_{sw} of the profiles at the start and end of the drainage period in Figure 3.7, represented by the dotted lines, there was a decrease in the mean EC_{sw} of the profiles for all the treatments. At the start of the drainage period the mean EC_{sw} of the profiles amounted to 200, 769, 1101, 1456 and 1852 mS m^{-1} for the $EC_{i\ 15}$ to $EC_{i\ 600}$ treatments of the Cv soil, respectively and 103, 592, 1088, 1303 and 1628 mS m^{-1} for the Bv soil, respectively. After the drainage cycle was completed the mean EC_{sw} of the profiles decreased to 85, 261, 315, 521 and 671 for the Cv soil, respectively and 83, 271, 467, 647 and 1014 for the Bv soil, respectively. For all the treatments the larger decline in soil water salinity, as shown in Figure 3.7 between the dotted lines, for the Cv soil compared to the Bv soil, is mainly attributed to the larger volume of drainage from the Cv soil. The difference between the dotted lines in Figure 3.7 also increases with an increase in EC_i treatments suggesting that when the initial EC_{sw} is high more salt will be removed during the initial leaching stage.

3.3.5 Quantifying salt removed during a complete drainage cycle

The mean total drainage measured per treatment during the drainage period is summarized in Table 3.5 for both soils. The mean drainage for the more sandy Cv soil was 55% more than that of the Bv soil. The total drainage for $EC_{i\ 15}$ to $EC_{i\ 600}$ treatments varied between 242 and 334 mm for the Cv soil and between 158 and 199 mm for the Bv soil. As the electrical conductivity of the drainage water (EC_d) was regularly measured during the drainage period an attempt was made to determine a relationship between EC_d and time after saturation. Extremely poor relationships were obtained (data not shown), which indicated that salt concentration of the drainage water remained constant over time. Consequently the mean EC_d of the drainage water, total volume of drained water over the entire drainage period and the area of the lysimeters per treatment were used as constants for computing the total amount of salts removed in kg ha^{-1} (Table 3.5). The total dissolved salts of the drainage water (TDS_d, mg L^{-1}) were calculated by multiplying EC_d (mS m^{-1}) with a factor of 7.568 which was found to describe the relationship between EC_{sw} and TDS best (Ehlers *et al*., 2006).

Table 3.5 The mean electrical conductivity of drainage water (EC_d), cumulative drainage (∑D) and cumulative salt removal (∑SR) for both soils during the drainage period

Soil	**EC_i (mS m^{-1})**	**EC_d (mS m^{-1})**	**∑ D (mm)**	**∑ SR (kg ha^{-1})**
Cv	**15**	108	242	1975
	150	428	258	8435
	300	777	312	18171
	450	1094	289	23993
	600	1381	334	34901
	Mean	**757**	**287**	**17495**
Bv	**15**	67	158	808
	150	275	195	4066
	300	544	192	8004
	450	738	199	11147
	600	954	186	13448
	Mean	**516**	**186**	**7494**

Depending on the treatment a single drainage cycle of the Cv soil removed between 1 975 and 34 901 kg salts ha^{-1}, while the Bv soil discharged between 808 and 13 448 kg salts ha^{-1} from a soil profile depth of 1800 mm. The results indicate clearly that there is a relationship between salt discharged or removed and the initial salt concentration of the soil and that more salts were discharged from the more sandy Cv soil as compared to the clayey Bv soil.

The rate at which salts were removed (kg salt ha^{-1} mm^{-1} drainage at 1800 mm depth) were calculated by dividing cumulative salt removed (kg ha^{-1}) with the corresponding amount of drainage (mm). The salt removal rate was related to the initial EC_{sw} at the start of the drainage period by forcing the regressions through the zero co-ordinates. As shown in Figure 3.9 the relationships illustrates that the salt removal rate is a function of the texture and salt content of the soils. The slope suggests that under these drainage conditions a constant amount of salts are discharged per ha per mm water drained per EC_{sw} (mS m^{-1}).

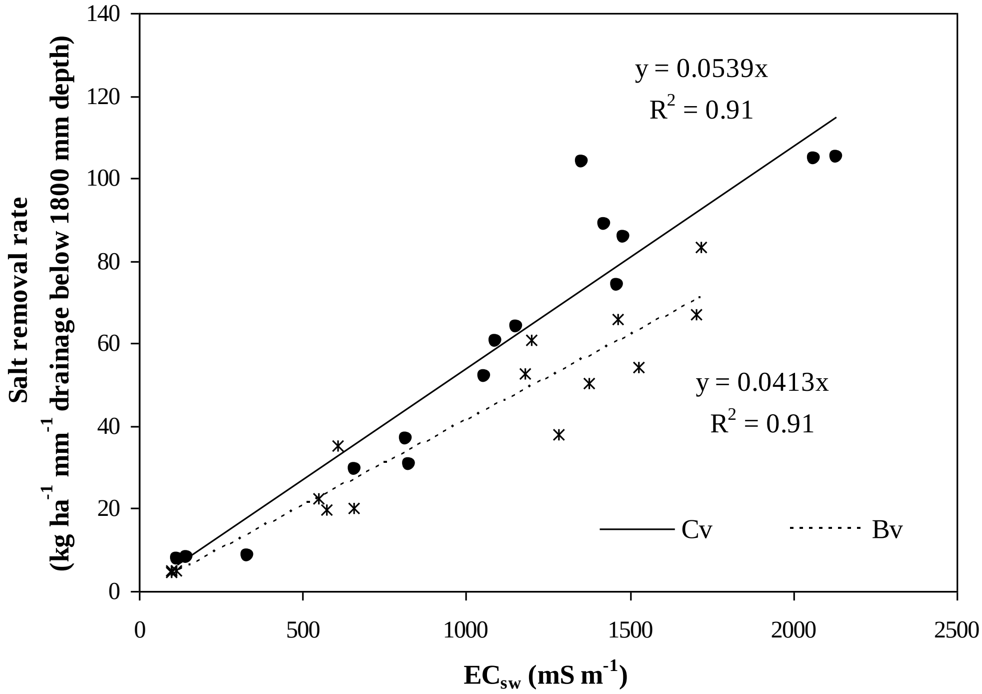


Figure 3.9 Salt removal rate (kg salts ha^{-1} mm^{-1} drainage below 1800 mm depth) of all the lysimeters for both soils as a function of salinity of the soil water (EC_{sw}).

3.4 Conclusions

The irrigated maize experiment in the lysimeters, showed clearly that salts will accumulate in the profile during one growing season. The rate of salinization depends on the salinity of the irrigation water when zero drainage occurs. Application of a mean 612 mm of irrigation between the treatments almost doubled the electrical conductivity of the soil solution during the maize growing season. This illustrated the importance of free drainage because the salt content of the soil increases linearly with an increase in the salinity of the irrigation water with a factor of 1.8. The soils were classified as saline as the mean SAR of the profile did not exceed 15 because the SAR of the treatments was kept below 5. The high electrolyte concentration of the irrigation water prevented a decline in hydraulic conductivity of the soils. This was confirmed with results illustrating that soil water salinity did not significantly affect drainage rates over a soil depth of 1800 mm. Soil salinity therefore had no effect on the drainage characteristic of the two apedal soils used in the study. The data of all the salinity treatments were thus combined and a single drainage curve was derived for each soil. It was confirmed that quantification of the drained upper limit is important because leaching of salts under adequate drainage conditions can be expected when soils are wetted above this level with irrigation.

The drainage period following saturation of the soils was described as transient-state displacement of the residual solution by the influx of soil solution from higher layers. A salt peak at the top of the profile was largely pushed downward into the profile. The mean drainage of 287 and 186 mm from the Cv and Bv soils respectively only effectively removed salts from the top 1250 and 900 mm of soil. Concluding that soil depth plays an important roll in determining the amount of water required to leach salts from the root zone. Although all the salts were not removed from a root zone of 1800 mm the mean salinity of all the various profiles decreased with the corresponding amount of drainage. The single drainage cycle of the Cv soil removed between 1975 and 34 901 kg salts ha^{-1}, and that of the Bv soil between 808 and 13 448 kg salts ha^{-1} depending on the initial salinity. It can be concluded that the rate of salt removed from a saturated soil when artificial drainage is installed, expressed as kg salts ha^{-1} mm^{-1} drainage, is a function of texture and salt content of a soil.

A sustainable salt balance can not be achieved during a single drainage cycle because the soil profile of 1800 mm depth was not effectively leached throughout. Various irrigation water salinities obviously influence the amount of leaching required to bring the salt content in equilibrium with the irrigation water salinity. Research on salt removal with water of a constant salinity and the volume of drainage needed for efficient leaching is necessary. This will be the topic of the research reported in the next chapter.

CHAPTER 4

SALT REMOVAL THROUGH LEACHING WITH IRRIGATION WATER OF A CONSTANT SALINITY

4.1 Introduction

Salt accumulation in the root zone will through osmotic effects eventually induce moderate to severe water stress that reduces crop yield (Ehlers *et al*., 2006). The previous chapter emphasized that the only reliable option to control salinity levels in the rooting zone is through controlled leaching of salts to below the active root zone. Leaching will only be effective (real ability to remove salts below the root zone) when the depth of the root zone leached is considered during the up and downward movement of water. Saline drainage water must be removed through subsurface drains or transported into deeper subsoil with sufficient natural drainage. Lower saline irrigation water will however be more effective in leaching salts since leaching brings the salinity of the root zone close to that of the irrigation water.

Much attention has therefore been devoted to the optimal depth of water to be employed for effective leaching, *viz.* the leaching efficiency. The initial salinity of the soil, desired salinity level after leaching, depth to which leaching is desired and soil characteristics are major factors that determine the amount of water required (Abrol *et al*., 1988). Following Al-Sibai *et al*. (1997) solute transport or for that matter salt leaching in an aggregated system can best be described, using the dual-porosity approach in which the pore space is assumed to comprise two regions; (i) a mobile-water region in the larger pores between aggregates, where solute transport occurs by convection and dispersion and (ii) an immobile-water region in micropores within aggregates where diffusion occurs alone. It's apparent that with regard to salt leaching the mobile-water region in the larger pores between aggregates governs the main transport of salts through soil.

Several researchers indicated with laboratory (Nielsen & Biggar, 1961; Miller *et al*., 1965) and field (Nielson *et al*., 1966; Oster *et al*., 1972) experiments that leaching of salts will be more efficient under unsaturated conditions where more salts can be removed per unit depth of water leached. These conditions allow time for solutes to diffuse to the surface of aggregates between irrigation intervals, which can subsequently be removed in the main convective dispersion transport stream through larger pores. A large portion of the applied water also flows through the soil matrix under unsaturated conditions, reducing therefore preferential or macropore flow. Structured high clay content soils mostly benefit from these unsaturated flow conditions (Tanton *et al*., 1995; Armstrong *et al*., 1998).

In apedal to weakly structured soils preferential flow is unlikely to occur. In these soils diffusion or the immobile-water region is therefore not of great consequence. Zeleke (2003) illustrated this with an *in situ* leaching experiment using Br as a tracer in a Bainsvlei soil. He concluded that solute transport in this weakly structured subsoil can be described as piston flow. A sensitivity analysis of the results showed that convection determines the solute velocity, while dispersion determines the spreading of the solute. According to piston flow transport the incoming solution replaces the solution initially present in the soil. It requires thus approximately one pore volume of water to move a mobile solute through a soil volume of a given water content and length. Solutes however which do not react chemically or biologically in soil, might still adsorb to stationary soil colloids. Since it requires one pore volume to move a mobile solute through soil, it will require x pore volumes to move a sorbing solute through a soil profile (Jury & Horton, 2004). The first objective of this chapter will be to quantify the pore volume of water required to replace various soil salinity solutions with water of a constant salinity under unsaturated conditions.

A rational management approach is however not necessarily aimed at minimizing the salt content in the rooting zone, but rather to control or manage salt concentrations within limits that will maintain sustainable production levels. Replacing the soil solution will therefore not be entirely rational in terms of the amount of water required for efficient leaching. Leaching curves have been used in adequately describing the amount of water required to leach the soil to a predetermined salinity level (Reeve, 1957; Dieleman, 1963). The second objective will therefore be to develop leaching curves for two apedal soils with various soil water salinities, leached with water of a constant salinity under unsaturated conditions.

4.2 Materials and methods

4.2.1 Experimental layout and treatments

For this trial the lysimeter facilities located at the experimental farm of the Department of Soil, Crop and Climate Science (UFS) near Bloemfontein as described in Chapter 3 was used. The 15 saline profiles per soil type, established during the maize trail were leached with a total mean between the lysimeters of, 287 mm for the Cv soil and 184 mm for Bv soil with various irrigation water salinities (Chapter 3). The salinity levels of the profiles for the various treatments ($EC_{i\ 15}$ – $EC_{i\ 600}$) at the end of this drainage period was taken as the starting point for the soil water salinity levels (SL) of the next leaching trial. At that point the mean EC_{sw} of the profile for the various treatments were 85 (level 1, SL1), 261 (level 2, SL2), 315 (level 3, SL3), 521 (level 4, SL4) and 671 (level 5, SL5) mS m^{-1} for the Cv soil and 83 (SL1), 271 (SL2), 467 (SL3), 647 (SL4) and 1014 (SL5) mS m^{-1} for the Bv soil. All the saline profiles were irrigated with water of the same salinity, *viz*. 75 mS m^{-1}. Before irrigation started the water content of the various saline soil profiles were near the drained upper limit (DUL). Both soils were irrigated by flooding the surface with a depth of 50 mm per irrigation event. Two irrigations per week were applied for seven weeks which amounted to a total of 700 mm.

4.2.2 Measurements

The amount of water that drained from the bottom of each lysimeter were measured directly and calculated indirectly with Equation 3.3 (Section 3.2.3). Water content measurements were made at 300 mm depth intervals with the calibrated neutron water meter (Chapter 3) on a daily basis. Direct measurements were made daily by opening the drained-outlet at the bottom of each lysimeter every morning and closing it every evening. The measured volume of drainage water was converted to depth (mm). Drainage water from every lysimeter was stored in a separate container, on a daily basis it was thoroughly stirred and the electrical conductivity measured as described earlier (EC_d, mS m^{-1}). The soil surface of the lysimeters was covered with a plastic sheet to prevent evaporation (E), except for 2-3 hours per day when the soil water measurements were made or when irrigations were applied. For the entire period the lysimeter unit was covered by a rain shelter to prevent rain from entering the lysimeters and to restrict E further during measurements.

4.3 Results and discussion

4.3.1 Soil water balance

In Figure 4.1 the irrigation frequency intervals can be followed for the 50-day leaching period. The actual measured soil water content of the profiles (Appendix 4.1), express as the mean of 15 lysimeters, is also displayed in Figure 4.1.

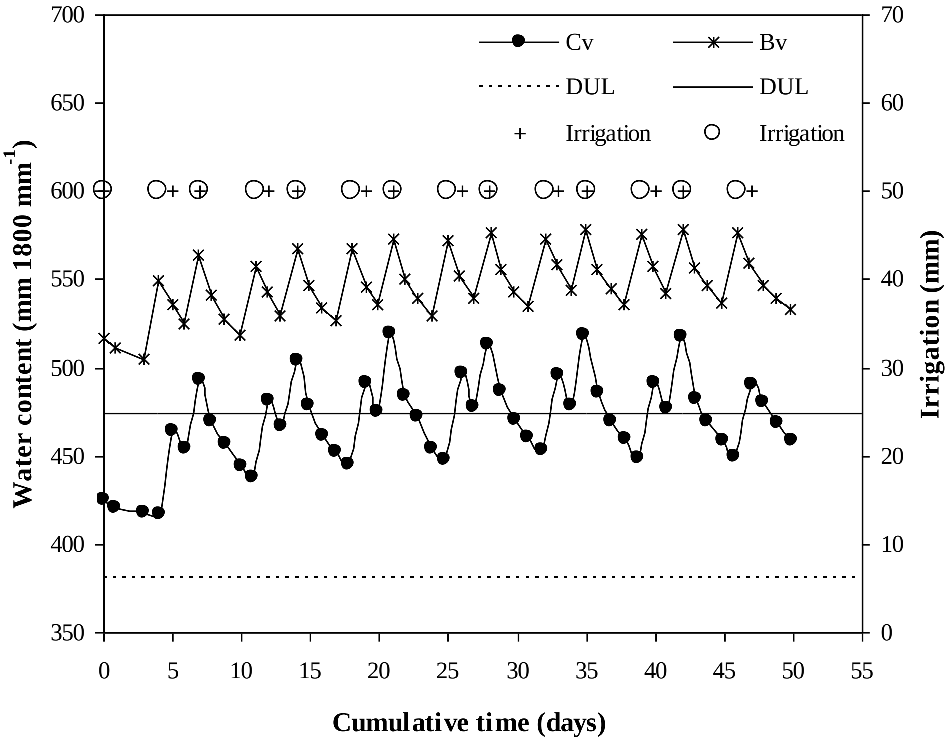


Figure 4.1 Mean water content (mm 1800 mm^{-1}) between the lysimeters of both soils and the irrigation intervals during the leaching period.

In the case of the Bv soil, the water content varied in a narrow band between 520 and 570 mm, after the initial irrigations were completed, which was higher than the DUL of 474 mm 1800 mm^{-1}. The water content of the Cv soil varied from 445 to 510 mm between irrigations which is higher than the DUL of 381 mm 1800 mm^{-1}. The Cv soil which is more sandy than the Bv soil also showed a slightly higher decrease in water content between irrigation intervals due to more rapid movement of drainage water. However at the end of the 50 day measuring period, the measured cumulative drainage was approximately similar, *viz.* 588 and 590 mm for the Bv and Cv soils respectively, because of the same amount of irrigation (700 mm).

Using the water balance equation to calculate evaporation (E = ΔW + I – D) gives total E values of respectively 93 and 76 mm for the Bv and Cv soils over the measuring period, respectively. The increase in the soil water content (ΔW) of the profile during the leaching period was 34 and 17 mm for the Cv and Bv soils respectively. The remaining 700 mm of the applied water drained from a soil depth of 1800 mm. Daily E was calculated as the total E divided by the number of measuring days, resulting in 1.9 and 1.5 mm day^{-1} for the Bv and Cv soils, respectively. To illustrate an alternative method, the daily drainage was also computed using the water balance equation with daily values of ΔW and E as inputs for all the lysimeters of both soils. The cumulative drainage calculated in this manner was compared with the actual measured cumulative drainage in Figure 4.2.

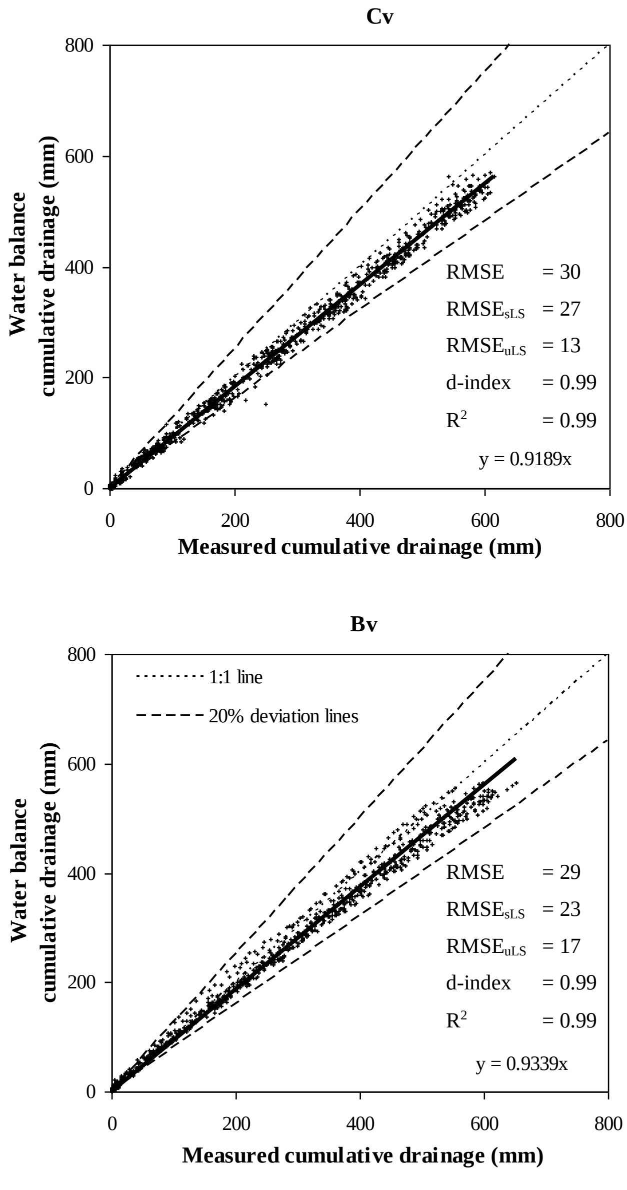


Figure 4.2 Relationship between measured and estimated cumulative drainage (mm) for all the lysimeters of both soils.

The corresponding linear regression line and the 20% deviation lines from the 1:1 line are also presented. The measured cumulative drainage was compared with the estimated values using graphical and statistical analysis as described by Willmott (1982). IRENE (Fila *et al*., 2001) was used in the calculation of the different statistical parameters. It provides the least squares (LS) of the systematic (s) and unsystematic (u) root mean square error (RMSE). The following criteria were used as approximate guidelines for assessment of the accuracy between measured and estimated values. The d-index should be > 0.90, the R^2 > 0.90 and the $RMSE_{s\ LS}$ < 90% of RMSE. For both soils all the statistical parameters met the set of criteria. The slope of the linear regression lines of both soils was close to one, confirming the accuracy between the measured and estimated values.

The mean pore water velocity over the leaching period was calculated with Equation 4.1 (Zeleke, 2003):

$$v_w = q / \theta \qquad (4.1)$$

where v_w = pore water velocity (mm day^{-1})

q = the Darcian flux

θ = the mean volumetric water content during the leaching period, from the soil surface to a depth of 1800 mm

The mean Darcian flux was calculated as the total amount of drainage during the leaching period divided by the number of days. For the Cv and Bv soils respectively the mean q was estimated as 11.8 mm day^{-1}. The mean volumetric water content during the 50 day period was 0.261 and 0.304 for the Cv and Bv soils respectively. The mean pore water velocity during the leaching period for the 1800 mm profiles of the Cv and Bv soils respectively was calculated as 45 and 39 mm day^{-1}, confirming the higher drainage rate of the more sandy Cv soil as compared to the more clayey Bv soil.

4.3.2 Change in salt distribution of profiles

Figure 4.3 illustrates the changing salt distribution patterns in the profiles (SL1 – SL2) after 2, 4, 6, 8, 10, 12 and 14 irrigations of 50 mm each with water of constant salinity, namely 75 mS m^{-1}.

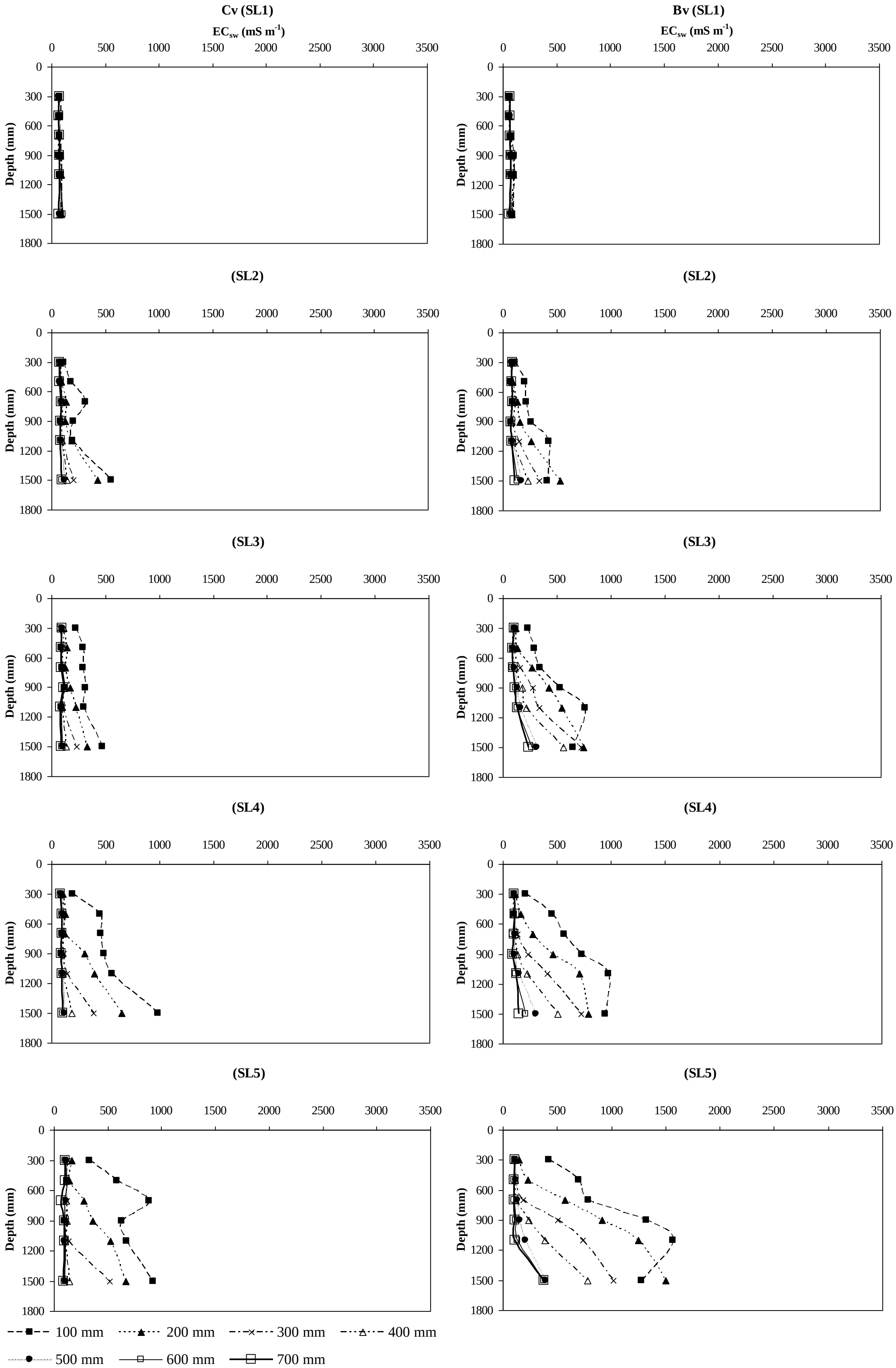


Figure 4.3 Change in salt distribution profiles (EC_{sw}, mS m^{-1}) of both soils, for the various levels of profile salinity (SL1 – SL5), during the entire leaching period.

The salt content for the various treatments and depths was expressed in EC_{sw} (mS m^{-1}) as measured in the water extracted with the suction cups. From Figure 4.1 it is evident that very little water drained from the soil profiles after the first two irrigations. The EC_{sw} corresponding to the 100 mm irrigation represents therefore effectively the EC_{sw} at the start of this leaching procedure which corresponds to the EC_{sw} at the end of the drainage period in Chapter 3. All the other salt distribution lines correspond with the successive cumulative irrigation intervals. After the 200 mm irrigation interval the salt distribution changed in comparison to the 100 mm irrigation line.

In the Cv soil the EC_{sw} of the top meter of the profiles were close to EC_i after 200 mm of irrigation was applied. For the Bv soil this stage was only reached after 300 mm of irrigation water was applied. The lag in response of the Bv soil can be ascribed by the lower drainage rates or pore water velocity as compared to the Cv soil. Again it is apparent that as water infiltrates from the top of the profile the residual solution is displaced and pushed downwards into the profile therefore increasing the salt content in the deeper soil layers.

4.3.3 Salt removal

The changing pattern of salt concentration in the root zone will approach some equilibrium concentration after many successive irrigations based on the salinity of the applied water (Chapter 3). In turn the salinity of the water percolating beneath the root zone will be in equilibrium with the soil solution. Figure 4.4 shows the mean EC_d corresponding to cumulative drainage of the various EC_i treatments of both soils.

For both soils no change in EC_d for the SL1 level were observed, as the soil solution was in near equilibrium with the applied irrigation water. Generally the Cv soil indicated a sharp decline in EC_d with an increase in drainage over soil salinity levels SL2 to SL5. After a mean 590 mm of drainage, the EC_d was close to the irrigation water salinity (75 mS m^{-1}), *viz.* 96, 102, 122 and 103 mS m^{-1} for the SL2 to SL5 levels. At a cumulative drainage of 150 mm, the Bv soil generally indicated for the SL2 to SL5 levels an increase in the EC_d were after a sharp decline followed. This increase is attributed to the salt peak, observed in Figure 4.3, being removed from the soil profile. For the Cv soil this slight increase in EC_d was not observed as the salt peak was largely removed with the mean 287 mm of drainage in Chapter 3. The EC_d of the Bv soil, after a mean 588 mm of drainage passed through the soil profiles, was 108, 152, 217 and 276 mS m^{-1} for the SL2 to SL5 levels illustrating the slower salt removal rate of the Bv soil.

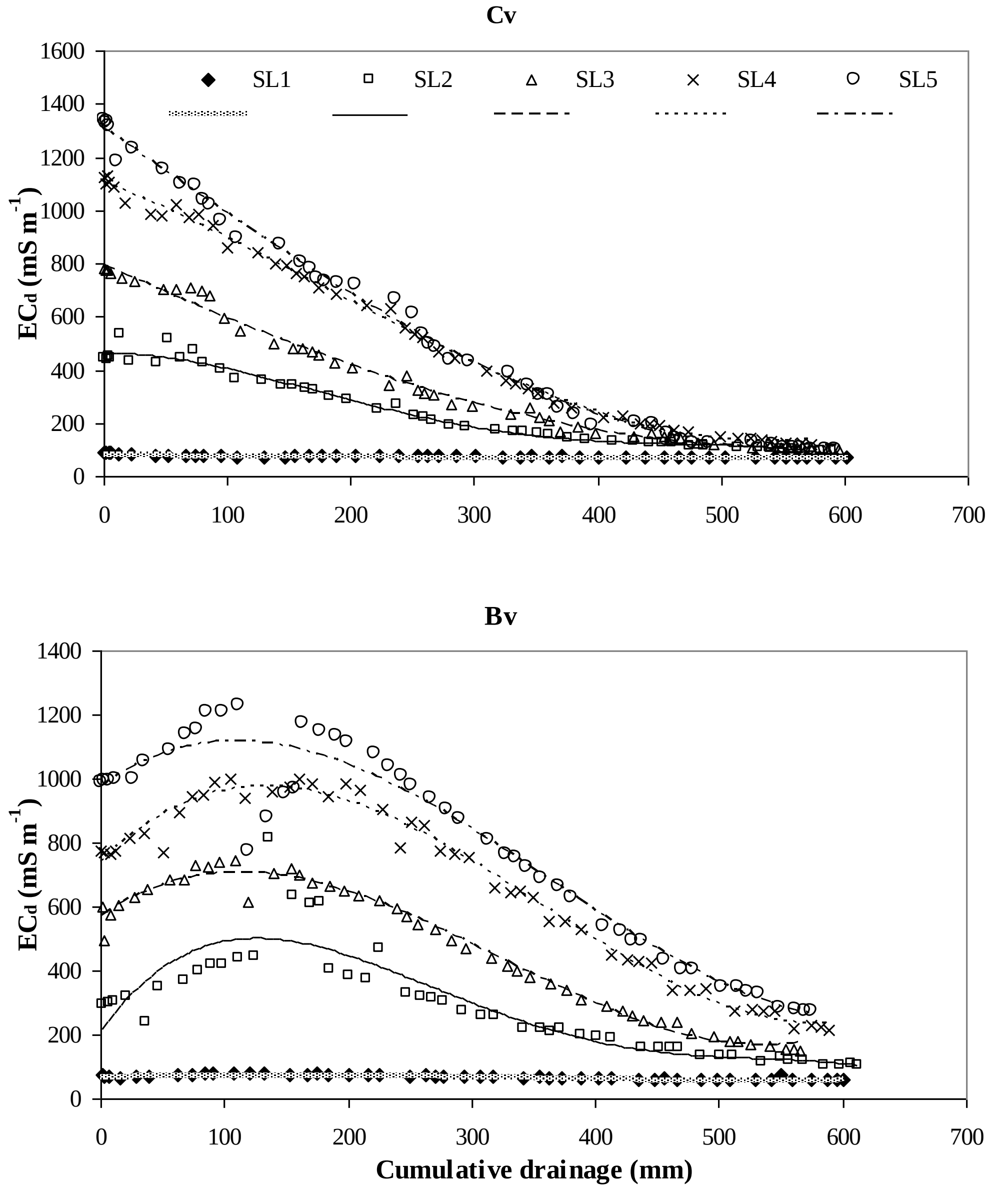


Figure 4.4 The mean electrical conductivity of the drainage water (EC_d) over a depth of 1800 mm for the various irrigated soil water salinity levels (SL1 – SL5) of both soils, corresponding to its cumulative drainage.

It was assumed that the water extracted through the various suction cups represents the salt concentration of a wet profile. Therefore the mean EC_{sw} of the six soil layers was used to give the mean salt concentration of the soil water in the profile. The decline in the mean EC_{sw} of both soils as affected by cumulative drainage is displayed in Figure 4.5. The decrease in salt concentration is best described by a semi-logarithmic function ($y = a \ln x + b$), indicating that salt removal is very efficient over the first 100 mm of drainage, where after the efficiency decline as more water is needed for reducing an unit EC_{sw}.

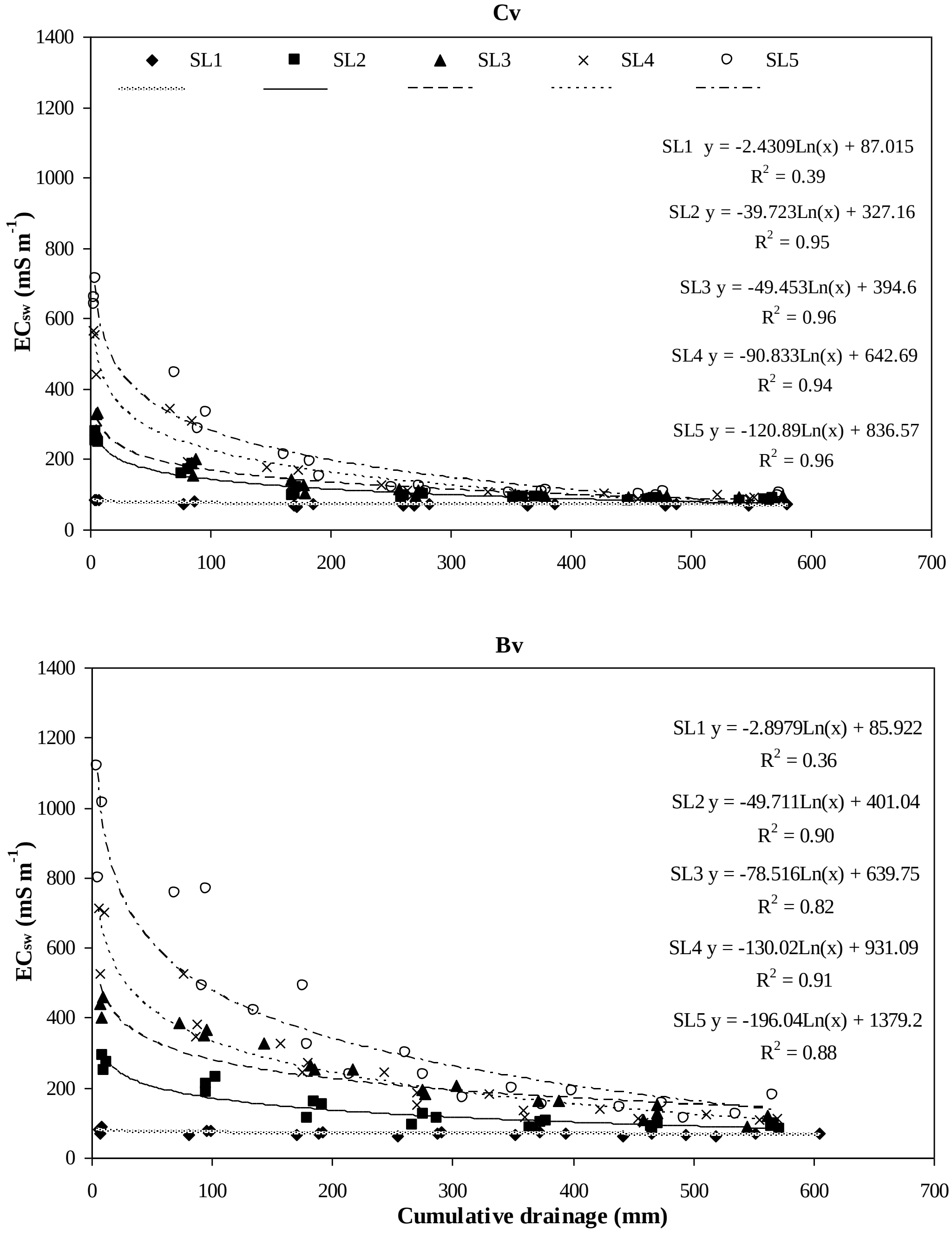


Figure 4.5 The mean electrical conductivity of the soil water (EC_{sw}) over a depth of 1800 mm of the various irrigated soil water salinity levels (SL1 – SL5) for both soils, corresponding to its cumulative drainage.

The mean EC_{sw} of the profiles for the levels SL2 to SL5 of the Bv soil was at 84, 139, 102 and 129 mS m^{-1}, after 588 mm of drainage water passed through the profile, which is slightly lower than the EC_d values at the same time. The mean EC_{sw} of the profiles for the Cv soil were in equilibrium with the irrigation water after 590 mm of drainage, *viz*. 73, 79, 63 and 65 mS m^{-1} for the SL2 to SL5 levels. The R^2 values of the regressed semi-logarithmic functions for levels SL2 to SL5, varied between 0.94 and 0.95 for the Cv soil and 0.82 and 0.91 for the Bv soil, respectively.

In Chapter 3 field saturation was measured as 668 and 658 mm 1800 mm^{-1} which relates to one pore volume for the Cv and Bv soils respectively. Theoretically it requires approximately one pore volume of water to move a mobile solute through a soil column. The total mean drainage between the treatments for the Cv and Bv soils respectively was related to 0.88 and 0.89 pore volumes. Figure 4.4 shows for all practical purposes that in displacing almost one pore volume (0.90) of the soil, with a solution of 75 mS m^{-1} will remove approximately all of the salts and bring the solution in equilibrium with the irrigation water.

Both the mean EC_{sw} of the profile and the EC_d of the Cv soil after almost one pore volume displacement were in equilibrium with the EC_i used. For the Bv soil a little more water was required to bring the mean EC_{sw} of the profile and the EC_d in equilibrium with the irrigation water especially for the more saline soils. This could mainly be attributed to the better sorbtion characteristics of the Bv soil, with the higher clay content, as compared to the Cv soil.

4.3.4 Leaching curves

Salt removal can also be expressed on a relative basis, in other words as a fraction of the maximum excess salts removed. Excess salts refer to the salts that will be removed until a level of electrical conductivity under the existing soil-irrigation-water-drainage equilibrium conditions is reached. According to the above-mentioned section this equilibrium will be equal to the salinity of the irrigation water. Figure 4.6 shows this fraction of excess salts removed for both soils, constructed by plotting 1 – ($EC_{sw\ actual}$ – EC_i / $EC_{sw\ initial}$ - EC_i) as a function of depth of leaching water per unit depth of soil (Dw / Ds).

The EC_{sw} initial and actual denotes the EC of the soil water, collected from the suction cups during the leaching procedure, before and after leaching and EC_i the electrical conductivity of the irrigation water. Data are shown for depths of 0-300, 0-600, 0-900, 0-1200, 0-1500 and 0-1800 mm for SL2 to SL5 salinity levels of both soils. The full data set presented in

Appendix 4.2 was used to calculate the ratios for the different depth intervals. Only the data that is not mark bold, presents active salt removed and were used. Once equilibrium was reached the data were excluded.

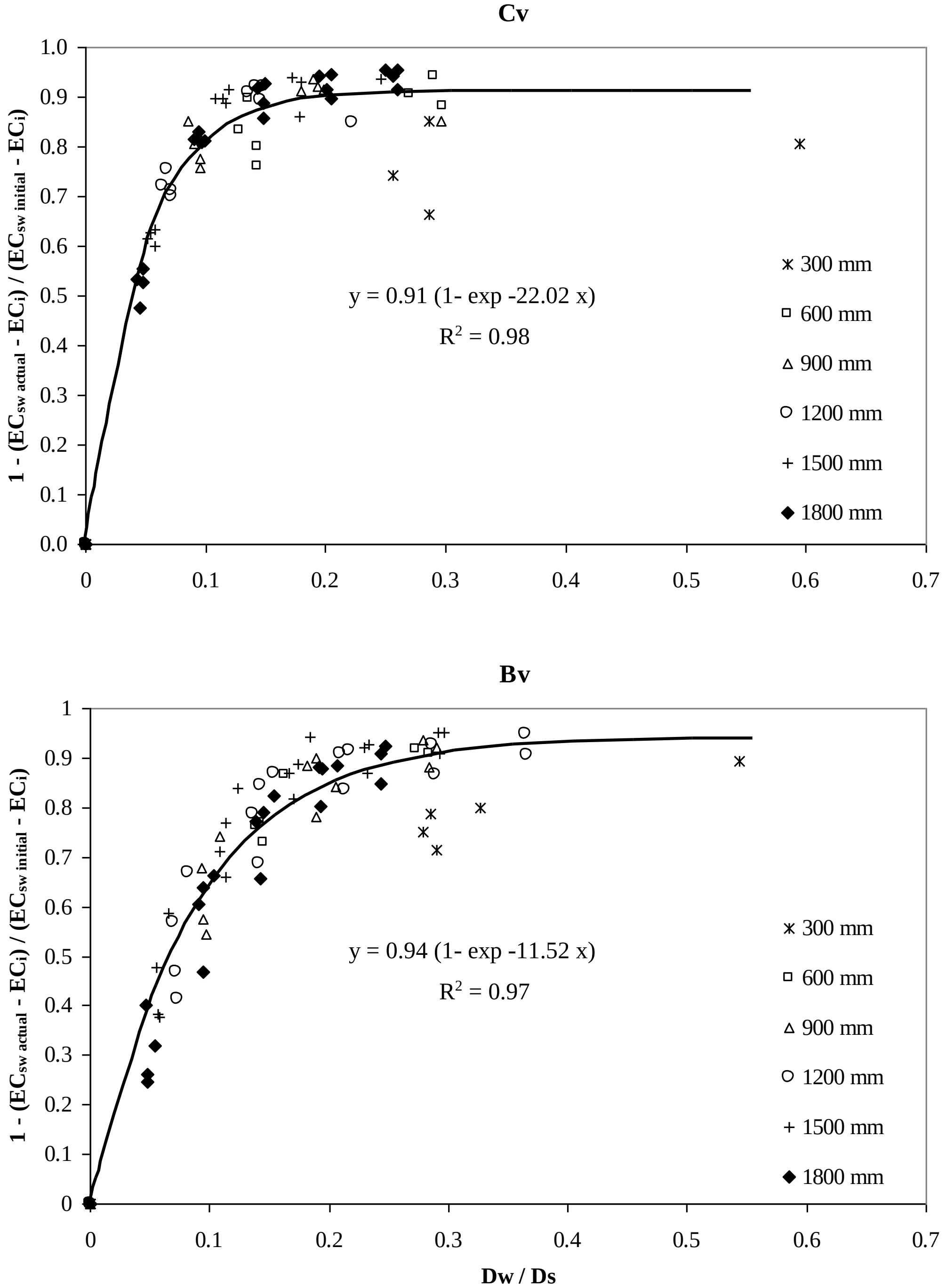


Figure 4.6 Fraction of excess salts removed ($1 - \{EC_{sw\ actual} - EC_i\} / \{EC_{sw\ initial} - EC_i\}$) in relation to depth of leaching water per unit depth of soil (Dw / Ds).

The exponential association (y = a {1 – exp –b x}) gave a single mathematical function for describing salt removal as a function of drainage water per unit soil depth. The fraction of excess salt removed correlated well with leaching water per unit soil depth ($R^2 > 0.97$) for both soils. From the shape of the curves it's clear that the economic use of water will play an important role in salt removal through leaching. For example, to remove 50% of the excess salts, 0.04 mm of drainage was required for the Cv soil and 0.07 mm for the Bv soil, to pass through per mm of soil depth leached with an EC_i of 75 mS m^{-1}. Removing the remaining 90% of excess salt requires approximately 4 times more drainage, since 100% of excess salts as illustrated in Section 4.3.3 for all practical purposes cannot be removed due to the dynamic nature of soils. Leaching of soils until 80% of excess salts are removed will be extremely efficient where after the efficiency declines rapidly as a large amount of water is needed in removing 100% of excess salts. The 80% removal level is widely accepted as a guideline for determining the optimum amount of water required for managing salinity efficiently. From the observed relationship it is apparent that for 80% removal of excess salts, 0.1 and 0.17 mm of leaching is needed per mm soil depth for the Cv and Bv soils respectively, relating to 0.27 and 0.47 pore volume displacement.

The validity of the observed empirical relationship is likely restricted to experimental conditions and soil and salinity characteristics of the present study. Khosla *et al*., (1979) illustrated that for 75% salt removal from a highly sodic sandy loam soil approximately one pore volume displacement was needed. Van der Molen (1956) removed 50% of chloride with one pore volume, while Talsma (1966) removed 98% of chloride from a soil depth of 1200 mm with drainage water equivalent to about 3.5 pore volumes. By subtracting EC_i from the actual and initial EC_{sw} the relationship, between the fraction of excess salts removed and depth of leaching water, becomes independent of the salinity of irrigation water, existing drainage conditions and evaporation conditions. If this fraction of excess salts removed is plotted against Ds / Dw the influence of soil characteristics can be illustrated.

Figure 4.7 shows the relationship between ($EC_{sw\ actual} - EC_i$) / ($EC_{sw\ initial} - EC_i$) and Ds / Dw for the Cv and Bv soils respectively, those of Leffelaar and Sharma (1977) representing sandy loam to silty loam soils and those of Pazira and Sadeghzadeh (1999) representing silty clay to clay soils located in the Khuzistan Province southwest Iran. The same data set as described in Figure 4.6 was used. For the Cv and Bv soils respectively an excelled correlation was found, with an R^2 of 0.72 and 0.86, in describing the efficiency of salt leaching as influenced by soil texture and salinity status. The difference between the graphs of the sandy loam Bv soil and those of Leffelaar and Sharma (1977) is attributed to the salinity status, as the Bv was classified as saline while the sandy loam of Leffelaar and Sharma (1977) was classified as highly saline sodic.

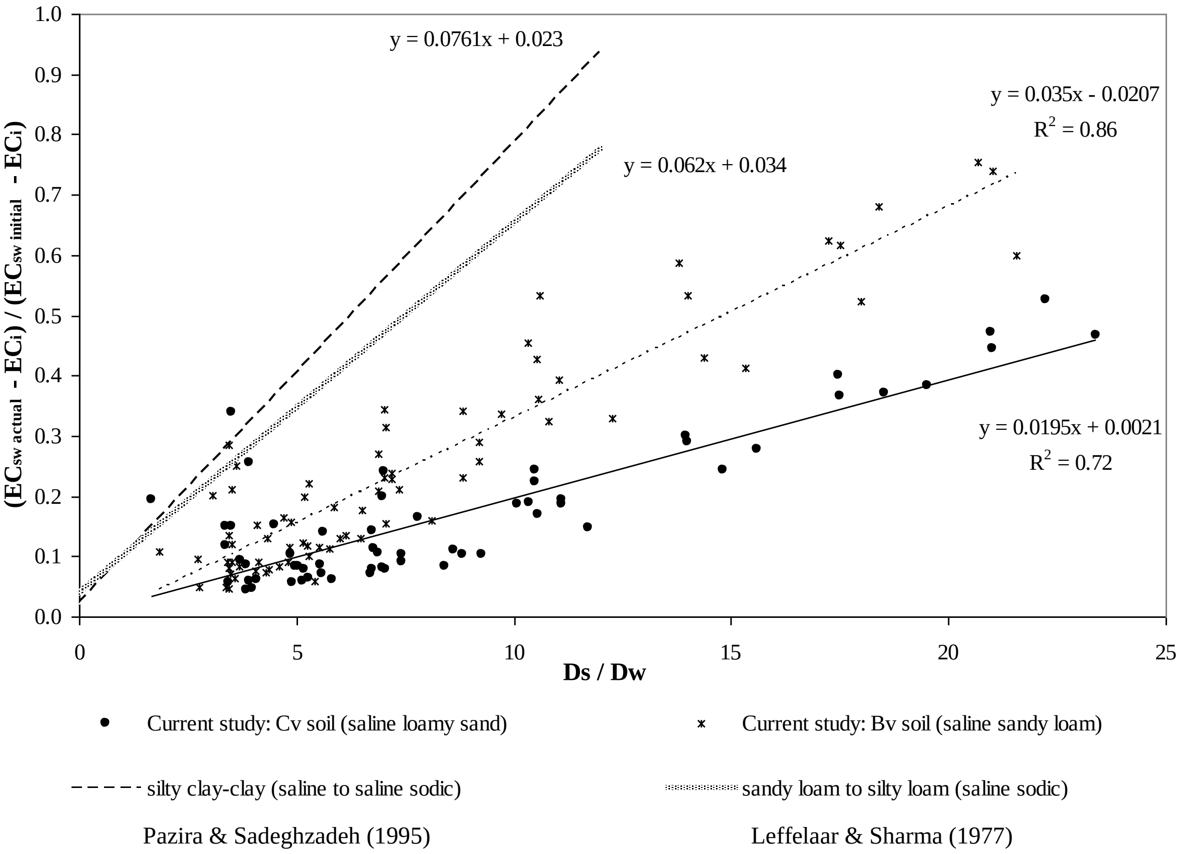


Figure 4.7 Leaching curves relating ($EC_{sw\ actual} - EC_i$) / ($EC_{sw\ initial} - EC_i$) against Ds / Dw for a range of soil textural and salinity levels.

It must be said that the leaching curves is only valid for the initial salinity ranges through the soil profile it was derived from (Pazira & Sadeghzadeh, 1999). For similar salinity status and soil textural classes, it was found that leaching was less efficient in the soils where the initial salinity was lower as compared to soils with higher initial salinity levels.

4.4 Conclusions

In this chapter various saline soils where leached with water of a constant salinity. From the water balance it was calculated that the mean drainage rate between the two soils, under these conditions, was 11.8 mm day^{-1}, which amounted to 590 mm drainage over the leaching period of 50 days. For the Cv soil the mean pore water velocity over the leaching period for the 1800 mm profiles was calculated as 45 mm day^{-1}, while the Bv soil amounted to 39 mm day^{-1}, illustrating the slower drainage rate and salt removal rate of the Bv soil as compared to the Cv soil. After 2, 4, 6, 8, 10, 12 and 14 irrigations of 50 mm each the salt distribution patterns in the profiles changed as the residual solution was displaced and pushed downward. Under these conditions the changing pattern of salt concentration in the profiles approached an equilibrium concentration equal to the irrigation water salinity after approximately one pore volume of water passed through the soils. The salts removed until this level of electrical conductivity under the existing soil-irrigation-water-drainage equilibrium conditions is reached were referred to as excess salts.

In terms of managing salinity levels in the root zone, removing all of the excess salts will not be sustainable in the long run. The leaching curves showed that in leaching the soil until 80% of excess salts were removed, to be extremely efficient where after the efficiency declined rapidly as approximately one pore volume of water was needed in removing all of the excess salts. When only 80% of the excess salts were removed the efficiency of leaching increased with an increase in initial salinity.

It can be concluded that in apedal to weakly structured relative homogeneous soils, salt leaching under these conditions can be described as piston flow. Leaching curves can therefore be used in calculating the leaching requirement. The empirical relationship is however only valid to the experimental conditions, soil and salinity characteristics and for the range of initial salinities it was derived from. Developing leaching curves for a range of initial salinities of two apedal soils, leached with various irrigation water salinities under unsaturated conditions can be useful in managing root zone salinity, which will be examined in the next chapter. Estimates on the amount of water needed for efficient leaching is usually based on guidelines established from empirical relationships derived from field experiments and experience.

CHAPTER 5

MANAGING ROOT ZONE SALINITY THROUGH LEACHING WITH IRRIGATION WATER OF VARIOUS SALINITIES

5.1 Introduction

The management of saline or potential saline soils may involve a number of complex processes. Modelling enables us to compare these processes and may indicate how to modify these processes for optimization of the problems encountered. Modelling solute transport in the unsaturated zone depends very much on the simulation of soil water fluxes that are strongly influenced by precipitation, evapotranspiration, surface runoff and land-surface properties. To provide good approximations of soil water fluxes, a model capable of simulating flow in the unsaturated zone, overland flow and water table movement is required (Xu & Shao, 2002).

The main focus of this study, as illustrated in the preceding chapters, is the processes in the unsaturated zone. Here the simpler single-process oriented model i.e. models for infiltration, root water uptake, leaching or solute transport models, can be very useful in modelling soil salinity. A number of hyrosalinity models have been developed to examine and manage soil water and solute movement. Developers of hydrosalinity models have adopted either one of two common approaches, the capacity approach and the thermodynamic approach. Moolman (1993) and Eigenhuis (1997) conducted a review on water and solute transport models (Burns, Addiscott, TETrans, Rose, Shaffer, Jury, Wagenet-Hutson) simulating leaching processes in the unsaturated zone. It was concluded that the more mechanistic models are superior to the more simple non-mechanistic, capacity type models because all the comparisons was conducted on small plots. The alleged superiority might not be so conclusive when the models are used to predict responses in large irrigated areas where the influence of spatial variability of rate parameters is expected to be more.

Herald (1999) gave a summary of hydrosalinity models tested with field data representative of the lower Coerney River irrigation area. Three of these leaching models were management models, which varied in complexity from the very simple leaching requirement model, LR, to the intermediate complex model SODICS, and the more complex PEAK model. The research model, LEACHC, is considerably more complex and requires more detailed inputs. All of these models showed reasonable comparisons between measured and simulated results. It was concluded by Herald (1999) that the results were unsatisfactory because it excluded macropore or by-pass flow.

Modelling soil salinity is a complicated process that must be understood when deciding on what model to use. Moolman (1993) explained that the choice of the appropriate model to use will depend on four factors: (i) the specific application; (ii) the required accuracy of prediction; (iii) how much information is available and how much time and effort can be spent in obtaining the required information; and (iv) the experience and knowledge of the user of the model.

Little general use has been made of the dynamic more physically based models beyond their initial development and testing due to the intensive data requirements (Herald, 1999). These so-called research models are generally not suitable for management purposes. The strength of these models is that they comprehensively integrate the knowledge of the processes controlling water and solute movement. Management models are less intensive and are commensurately less quantitative in their ability to predict solute and water movement under field conditions where estimations are usually based on empirical relationships. In this chapter an attempt will be made to derive an empirical model capable of estimating salt removal from apedal soils with various salinity levels, irrigated with water of various salinities in order to effectively and efficiently manage root zone salinity.

5.2 Materials and methods

5.2.1 Background on salinity profiles

As indicated through the aims, this chapter will focus on the leaching of salt and not the accumulation of salt in the profiles. The salt accumulation and implications were reported in Ehlers *et al*. (2006). Conveniently the salt accumulation procedure can be summarized as follows. Wheat and beans were consecutively grown in the lysimeters (Figure 5.1), as described in Chapter 3 under shallow water table conditions and irrigated with various irrigation water salinities (EC_i) replicated three times per soil type *viz*. 15, 150, 300, 450 and 600 mS m^{-1}.

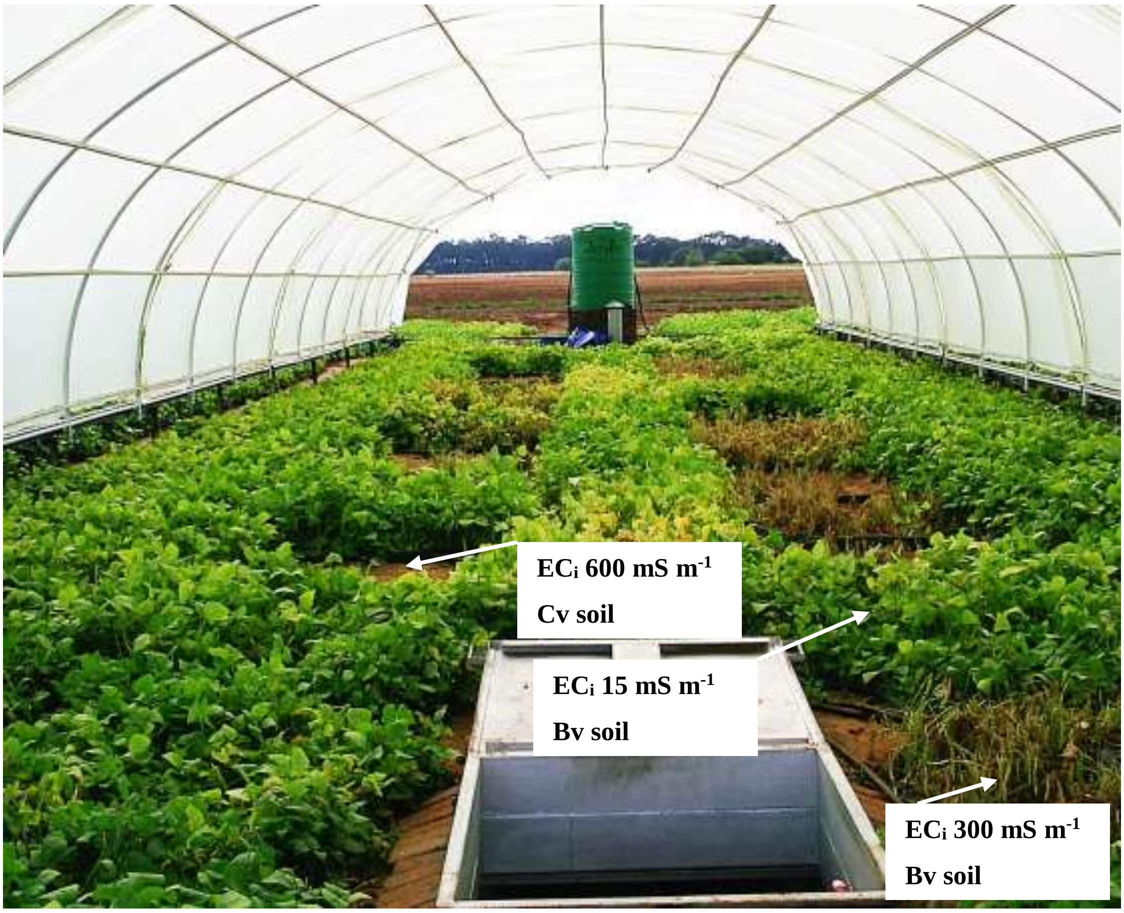


Figure 5.1 Photo of beans irrigated with various irrigation water salinities of both soils, under shallow water table conditions.

A total mean of 447 mm of water was applied between the treatments of both soils through surface irrigation and by recharging the water table to a constant depth during the growing season of wheat and beans. This resulted in salt accumulating in the profiles of both soils according to the salinity of the irrigation water. The effect of salt accumulation (soil water salinity) on plant growth at the end of the wheat and bean growing seasons are visible in Figure 5.1. It is apparent that the 600 mS m^{-1} irrigation water salinity had the most significant effect on plant growth as compared to the 15 mS m^{-1} irrigation water salinity because of water stress induced by the osmotic effect of the high soil water salinity (Ehlers et al., 2006).

5.2.2 Leaching procedure

The various saline profiles which resulted from the salt accumulating during the wheat and beans experiment, were categorised into five salinity levels (SL1 – SL5) according to the electrical conductivity of the soil water (EC_{sw}, mS m^{-1}) per soil type with three replications. Profile SL1 was irrigated with water of an EC_i of 15 mS m^{-1}, SL2 with 75 mS m^{-1}, SL3 with 150 mS m^{-1}, SL4 with 225 mS m^{-1} and SL5 with 300 mS m^{-1}. The five EC_i irrigation water salinities were regarded as the five treatments that will be used in this leaching experiment (Table 5.1). Six irrigations were given over a period of nine weeks, which amounted to 848 and 911 mm for the Cv and Bv soils, respectively. Irrigations were manually applied on the surface through the use of buckets, to represent flood irrigation.

5.2.3 Measurements

Percolation: Drainage was measured manually at the bottom of the lysimeters on a daily basis throughout the entire measuring period. Figure 5.2 shows the ceramic suction cups installed from the access chamber side at various depths and the manometers and buckets connected to the bottom of the lysimeters.

Figure 5.2 Photo of ceramic cups installed from the access chamber side of the lysimeters as well as the manometers and buckets connected to the bottom of the lysimeters.

The manometer and bucket were disconnected in order to allow the water to drain from the soil. Drainage water was collected in 10 L buckets, via the drained-outlet of each lysimeter. The number of buckets was recorded throughout the measuring period and the volume of measured drainage water converted to depth (mm). Unfortunately the electrical conductivity of the drainage water was not measured.

Soil water salinity: Soil water was extracted from the soils in the lysimeters with ceramic suction cups, installed at depths of 300, 500, 700, 900, 1100 and 1500 mm from the soil surface. The electrical conductivity of the soil water (EC_{sw}) was measured with an Ecoscan Electrical Conductivity Meter, six times during the leaching period.

5.3 Results and discussion

5.3.1 Status of salinity profiles

The mean EC_{sw} and SAR over the depth of the different profiles at the start of the leaching experiment are summarized in Table 5.1. The mean EC_{sw} over the depth of the profiles ranged from 158 (SL1) to 1887 (SL5) mS m^{-1} for the Cv soil and 160 (SL1) to 1698 (SL5) mS m^{-1} for the Bv soil. The mean SAR over the depth of the profiles ranged from 3 (SL1) to 10 (SL5) and 2 (SL1) to 9 (SL5) for the Cv and Bv soils, respectively. For both soils no significant increase in the mean SAR of the profiles was found with an increase in mean EC_{sw} of the profiles. Applying the criteria of the United States Salinity Laboratory Staff as described in Chapter 3, it is obvious that these profiles are all saline, accept the SL1 profiles, which is classified as non-saline.

Table 5.1 Mean salinity (EC_{sw}) and sodium adsorption ratio (SAR) over the depth of the different salinity profiles (SL1 – SL5) at the onset of the leaching experiment

Soil	EC_i treatments (mS m^{-1})	15	75	150	225	300
	Salinity level	**SL1**	**SL2**	**SL3**	**SL4**	**SL5**
Cv	**Mean EC_{sw} (mS m^{-1})**	158	544	835	1492	1887
	Mean SAR (mS m^{-1})	3	8	9	10	8
Bv	**Mean EC_{sw} (mS m^{-1})**	160	636	1372	1520	1698
	Mean SAR (mS m^{-1})	2	5	9	9	8

5.3.2 Irrigation, drainage and salt removal

A total of 848 and 911 mm of irrigation was used to leach the excess salts from the profiles of the Cv and Bv soils, respectively. Excess salts were defined as the difference between the initial salt content (mS m^{-1}) and the target salinity of the irrigation water or EC_i treatment (Table 5.2). The mean EC_{sw} over the depth of the profiles at the end of the leaching period were close to that of the irrigation water treatment applied for both soils, indicating that all of the excess salts have been removed. The $EC_{sw\ end}$ which corresponds to the end of the leaching period varied between 53 and 397 mS m^{-1} for the $EC_{i\ 15}$ to $EC_{i\ 300}$ treatments of the Cv soil and between 53 and 382 mS m^{-1} for the various treatments of the Bv soil.

The excess salts were removed through drainage that varied between 723 and 781 mm in total over the profiles of the Cv soil and between 799 and 850 mm over the Bv profiles. The ratios between drainage and irrigation depth of water varied between 0.85 and 0.92 for the Cv soil and between 0.88 and 0.93 for the Bv soil. In fact the values should be close to one if water storage in the profile was zero and evaporation negligible low. To apply so much extra water during the crop growing season, when ET dominates the water balance, is not practical. However it provides sound information on salt removal in the absence of a crop.

Table 5.2 Mean salinity levels of the profiles (EC_{sw}) at the start ($EC_{sw\ initial}$) and end ($EC_{sw\ end}$) of the leaching period, leached with various irrigation water salinities (EC_i)

Soil	Parameter	Units	$EC_{i\ 15}$	$EC_{i\ 75}$	$EC_{i\ 150}$	$EC_{i\ 225}$	$EC_{i\ 300}$
Cv	$EC_{sw\ initial}$	mS m^{-1}	SL1: 158	SL2: 544	SL3: 835	SL4: 1491	SL5: 1888
	$EC_{sw\ end}$		53	117	124	251	397
	Irrigation	mm	848	848	848	848	848
	Drainage		777	757	764	781	723
	Drainage : irrigation ratios		0.92	0.89	0.90	0.92	0.85
Bv	$EC_{sw\ initial}$	mS m^{-1}	SL1: 160	SL2: 636	SL3: 1372	SL4: 1520	SL5: 1698
	$EC_{sw\ end}$		53	109	155	221	382
	Irrigation	mm	911	911	911	911	911
	Drainage		799	850	803	855	814
	Drainage : irrigation ratios		0.88	0.93	0.88	0.93	0.89

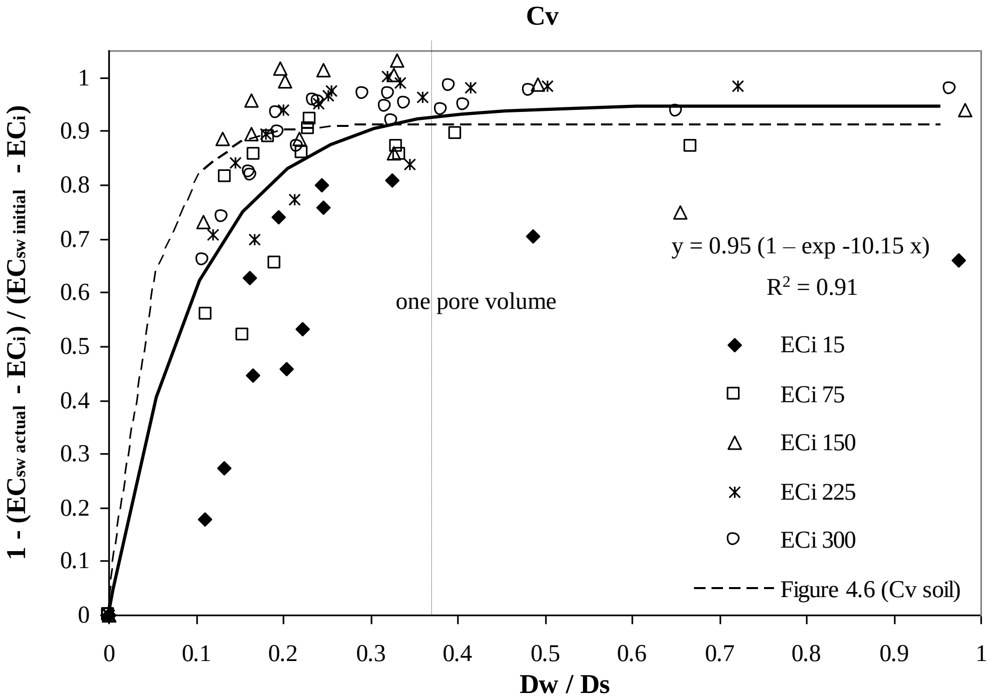
5.3.3 Leaching requirement

The concept of leaching curve were described in the previous chapter and it was concluded that it provide reliable estimates of the quantity of water required to accomplish salt leaching. The solid line in Figure 5.3 shows similar leaching curves that were developed from the current leaching experiment based on the fraction of excess salts removed (1 – {$EC_{sw\ actual}$ – EC_i} / {$EC_{sw\ initial}$ – EC_i}) per depth of leaching water (Dw) per unit soil depth (Ds) for both soils leached with a range of irrigation water salinities ($EC_{i\ 15}$ – $EC_{i\ 300}$). Data are shown for depths of 0-300, 0-900, 0-1200, 0-1500 and 0-1800 mm for both soils (Appendix 5.1). Only the data that is not mark bold, presents active salt removed and were used. The $EC_{sw\ actual}$ represents the salinity at a specific soil depth after a certain amount of cumulative drainage, as can be seen in Appendix 5.1. The initial salinity levels for the different soil depths, ranged from 142 to 2815 mS m^{-1} for the Cv soil and from 160 to 2042 mS m^{-1} for the Bv soil (Appendix 5.1).

The multiple EC_i leaching curves shows that irrespective the salinity of the soil and the salinity of the irrigation water, almost all of the excess salts (> 90%) were removed from both soils with one pore volume of drainage. This confirmed that piston flow can describe leaching of salt in apedal soils as both the leaching curves of the Cv and Bv soils, respectively, require approximately one pore volume.

In Chapter 4 it was emphasized that the relationship of leaching curves is empirical and consequently only valid for the experimental conditions, soil and salinity characteristics and initial salinity levels it was derived from. The general idea of the leaching curves, which are based on the relationships, as expressed in Figure 5.3, is that once it has been characterized with a particular EC_i, it could be used for a range of irrigation water salinities (Khosla *et al.*, 1979). This hypothesis was tested by comparing the leaching curves from Figure 4.6 (dotted lines), which was derived from irrigation water with a constant EC_i level of 75 mS m^{-1} with the multiple EC_i leaching curve of this experiment (solid line in Figure 5.3). These lines showed generally similar shapes per soil type, which confirms that it requires approximately one pore volume of drainage to remove 90% of excess salts over a particular soil depth, irrespective EC_i (Figure 5.3). Closer inspection of the leaching curves reveals that EC_i does have however an influence on the gradient of the lines. For example, to remove 50% of the excess salts for the Cv soil a Dw / Ds ratio of 0.04 and 0.06 are required for the single EC_i

derived curves versus the multiple EC_i derived curves, respectively. The Bv soil confirmed the difference between the two leaching curves.



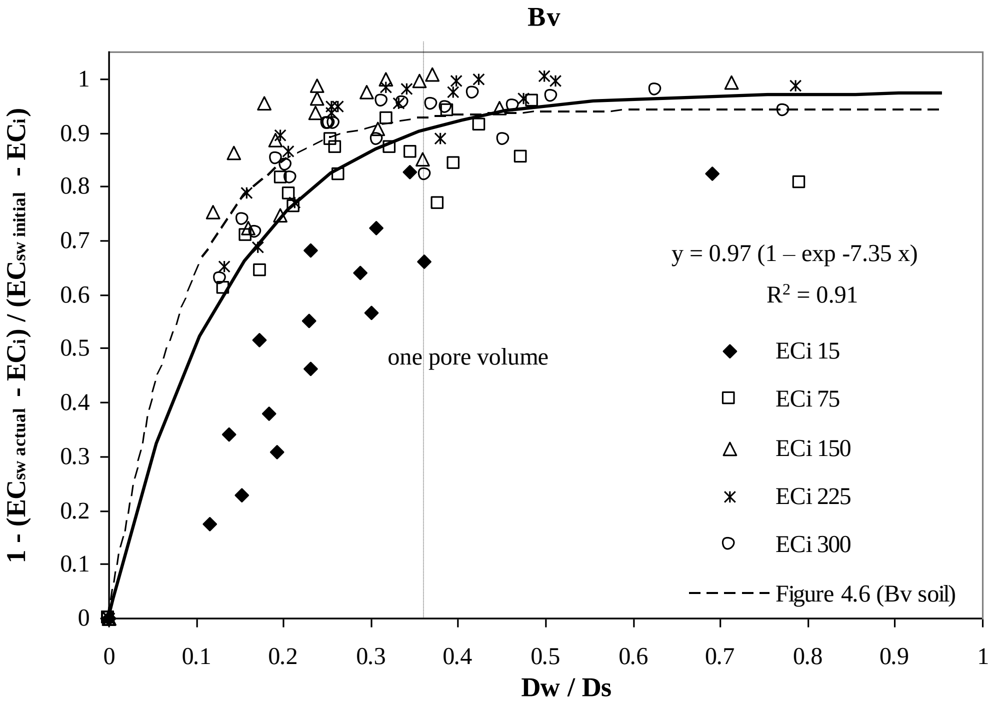


Figure 5.3 Fraction of excess salts removed ($1 - \{EC_{sw\ actual} - EC_i\} / \{EC_{sw\ initial} - EC_i\}$) in relation to depth of leaching water per unit depth of soil (Dw / Ds).

It is interesting to note that all the data points in Figure 5.3 of the $EC_{i\ 15}$ treatments for both soils are slight out of correlation with respect to the data points of the $EC_{i\ 75}$ to EC_i 300 treatments. These points represent the lower initial EC_{sw} levels of the $EC_{i\ 15}$ treatments, which confirmed the findings of Pazira & Sadeghzadeh (1999). They illustrated that leaching will be less efficient in soils where the initial salinity levels were lower as compared to soils with higher initial salinity levels.

Taking into account all these factors it is apparent that the leaching curves in Figure 5.3 established with the multiple EC_i derived curves will provide more reliable estimates of the leaching requirement as they are applicable to a range of irrigation water salinities, *viz.* 15 to 300 mS m^{-1}, with a wider range of initial salinity levels. Hence the depth of leaching requirement (Dw) irrespective soil depth, soil salinity and irrigation water salinity can be derived from the general regression equation (Equation 5.1) illustrated in Figure 5.3:

$$y = a\,(1 - \exp -b\,x) \qquad (5.1)$$

where x = Dw / Ds.

Solving Dw will then give:

$$Dw = [(\ln(-y / a + 1)) / b]\,Ds \qquad (5.2)$$

where y = $1 - (EC_{sw\ actual} - EC_i) / (EC_{sw\ initial} - EC_i)$
$EC_{sw\ actual}$ = target soil water salinity (mS m^{-1})
a = 1
b = -10.15 for the Cv soil and -7.35 for the Bv soil
Ds = depth of soil (mm).

The parameter a, should theoretical be one, as the soil is leached to the EC_i removing therefore all of the excess salts. Parameter b should be a function of the experimental conditions, initial salinity levels and soil and salinity characteristics with the last probably considered as the most important referring to the drainage characteristics of soils.

The leaching equations are therefore unique for a specific soil type and can only be extrapolated to different soil types, if it is possible to relate the variable b to easily measurable soil properties associated with its drainage characteristics. The drainage rate of soils is mainly a function of pore size distribution. For apedal soils, the percentage silt-plus-clay is well correlated with the hydraulic and water holding characteristics of soils (Bennie *et al*., 1998). The relationship between the mean silt-plus-clay percentages of the two soils and the corresponding b-values is presented in Figure 5.4.

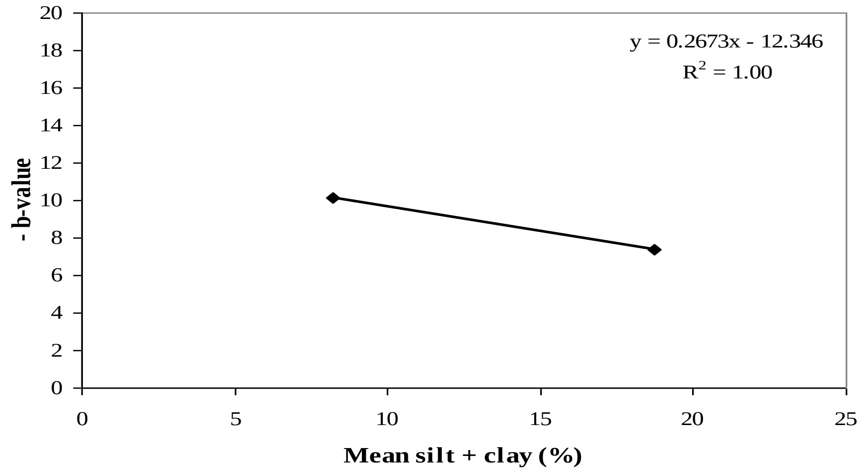


Figure 5.4 Relationship between the mean silt-plus-clay percentage of the two soils and the corresponding b-values for the salt leaching equations.

Unfortunately two data pairs are insufficient to obtain a valid relationship. If it is not possible to determine leaching curves in the field, the aid of models such as SWB (Annandale *et al*., 1999) and SALTMED (Ragab, 2002) can be consulted. However users should take note that simulation with these models requires special skills and support from the modellers.

5.3.4 Application of leaching curves

The application of leaching curves is illustrated in Table 5.3. Equation 5.2 was used to calculate for the Cv and Bv soils, respectively, the depth of drainage (Dw) required to remove 100 and 80% of excess salts from various soil water salinity levels at various depths through the profile when irrigated with various irrigation water salinities. The two soils under discussion represent a significant area of the total irrigated land in the Free State, Northern Cape and North West provinces in South Africa.

In general Table 5.3 shows that the sandier Cv soil will require less water for leaching of salts as compared to the more clayey Bv soil. The target EC_{sw} when 100% of excess salts have been removed was taken slightly higher than the EC_i, because it is difficult to obtain 100% equilibrium conditions between EC_i and EC_{sw} due to the dynamic nature of soils. The depth of leaching required (Dw) when 100% of excess salts were removed increased with an increase in initial salinities for both soils. There was however no significant influence of irrigation water salinity on the leaching requirement for both soils.

Table 5.3 Guidelines for approximate depth of leaching requirement (mm) to leach 100 and 80% of excess salts from different depths of various saline profiles, irrigated with various irrigation water salinities.

Soil	EC_i	$EC_{sw\ initial}$	$EC_{sw\ target}$		Dw for 100% removal				Dw for 80% removal			
					Soil depth (mm)							
	$mS\ m^{-1}$	$mS\ m^{-1}$	$mS\ m^{-1}$ 100%	80%	0-300	0-600	0-900	0-1200	0-300	0-600	0-900	0-1200
Cv	50	400	55	124	126	251	377	502	46	92	138	184
		600	55	164	139	278	417	556	47	93	140	186
		800	55	204	148	296	444	592	47	94	140	187
		1600	55	364	170	339	509	678	47	94	142	189
	100	400	105	164	121	242	363	484	46	91	137	183
		600	105	204	136	272	408	544	46	93	139	186
		800	105	244	146	292	438	584	47	93	140	187
		1600	105	404	169	337	506	674	47	94	142	189
	150	400	155	204	116	231	347	463	45	91	136	181
		600	155	244	133	266	399	532	46	93	139	185
		800	155	284	144	288	432	575	47	93	140	187
		1600	155	444	168	335	503	670	47	94	141	189
Bv	50	400	55	124	173	347	520	694	63	127	190	254
		600	55	164	192	384	576	767	64	128	193	257
		800	55	204	205	409	614	818	65	129	194	258
		1600	55	364	234	468	702	937	65	130	196	261
	100	400	105	164	167	334	501	668	63	126	189	252
		600	105	204	188	376	564	752	64	128	192	256
		800	105	244	202	403	605	807	65	129	194	258
		1600	105	404	233	466	698	931	65	130	195	261
	150	400	155	204	160	319	479	639	63	125	188	250
		600	155	244	184	367	551	735	64	128	192	256
		800	155	284	199	397	596	795	64	129	193	258
		1600	155	444	231	463	694	926	65	130	195	261

It is obvious that when 100% of the excess salts were removed, soil depth and initial salinity of the soil plays an important roll in determining the leaching requirement. Removing 100% of excess salts will however not be sustainable. When 80% of the excess salts were removed, Table 5.3 shows that only soil depth plays a roll in determining the amount of leaching water required, as there was no significant difference in the depth of water required for the various initial salinities leached with the various irrigation water salinities. For both the 100 and 80% of excess salts removed for both soils there was an increase in leaching requirement with an increase in soil depth. The target EC_{sw}, after 80% of excess salts were removed, will however increase with an increase in initial salinity status of the soil. This indicates that although leaching will always be effective, its efficiency will increase from a low to high soil salinity content (Monteleone *et al.*, 2004). It will therefore be advisable to only leach the root zone when the salinity has reached the threshold salinity level of the crop grown capable of significantly interfering with the yield.

5.3.5 Verification of leaching curves

Equation 5.2 was verified against the independent data set from Chapter 4, where irrigation water of an EC_i of 75 mS m^{-1} was used. Soil depths of 0-300, 0-600, 0-900, 0-1200, 0-1500 and 0-1800 mm were used in the analysis. The target EC_{sw} values were calculated with Equation 5.2 for specific soils using the measured drainage at various measured initial EC_{sw} values and for the mentioned depths. In Figure 5.5 the calculated EC of the soil water values derived as $EC_{sw\ actual}$ were compared with the measured values using graphical and statistical analysis as described by Willmott (1982). Generally all the statistical parameters met the set of criteria. Both soils showed good agreement between measured and estimated salinity levels as the slopes were close to one with R^2 of 0.76 and 0.91 for the Cv and Bv soils, respectively. Most of the estimated salinity levels were within the 20% variation lines. Estimations of the leaching requirement for the Cv and Bv soils respectively were also made with Equation 5.2, where various initial EC_{sw} levels were leached with an EC_i of 50 mS m^{-1} until almost 100% of excess salts were removed from a soil depth of 1200 mm. The actual EC_{sw} at the end of leaching was taken as 80 mS m^{-1} for all the initial EC_{sw} levels. The results were compared with values recommended by Van der Merwe *et al*. (1975) in Table 5.4. The guidelines recommended by Van der Merwe *et al*. (1975) and the guidelines estimated with Equation 5.2 are similar with the mean between the various salinity levels corresponding well with each other.

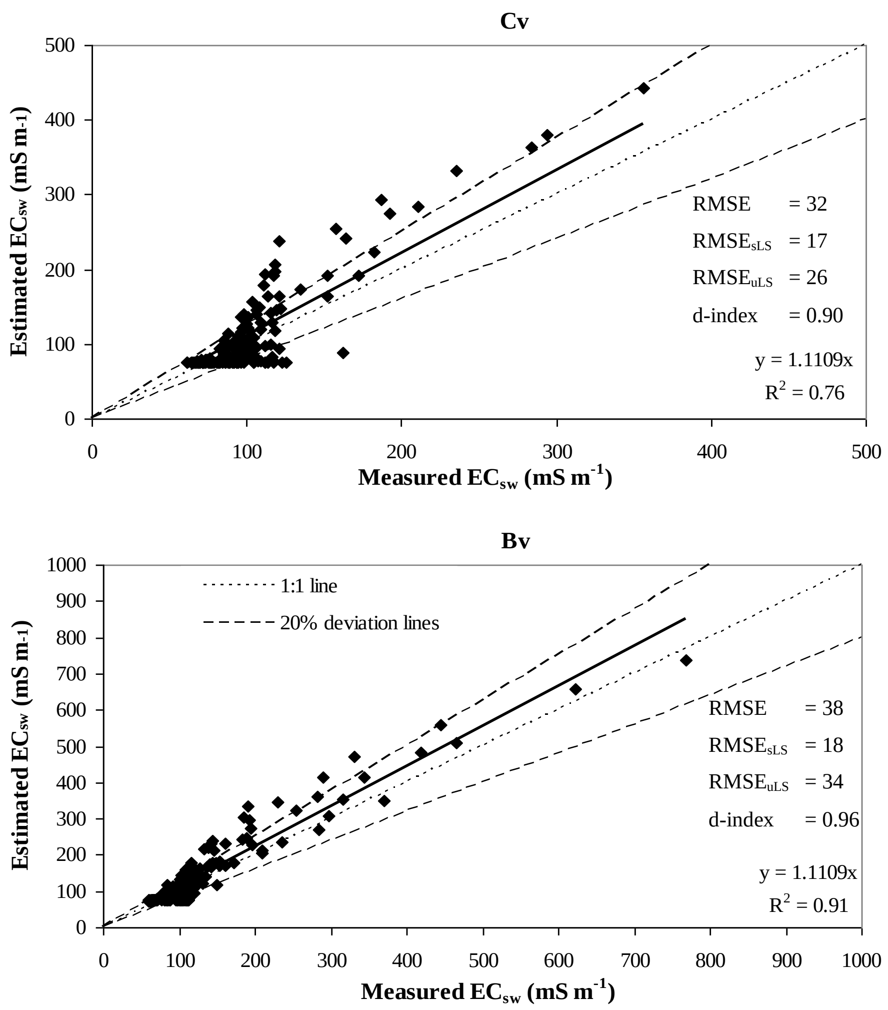


Figure 5.5 Statistical comparison of the EC_{sw} estimated with Equation 5.2, against the actual measured EC_{sw} values after leaching, of both soils using the independent data set obtained with the leaching experiment described in Chapter 4.

Table 5.4 Comparison of guidelines generated with Equation 5.2 of both soils against the recommended leaching requirement (mm 1200 mm^{-1} soil depth) of Van der Merwe *et al*. (1975)

$EC_{sw\ initial}$	$EC_{sw\ actual}$	Soil			
		Loamy sand (Cv)		Sandy loam (Bv)	
mS m^{-1}		Van der Merwe *et al*. (1975)	Eq 4.1	Van der Merwe *et al*. (1975)	Eq 4.1
400	**80**	160	290	260	401
600	**80**	240	344	390	475
800	**80**	320	381	520	526
1000	**80**	400	409	650	564
1600	**80**	560	466	910	644
Mean		**336**	**378**	**546**	**522**

5.4 Conclusions

Saline profiles were leached with various irrigation water salinities. Almost all of the applied irrigation water drained from the soil with a drainage: irrigation ratio > 0.85. The actual target salinity of the profile ended close to the irrigation water salinity, as the accumulated salts were replaced with the incoming irrigation water solution.

Leaching curves were developed for these experimental conditions. It was revealed that the empirical relationship of leaching curves is extremely sensitive to experimental conditions, soil and salinity characteristics and initial salinity levels for which it was derived from. Keeping all this factors in mind it was concluded that the leaching requirement can be calculated with the empirical leaching curves established in this chapter. Leaching equations were developed for estimating the depth of leaching requirement irrespective soil depth, soil salinity and irrigation water salinity. These equations are however unique for a specific soil type and can unfortunately only be extrapolated to different soil types when sufficient data is available. For a relationship between mean silt-plus-clay content of the two soils and the corresponding b values of leaching equations, the two data pairs were insufficient to obtain a valid relationship. Future research on leaching curves with the same experimental conditions salinity characteristics and initial salinity range, as influenced by soil properties, is therefore needed.

By using the leaching equations, guidelines for the approximate depth of leaching required in order to leach 100 and 80% of excess salts, from different depths of various saline profiles, irrigated with various irrigation water salinities, were established. The practical implications of the leaching equations are that leaching will not be sustainable in the long run in removing 100% of excess salts. When 80% of excess salts were removed, root zone salinity can be efficiently managed. It can be concluded therefore that the empirical model developed in this chapter can accurately estimate salt removal from apedal saline soils and be used in effectively and efficiently manage root zone salinity.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

A huge amount of energy was allocated to research on irrigation scheduling during the past 20 to 30 years in South Africa (Bennie *et al*., 1988; Dent *et al*., 1988; Van Zyl *et al*., 1989; Burgers & Kirk, 1993; Walker *et al*., 1995; Bennie *et al*., 1997; Crosby & Crosby, 1999; Annandale *et al*., 1999). All these research focussed intensively on the optimization of water application in order to prevent any crop water stress. Optimization of water can only be reached if reduction in losses through runoff, evaporation and drainage are restricted. Improved irrigation systems also helped to reduce these losses. During this optimizing of water application, the need for leaching excess salts from the root zone was almost neglected. Even today most of the irrigation service providers are neglecting salinity because there focus are mainly on scheduling to prevent crop water stress rather than salt management. Results from Du Preez *et al*., (2000) at selected farms along the lower Vaal River showed that the quality of the river system decreased downstream and that this trend will increase in the next 50 years. Irrigation will bring more salts into the root zone of irrigated crops that needs to be managed carefully in order to be sustainable.

Earlier research done by Van der Merwe (1973), Du Plessis (1986) and Moolman (1993) helped the farming community tremendously in managing of salt affected soils. Despite this work several farmers were concerned about the accumulation of salts in their soils and the impact on crops (Du Preez *et al*., 2000). Consequently a project was proposed to the Water Research Commission for funding to investigate the bio-physical component of the problem. This dissertation forms part of the research report to the WRC (Ehlers *et al*., 2006) and focus mainly on the salt removal or leaching aspect of salinity management of apedal soils.

The literature review that was conducted revealed that salt movement in soil follow the basic saturated and unsaturated flow processes. The flux of salt through the root zone occurs in response to two processes, convection and dispersion with the water flux determining the relative importance of each of these processes. Chapter 2 emphasised that the only reliable option of removing excess salts from the root zone is through a flux of water percolating below the root zone. Factors such as soil characteristics, irrigation water salinity, irrigation systems and management practises will influence leaching of excess salts considerably. Basic knowledge and the relative contribution of these processes and factors towards salt leaching will be essential in formulating management strategies regarding salt removal from the root zone of apedal soils.

The first objective of the research was to determine the effect of irrigation water salinity on soil salinity in the absence of freely drained conditions, its impact on the drainage characteristics of apedal soils and how much salts will be removed during a single drainage cycle from a saturated soil profile. In restricted drainage conditions, like for instance in the presence of a shallow water table, the soil water salinity increased with an increase in irrigation water salinity with a factor of 1.8. During one growing season the application of a total mean between the treatments of 612 mm irrigation therefore almost doubled the salinity of the soil water. Although there was an increase in soil water salinity the mean sodium adsorption ratio (SAR) over the depth of the profile did not significantly increase with an increase in irrigation water salinity because the SAR of the irrigation water was kept below 5. These various salt accumulated profiles were classified as non-saline and saline and therefore it was consequently concluded that soil water salinity will not have an influence on the drainage characteristics of these soils. This was confirmed with results illustrating that soil water salinity did not significantly affect drainage rates over a soil depth of 1800 mm. The drained upper limit was confirmed as being crucial in leaching of salts since drainage will only occur when the soil profile is irrigated to above this level. During the drainage cycle of 27 days it was established that the rate of salt removal is a function of soil texture and salt content of the soil. The salt peak in the top of the profiles was merely pushed downward. Concluding thereby, that not all of the salts will be removed from saturated saline soils when artificial drainage systems are installed. The potential rooting depth must be considered when estimating the amount of leaching required.

In the second objective an attempt was made to quantify the pore volume of water required to replace various soil salinity solutions with water of a constant salinity under unsaturated conditions and to develop leaching curves for these conditions. It was revealed that as irrigation water enters the soil the salt distribution patterns in the profile will change as the residual solution was displaced and pushed downward and out of the profile. In apedal soils piston flow can describe the transport of solutes because the changing pattern of salt concentration in the profile will approach an equilibrium concentration equal to the salinity of the irrigation water after approximately one pore volume of displacement. Salt that was removed until this level of equilibrium is reached was revered to as excess salts. There was a linear increase in the percentage of excess salts removed for a unit depth of water per unit depth of soil leached until approximately 80% of excess salts were removed. The leaching curves also illustrated that leaching of the last 20% of the remaining excess salts are not very efficient in terms of water requirements.

The final objective of the research were to derive an empirical model capable of estimating salt removal from apedal soils with various salinity levels, irrigated various irrigation water salinities in order to effectively and efficiently manage root zone salinity. The non-linear exponential association ($y = a \{1- \exp -b x\}$) of the leaching curve gave the bets description of the fraction of excess salts removed in relation to depth of leaching water per unit depth of soil. The empirical relationship of the leaching curves was found to be particularly sensitive to experimental conditions, soil and salinity characteristics and initial salinity levels for which it was derived from. However it was concluded that the empirical model developed is reasonably accurate to estimate the depth of leaching requirement (Dw), when used within its limits. Guidelines were established for the approximate depth of leaching required in order to leach 100 and 80% of excess salts, from different depth of various saline profiles, irrigated with various irrigation water salinities. The application of leaching curves revealed that when 100% of excess salts were removed leaching will not be sustainable. When 80% of excess salts were removed root zone salinity can be efficiently managed with soil depth being of vital importance in determining the depth of leaching required. In these two apedal soils, with mean silt-plus-clay percentages of smaller than 19, approximately one pore volume of drainage will remove relative all of the excess salts, irrespective soil water and irrigation water salinity.

6.2 Recommendations

6.2.1 Proposed procedure for managing root zone salinity in freely drained soils

It is important to notice that in terms of root zone salinity in restricted drainage conditions, management is aimed at alleviating the impact of salinity on crop growth rather than solving or controlling the problem. On freely drained soils however it is possible to manage the salinity level in the root zone though leaching. The empirical model, Equation 5.2, can be used in estimating the drainage required for salt leaching. The potential depth of the root zone, initial root zone salinity, irrigation water salinity, crop salt tolerance, crop water demand and the drained upper limit were all identified, from the above mentioned general conclusions, as essential information, which will be required for managing root zone salinity.

Managing root zone salinity in freely drained soils involves two basic conditions rendering therefore two different procedures. The first is where the mean salinity of the root zone is smaller that the threshold salinity level of the cultivated crop. Here the added salts are assumed to be removed from the root zone through natural leaching processes. Irrigation should be applied according to the crop water demand in order to minimize the amount of applied salts. This procedure can be followed until the mean salinity of the root zone is greater than the threshold salinity level of the cultivated crop.

When this happens the natural leaching of salts should be accelerated, by irrigating more than the required crop water demand. The additional irrigation must be sufficient to leach the excess salts from the root zone. The following steps can be followed. First determine the crop water demand for a target yield. Calculate the leaching required (Dw) with Equation 5.2 and set the actual or target salinity equal to the threshold salinity of the cultivated crop. Determine the amount of irrigation required to wet the root zone to the drained upper limit of plant available water (mm). The seasonal irrigation requirement in order to keep the mean salinity of the root zone below the threshold level of the cultivated crop will be equal to the crop water demand plus the leaching requirement plus irrigation to wet the root zone.

Salinization of irrigated soils is a reality and proper management of the salinity in the root zone is of great importance.

6.2.2 Recommendations for future research

(i) This research provided a theoretical frame work on how to manage root zone salinity effectively and efficiently in freely drained soils. The proposed procedure however needs to be verified under controlled and on-farm conditions. Research on this aspect is already underway by the Department of Soil, Crop and Climate Sciences (U.F.S) through a Water Research Commission project “Managing salinity associated with irrigation in selected areas of South Africa.”

(ii) Special attention should be given to overcome the empirical nature of the proposed model for determining the leaching required (Equation 5.2). It is suggested that a wider range of soils, with respect to texture and structure characteristics, should be included in the correlation to improve the application of the leaching model.

Leaching salts from the root zone which ensures the sustainability of irrigation from an agricultural perspective, has the undesirable side effect of salinization of ground and surface waters. Hillel (2000) probably came up with the best explanation for the dilemma when he stated that the problem is similar to that of the proverbial frog in the frying pan. To escape being fried, the frog must leap; but in leaping the frog may fall into the fire and be burned. So the leap must be just the right trajectory to escape both misfortunes.

There is an increasing range of initiatives that are being investigated both locally and internationally to improve the way in which to manage this impact at both farm and scheme level. Although much on this regard has been learnt locally and internationally, the practical application in this regard is lagging behind. It is therefore suggested that research be conducted that would synthesis current knowledge and then select the appropriate management practices for application and testing at farm and scheme level.

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APPENDICES

Appendix 3.1 Regression variables, derived with the Curve Expert Program of Hyams (1995), describing the mathematical relationship ($y = \{a + bx\} / \{1+ cx + dx^2\}$) between time (x, days) and cumulative drainage (y, mm) for all the treatments (EC_i) of both soils

Soil	EC_i ($mS\ m^{-1}$)	Rep	a	b	c	d	R^2
Cv	15	1	-7.3222	478.5908	2.1034	-0.0046	0.998
		2	-7.8471	345.4001	1.4307	-0.0008	0.998
		3	-3.4366	177.2507	0.6647	0.0001	0.994
	150	1	-12.3080	802.9413	2.7219	-0.0019	0.996
		2	-9.7487	228.6349	0.9186	0.0002	0.996
		3	-6.1024	268.2978	1.1011	-0.0006	0.998
	300	1	-7.0908	1098.1595	4.2160	-0.0132	0.999
		2	3.5615	2661.6159	8.2127	-0.0367	0.997
		3	-9.6385	1022.4346	3.8324	-0.0120	0.998
	450	1	-5.6908	533.0296	2.1184	-0.0057	0.999
		2	-8.3385	433.8008	1.5246	-0.0012	0.998
		3	-5.7676	900.4149	3.0123	-0.0082	0.999
	600	1	-0.3068	1314.9859	4.7755	-0.0211	0.999
		2	-3.8328	1816.6118	6.0235	-0.0246	0.999
		3	-3.7188	1939.7837	6.0962	-0.0249	0.999
Bv	15	1	6.1967	151.1615	1.3997	-0.0071	0.997
		2	7.0494	350.5155	2.1447	-0.0097	0.998
		3	12.6701	351.9910	2.4074	-0.0143	0.993
	150	1	12.0713	603.7351	3.4397	-0.0193	0.995
		2	5.2246	447.4971	2.6066	-0.0105	0.988
		3	7.8496	457.7164	2.7186	-0.0129	0.997
	300	1	5.8253	206.9796	1.4249	-0.0066	0.997
		2	6.3796	610.5078	3.2651	-0.0155	0.998
		3	12.2061	544.7500	3.1237	-0.0172	0.996
	450	1	10.5594	387.9289	2.2625	-0.0110	0.996
		2	7.2106	543.7941	2.7762	-0.0126	0.999
		3	7.6945	407.5538	2.6022	-0.0147	0.991
	600	1	11.3312	375.2801	2.1575	-0.0111	0.996
		2	8.8140	292.8748	1.7386	-0.0075	0.998
		3	7.0017	315.9930	2.1124	-0.0125	0.996

Appendix 3.2 Mean ionic composition and concentration of the soil water extracted through the cups at the various depth intervals of both soils for each EC_i treatment, TDS = total dissolved salts (mg L^{-1})

Soil	EC_i (mS m^{-1})	Depth (mm)	Mean ionic concentration (mg L^{-1})						TDS	Measured EC_{sw}
			Ca^{2+}	K^+	Mg^{2+}	Na^+	SO_4	Cl^-	(mg L^{-1})	(mS m^{-1})
Cv	15	300	122	6	44	183	187	441	983	174
		500	325	14	179	647	453	2540	4158	578
		700	85	15	44	165	126	246	680	150
		900	73	42	41	133	61	131	481	121
		1100	78	40	30	98	33	118	398	101
		1500	48	30	21	99	16	86	301	78
	150	300	615	307	410	1523	1080	4810	8746	1209
		500	873	370	477	1573	828	5558	9680	1415
		700	700	121	283	1053	746	3521	6425	943
		900	296	86	149	753	403	1708	3396	540
		1100	147	72	68	396	226	709	1619	293
		1500	100	67	47	253	167	574	1209	212
	300	300	564	183	320	1540	1379	3632	7618	1131
		500	758	339	530	1837	1597	5754	10815	1456
		700	1127	573	503	2120	1805	7307	13436	1864
		900	636	198	273	1437	1131	3829	7505	1054
		1100	461	96	163	917	670	2228	4534	683
		1500	229	116	95	570	404	1327	2741	414
	450	300	967	734	710	2450	2036	7428	14325	2138
		500	1013	568	797	1987	1904	7318	13586	1844
		700	987	1013	750	1850	1924	7381	13905	1964
		900	605	801	367	1577	1234	4551	9134	1303
		1100	481	542	280	947	907	3192	6348	931
		1500	237	152	131	500	392	1395	2807	419
	600	300	975	773	847	2167	2031	7967	14760	2088
		500	1672	899	1567	2437	2456	12228	21260	3314
		700	1061	687	720	2463	1860	7646	14437	2216
		900	507	872	387	2127	1773	5348	11013	1512
		1100	443	792	320	1543	1378	4639	9115	1172
		1500	386	474	280	887	818	2653	5497	808
Bv	15	300	103	8	38	125	155	274	703	139
		500	82	4	33	102	66	219	168	108
		700	87	19	49	171	267	359	951	163
		900	31	1	17	94	79	79	302	67
		1100	45	3	20	76	66	210	419	70
		1500	43	4	19	41	46	102	256	50
	150	300	936	240	317	1220	891	4732	8335	1149
		500	908	53	230	757	415	3859	6221	923
		700	584	5	163	893	485	2809	4940	738
		900	131	3	81	380	286	1110	1992	298
		1100	115	5	67	279	231	748	1445	223
		1500	122	7	72	248	222	714	1385	223
	300	300	981	325	720	2173	1737	8341	14277	1970
		500	774	306	313	1337	729	4820	8280	1190
		700	838	24	340	1250	865	4684	8002	1110
		900	646	15	461	2093	950	5248	9413	1458
		1100	238	5	127	650	358	1499	2877	443
		1500	200	16	117	480	306	1316	2435	356
	450	300	1277	566	1030	1932	2278	9505	16588	2374
		500	959	470	530	1630	1320	6932	11841	1633
		700	1026	320	410	1500	1642	6951	11849	1548
		900	707	45	260	1187	762	3803	6763	1012
		1100	447	8	207	893	568	2563	4685	696
		1500	333	16	157	690	468	1938	3603	558
	600	300	1647	833	1030	1980	2343	9213	17046	2670
		500	1228	615	750	1383	1669	6830	12474	1883
		700	1092	920	487	1893	2025	8729	15146	1817
		900	946	180	380	1417	1342	4807	9073	1311
		1100	618	16	203	1003	698	3177	5716	794
		1500	516	48	177	827	628	2416	4611	664

Appendix 3.3 Total water content (mm 1800 mm^{-1} soil depth) measured with the CPN neutron soil water meter at the corresponding time in days for the Cv and Bv soils as affected by the EC_i treatment.

EC_i (mS m^{-1})	**15**			**150**			**300**			**450**			**600**		
	Replications														
Soil	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
	Water content (mm 1800 mm^{-1} soil depth)														
	640	634	621	629	629	611	701	724	682	679	694	688	702	702	687
	534	566	585	520	610	577	531	521	543	579	633	546	516	548	569
	482	524	558	459	556	543	492	490	505	529	576	502	488	493	526
	448	482	514	424	514	498	483	474	474	496	528	467	474	468	487
	437	467	504	415	490	486	471	463	471	484	508	464	466	461	479
	422	443	463	403	451	457	461	447	459	469	477	448	455	445	459
	410	429	456	394	424	442	452	435	454	459	460	441	442	432	453
	407	423	433	387	417	421	447	430	437	452	455	425	437	428	433
	397	411	420	381	403	405	435	419	428	442	443	410	438	416	421
	390	413	420	374	394	407	429	411	422	431	433	407	416	405	419
	389	403	407	371	390	396	423	407	416	428	429	404	410	398	411
	381	399	403	364	382	392	419	404	413	424	421	398	406	394	406
	379	393	400	363	381	389	414	401	408	420	417	392	400	393	401
	378	369	394	360	377	398	414	420	402	417	412	387	406	388	396
	370	387	388	355	371	380	408	392	397	411	407	380	396	379	391
	368	383	390	353	368	377	404	391	398	407	403	382	390	379	388
	365	380	385	350	367	378	400	388	392	406	401	377	386	377	381
	360	379	382	347	367	376	401	383	393	402	396	376	384	374	383
Cv	**Time (days)**														
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	0.3	0.3	0.2	0.2	0.1	0.2	0.3	0.3	0.2	0.2	0.2	0.2	0.3	0.1	0.2
	0.6	0.5	0.4	0.5	0.4	0.4	0.6	0.6	0.5	0.5	0.5	0.5	0.6	0.4	0.4
	0.9	0.9	1.0	0.9	0.7	0.9	1.0	0.9	1.0	0.9	0.9	1.0	1.0	0.8	1.0
	1.2	1.2	1.1	1.2	1.0	1.1	1.2	1.2	1.2	1.2	1.1	1.2	1.2	1.1	1.2
	2.0	2.0	2.1	1.9	1.8	2.1	2.0	2.0	2.2	1.9	1.9	2.2	2.0	1.8	2.1
	3.2	3.2	2.9	3.1	3.0	2.8	3.3	3.2	2.9	3.2	3.1	2.9	3.2	3.0	2.9
	3.9	3.9	5.0	3.8	3.7	5.0	3.9	3.9	5.1	3.8	3.8	5.0	3.9	3.7	5.0
	6.1	6.1	8.0	6.0	5.9	7.9	6.1	6.1	8.0	6.0	6.0	8.0	6.1	5.9	8.0
	9.1	9.0	9.0	9.0	8.8	8.9	9.1	9.1	9.0	9.0	8.9	9.0	9.1	8.9	9.0
	10.1	10.0	12.0	10.0	9.8	12.0	10.1	10.1	12.1	10.0	9.9	12.0	10.1	9.9	12.0
	13.1	13.1	14.0	13.0	12.9	13.9	13.1	13.1	14.0	13.0	13.0	14.0	13.1	12.9	14.0
	15.1	15.0	15.9	15.0	14.8	15.9	15.1	15.1	16.0	15.0	14.9	16.0	15.1	14.9	15.9
	17.0	17.0	19.0	17.0	16.8	19.0	17.1	17.0	19.1	17.0	16.9	19.1	17.0	16.8	19.0
	20.2	20.1	20.9	20.0	19.9	20.9	20.2	20.1	21.1	20.0	20.0	21.0	20.2	19.9	21.0
	22.1	22.1	23.1	22.0	21.8	23.1	22.1	22.1	23.2	22.0	22.0	23.2	22.1	21.8	23.2
	24.2	24.1	26.0	24.1	24.0	25.9	24.2	24.2	26.0	24.1	24.1	26.0	24.2	24.0	26.0
	27.0	27.0	28.0	26.9	26.8	27.9	27.0	27.0	28.0	26.9	26.9	28.0	27.0	26.8	28.0

Appendix 3.3 continue

EC_i (mS m^{-1})	**15**			**150**			**300**			**450**			**600**		
	Replications														
Soil	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
	Water content (mm 1800 mm^{-1} soil depth)														
	640	678	668	676	673	663	658	666	636	665	630	666	656	647	647
	595	598	613	603	585	584	603	574	553	596	552	578	597	587	594
	578	585	595	574	580	566	582	558	540	571	533	562	573	565	577
	563	556	577	546	555	547	564	533	522	547	506	541	554	537	555
	558	548	571	542	547	539	557	525	516	540	499	533	542	526	547
	550	538	558	530	535	530	544	516	505	527	487	522	534	510	533
	539	527	551	519	524	523	533	506	497	515	477	516	522	502	522
	534	523	544	513	520	516	529	501	490	513	470	507	519	492	513
	529	511	537	504	514	509	519	493	487	502	465	497	507	484	507
	523	512	532	498	512	506	513	492	481	495	461	502	505	483	498
	510	505	529	496	505	501	504	487	479	492	456	487	500	478	495
	514	503	524	492	504	497	504	482	475	487	453	484	499	475	488
	513	497	522	490	501	498	501	480	471	484	448	483	494	474	487
	509	497	518	485	497	492	497	476	468	476	442	476	496	470	481
	509	495	517	485	496	495	492	473	468	474	441	476	491	467	481
	504	490	514	483	493	490	492	469	465	475	442	472	489	464	477
	502	488	495	477	489	487	488	469	464	472	439	467	485	462	474
	499	487	507	475	488	487	488	463	462	467	434	469	484	459	474
	500	486		475	485		488	465		467	433		482	456	
Bv	**Time (days)**														
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.3	0.3	0.2	0.2	0.3	0.2	0.2	0.2
	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.4	0.5	0.4	0.4	0.4
	0.9	1.0	0.9	0.9	1.0	0.9	0.9	1.1	1.0	0.9	1.0	0.9	0.9	1.0	0.9
	1.2	1.2	1.2	1.1	1.2	1.2	1.2	1.3	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	1.9	1.9	1.9	1.9	1.9	1.9	2.0	2.0	1.9	2.0	1.9	1.9	1.9	1.9	1.9
	3.0	3.0	3.0	3.0	2.9	3.0	3.0	3.0	3.1	3.0	3.0	3.1	3.0	2.9	3.0
	3.9	3.9	5.0	3.9	3.9	5.0	4.0	4.0	5.1	4.0	4.0	5.1	4.0	3.9	5.0
	5.9	6.3	7.0	5.9	6.3	7.0	5.9	6.4	7.0	5.9	6.3	7.0	5.9	6.3	7.0
	8.0	7.1	9.1	8.0	7.1	9.1	8.1	7.1	9.1	8.1	7.1	9.1	8.0	7.0	9.1
	10.0	9.0	12.0	10.0	9.0	12.0	10.0	9.1	12.0	10.0	9.0	12.0	10.0	9.0	11.9
	12.0	11.1	15.0	11.9	11.1	15.0	12.0	11.2	15.0	12.0	11.1	15.0	12.0	11.1	14.9
	14.1	14.0	16.0	14.0	14.0	16.0	14.1	14.1	16.0	14.1	14.0	16.0	14.1	14.0	15.9
	16.9	17.0	19.0	16.9	17.0	19.0	17.0	17.1	19.0	17.0	17.0	19.0	17.0	17.0	18.9
	19.9	18.0	21.0	19.9	18.0	21.0	20.0	18.1	21.0	20.0	18.0	21.0	20.0	18.0	20.9
	20.9	21.0	22.9	20.9	21.0	22.9	21.0	21.1	22.9	21.0	21.0	22.9	21.0	21.0	22.9
	23.9	23.0	26.0	23.9	23.0	26.0	24.0	23.1	26.0	24.0	23.0	26.0	24.0	23.0	26.0
	25.9	24.9	27.9	25.9	24.9	27.9	26.0	25.0	28.0	26.0	24.9	28.0	26.0	24.9	27.9
	27.9	28.0		27.8	28.0		27.9	28.1		27.9	28.0		27.9	28.0	

Appendix 3.4 Salt distribution (mS m^{-1}) in the profiles of the Cv and Bv soils before (at saturation) and after (at the drained upper limit, DUL) a single drainage cycle

Soil	EC_i (mS m^{-1})	15	150	300	450	600
	Depth (mm)	**Mean EC_{sw} at saturation (mS m^{-1})**				
Cv	**300**	174	1209	1131	2138	2088
	500	578	1415	1456	1844	3314
	700	150	943	1864	1964	2216
	900	121	540	1054	1303	1512
	1100	101	293	683	931	1172
	1500	78	212	414	559	808
	Mean of the profile	**200**	**769**	**1101**	**1456**	**1852**
	Depth (mm)	**Mean EC_{sw} at the DUL (mS m^{-1})**				
	300	73	115	222	194	332
	500	85	181	289	449	586
	700	74	314	293	457	883
	900	94	203	315	484	628
	1100	90	197	302	556	674
	1500	93	555	470	986	923
	Mean of the profile	**85**	**261**	**315**	**521**	**671**
Bv	**Depth (mm)**	**Mean EC_{sw} at saturation (mS m^{-1})**				
	300	139	1149	1970	2374	2670
	500	108	923	1190	1633	2510
	700	163	738	1110	1548	1817
	900	89	298	1458	1012	1311
	1100	70	223	443	696	794
	1500	50	223	356	558	664
	Mean (profile)	**103**	**592**	**1088**	**1303**	**1628**
	Depth (mm)	**Mean EC_{sw} at the DUL (mS m^{-1})**				
	300	66	111	234	208	423
	500	62	202	289	453	701
	700	76	217	343	569	791
	900	101	263	527	728	1321
	1100	103	423	759	978	1567
	1500	89	413	651	946	1280
	Mean (profile)	**83**	**271**	**467**	**647**	**1014**

Appendix 4.1 Total water content (mm 1800 mm^{-1} soil depth) measured with the CPN neutron soil water meter at the corresponding time in days for the Cv and Bv soils as affected by the different salinity levels (SL1 – SL5) during the leaching period of 50 days

Soil	Salinity level	SL1			SL2			SL3			SL4			SL5		
		Replications														
	Time (days)	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
		Water content (mm 1800^{-1} soil depth)														
	0	409	419	427	389	401	423	453	435	436	444	438	421	428	418	434
	1	408	413	425	384	399	422	449	429	433	440	437	416	425	411	425
	3	402	411	422	382	393	417	443	424	431	434	430	414	420	411	430
	4	402	410	421	379	393	414	440	424	431	437	431	412	418	412	426
	5	444	455	469	422	438	455	491	473	478	481	481	461	468	467	475
	6	432	443	461	414	433	449	479	461	470	462	474	453	463	455	471
	7	462	478	493	444	472	485	518	501	509	518	513	498	494	495	514
	8	443	461	474	425	452	466	489	474	482	492	495	468	475	466	483
	9	427	450	458	411	440	454	478	462	471	481	482	456	465	450	465
	10	421	437	443	402	431	445	466	449	456	469	470	441	454	435	451
	11	417	431	434	395	422	434	459	440	456	461	464	435	446	419	451
	12	451	469	474	436	466	474	511	489	497	511	506	482	490	477	493
	13	442	457	460	423	449	439	491	473	483	493	493	468	481	472	482
	14	475	480	495	447	482	503	515	511	524	525	529	509	523	517	529
	15	455	463	480	433	460	475	496	482	492	504	506	475	491	478	495
	16	434	450	461	410	444	457	482	464	473	486	487	462	482	456	479
	17	425	439	452	406	438	448	471	456	464	480	478	452	467	450	467
	18	416	430	442	403	429	439	466	449	459	469	472	445	459	443	461
	19	456	469	479	437	472	480	516	497	515	516	524	498	506	496	516
	20	439	456	461	425	454	468	497	483	494	498	502	479	493	480	498
	21	479	495	494	470	500	500	545	524	540	546	561	533	539	534	533
	22	449	465	471	442	469	476	500	485	496	514	519	489	495	489	500
	23	431	451	454	504	452	464	484	463	479	490	512	467	510	444	473
	24	423	436	442	408	442	450	474	457	469	478	489	453	471	451	465
Cv	**25**	412	430	433	403	435	443	469	451	467	480	480	450	463	443	464
	26	461	474	474	442	469	482	520	508	524	526	534	507	520	494	513
	27	441	456	457	425	462	468	499	487	497	506	509	481	503	481	498
	28	477	492	490	458	488	496	545	525	530	546	550	515	539	519	533
	29	452	466	471	442	471	480	507	489	502	519	525	491	505	487	504
	30	439	454	457	423	457	467	496	471	484	501	506	469	487	464	484
	31	426	444	447	411	447	461	485	461	474	492	496	459	477	454	475
	32	422	437	439	407	443	447	476	453	470	483	491	453	469	449	467
	33	461	473	475	442	477	484	527	503	516	527	536	489	513	499	512
	34	436	453	460	429	463	471	503	485	496	506	514	480	500	481	501
	35	478	495	491	464	500	499	548	527	540	546	559	523	550	525	536
	36	447	467	473	437	457	482	503	492	501	523	525	492	507	483	500
	37	433	453	456	418	454	465	489	476	483	505	503	474	492	460	482
	38	422	444	445	410	449	455	482	465	473	494	495	459	480	452	469
	39	411	430	433	401	436	447	475	448	458	481	481	446	468	443	469
	40	451	465	472	444	474	481	520	499	507	525	528	497	514	491	511
	41	439	448	459	426	457	463	504	484	491	507	510	481	501	485	500
	42	470	486	488	472	499	499	549	525	538	548	565	527	545	520	536
	43	445	455	461	442	463	472	510	486	496	514	521	485	509	478	501
	44	429	447	449	426	452	463	492	478	483	503	510	475	494	462	484
	45	418	435	437	406	445	456	485	463	476	492	495	460	483	453	472
	46	412	428	402	406	439	448	479	459	466	483	489	447	481	444	466
	47	443	462	458	444	471	480	524	488	515	531	528	498	510	493	515
	48	430	451	459	431	461	471	504	489	499	515	515	489	503	487	504
	49	422	442	445	421	448	461	493	476	488	501	502	477	492	469	489
	50	414	431	436	414	437	453	483	465	478	493	495	466	481	458	479

Appendix 4.1 Continue

Soil	Salinity level	SL1			SL2			SL3			SL4			SL5		
		Replications														
	Time (days)	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
		Water content (mm 1800^{-1} soil depth)														
	0	525	500	527	519	526	533	518	504	528	509	502	513	532	500	515
	1	519	496	521	513	521	525	513	501	520	501	500	509	526	492	511
	3	514	490	518	509	513	519	510	495	515	494	492	500	516	485	504
	4	556	534	555	555	560	565	552	539	555	536	537	548	566	531	552
	5	548	519	540	540	545	542	547	527	542	534	525	536	546	518	536
	6	539	509	528	529	535	531	536	512	531	522	511	524	533	504	529
	7	573	549	565	567	572	574	576	549	571	565	555	562	579	530	568
	8	551	522	543	542	552	545	555	531	550	543	528	541	546	527	547
	9	539	509	529	526	535	534	540	517	535	528	515	528	537	509	535
	10	532	497	519	519	527	526	533	507	528	517	506	518	525	500	523
	11	565	537	559	556	566	570	566	545	567	557	546	560	573	539	561
	12	548	522	539	546	550	546	557	534	552	544	533	543	553	525	550
	13	540	507	530	528	534	534	542	520	544	531	517	528	542	511	534
	14	573	543	561	566	576	574	580	563	579	578	562	573	580	550	562
	15	553	520	540	546	553	552	563	541	558	554	537	546	559	530	552
	16	534	505	530	532	545	538	551	522	547	540	523	533	542	527	542
	17	533	501	521	527	532	536	544	517	539	534	514	526	539	508	534
	18	569	544	561	565	574	576	586	558	577	572	557	570	583	552	565
	19	556	519	540	543	552	549	563	538	559	551	535	548	558	530	551
	20	539	506	529	527	541	556	556	525	544	541	525	536	550	519	543
	21	570	551	567	568	576	588	586	560	584	574	561	579	586	564	581
	22	552	522	539	549	553	556	569	544	562	561	546	553	565	535	557
	23	547	515	527	546	542	540	561	530	548	546	527	541	554	523	544
	24	536	497	522	528	530	540	547	519	543	537	518	532	544	516	538
Bv	**25**	570	542	560	575	575	576	586	564	592	578	563	578	586	557	575
	26	552	522	544	552	557	554	568	544	564	558	545	551	566	539	561
	27	542	506	531	536	543	545	567	530	542	547	530	537	555	525	551
	28	573	555	559	574	581	584	594	567	583	586	572	585	589	562	586
	29	558	526	542	552	554	558	577	546	561	566	547	555	568	540	582
	30	547	514	532	541	543	547	562	539	551	553	534	543	557	529	555
	31	539	501	525	532	535	536	559	526	544	546	526	535	549	520	548
	32	568	547	564	569	571	580	593	562	584	583	563	575	591	562	585
	33	550	530	550	557	560	563	575	546	568	571	558	562	572	547	569
	34	543	509	535	542	548	550	562	532	557	555	536	545	561	532	557
	35	559	546	569	573	582	590	593	567	588	592	572	581	597	576	590
	36	550	524	545	556	561	557	575	550	564	571	551	560	569	545	565
	37	541	509	535	542	547	548	565	536	557	558	537	546	561	530	556
	38	535	499	525	533	540	543	557	527	548	548	529	538	551	525	547
	39	555	552	562	573	579	590	591	569	591	587	570	583	593	567	573
	40	549	525	545	555	561	559	575	551	563	578	554	562	575	545	567
	41	540	506	532	542	531	550	562	534	555	557	535	550	556	532	559
	42	561	547	566	583	574	586	597	569	592	587	575	588	597	572	592
	43	547	522	543	557	558	554	575	552	566	573	551	566	574	545	572
	44	547	514	530	544	548	551	563	538	558	562	538	551	566	535	559
	45	533	504	525	534	535	541	556	530	549	551	527	539	551	522	551
	46	562	547	562	576	572	589	596	567	588	592	575	577	594	569	593
	47	550	522	545	558	561	559	579	552	572	573	552	563	576	549	573
	48	539	509	534	542	547	554	567	537	560	559	538	550	564	536	563
	49	535	500	526	537	538	544	559	530	554	554	531	542	557	528	557
	50	530	494	521	531	534	539	553	525	546	549	527	534	549	521	551

Appendix 4.2 The full data set of EC_{sw} corresponding to cumulative drainage for all the soil depth intervals, of all the salinity levels (SL1 – SL5) for both soils

Soil	Salinity level	Depth (mm)	EC_{sw} (mS m^{-1})						
	SL1	0-300	**73**	**61**	**69**	**69**	**71**	**76**	**74**
		0-600	**79**	**62**	**66**	**67**	**70**	**71**	**71**
		0-900	**77**	**64**	**65**	**68**	**71**	**71**	**71**
		0-1200	**81**	**68**	**66**	**69**	**71**	**71**	**72**
		0-1500	**83**	**73**	**68**	**70**	**71**	**72**	**72**
		0-1800	**85**	**76**	**70**	**71**	**72**	**77**	**72**
		Drainage (mm)	0	81	176	271	371	476	569
	SL2	0-300	115	74	**69**	**75**	**83**	**76**	**76**
		0-600	148	82	**75**	**78**	**79**	**77**	**77**
		0-900	203	100	83	**84**	**84**	**82**	**80**
		0-1200	203	106	85	**85**	**84**	**83**	**82**
		0-1500	202	122	88	**87**	**85**	**83**	**82**
		0-1800	261	173	107	96	91	86	**84**
		Drainage (mm)	0	81	170	266	361	461	557
Cv	SL3	0-300	222	97	**76**	**112**	**98**	**86**	**95**
		0-600	256	119	85	**109**	**95**	**89**	**94**
		0-900	268	122	90	104	**95**	**91**	**93**
		0-1200	280	134	97	106	**101**	**98**	**97**
		0-1500	284	152	98	104	**99**	**96**	**94**
		0-1800	315	182	121	109	100	96	**93**
		Drainage (mm)	0	86	174	267	369	467	562
	SL4	0-300	194	106	**88**	**86**	**89**	**84**	**82**
		0-600	322	116	98	**91**	**96**	**91**	**89**
		0-900	367	118	100	**94**	**97**	**93**	**92**
		0-1200	396	164	104	**94**	**96**	**93**	**92**
		0-1500	428	210	112	96	**97**	**93**	**92**
		0-1800	521	284	158	111	101	95	**94**
		Drainage (mm)	0	77	162	258	351	450	541
	SL5	0-300	332	162	125	**123**	**114**	**104**	**104**
		0-600	459	152	121	**117**	**117**	**112**	**104**
		0-900	600	193	119	**116**	**116**	**107**	**93**
		0-1200	607	235	117	**116**	**112**	**104**	**94**
		0-1500	621	294	121	113	109	**104**	**95**
		0-1800	671	356	187	118	108	102	**95**
		Drainage (mm)	0	86	178	268	368	468	564

Appendix 4.2 Continue

Soil	Salinity level	Depth (mm)	EC_{sw} (mS m^{-1})						
		0-300	**66**	**63**	**60**	**62**	**63**	**64**	**70**
		0-600	**64**	**61**	**61**	**61**	**66**	**64**	**68**
		0-900	**68**	**63**	**61**	**61**	**67**	**65**	**68**
	SL1	**0-1200**	**76**	**69**	**65**	**64**	**68**	**66**	**70**
		0-1500	**82**	**74**	**67**	**66**	**69**	**66**	**70**
		0-1800	**83**	**76**	**70**	**69**	**70**	**66**	**69**
		Drainage (mm)	0	91	183	277	373	466	558
		0-300	111	82	**77**	**84**	**85**	**89**	**87**
		0-600	156	86	**77**	**81**	**81**	**82**	**85**
		0-900	177	101	91	**83**	**83**	**85**	**86**
	SL2	**0-1200**	198	116	91	**81**	**81**	**81**	**83**
		0-1500	243	145	102	85	**83**	**82**	**83**
		0-1800	271	209	141	110	98	**90**	**89**
		Drainage (mm)	0	98	185	276	372	468	568
		0-300	234	120	**110**	**96**	**109**	**105**	**108**
		0-600	262	126	**104**	**94**	**104**	**97**	**100**
		0-900	289	172	122	101	**104**	**95**	**99**
Bv	**SL3**	**0-1200**	348	235	161	120	112	101	**103**
		0-1500	431	297	196	139	122	107	**109**
		0-1800	467	371	284	209	153	135	**131**
		Drainage (mm)	0	87	170	256	347	439	525
		0-300	208	108	**98**	**98**	**103**	**101**	**103**
		0-600	331	136	98	**98**	**102**	**101**	**107**
		0-900	410	184	109	102	**104**	**98**	**107**
	SL4	**0-1200**	490	253	139	110	**104**	**96**	**103**
		0-1500	587	344	193	133	113	101	**108**
		0-1800	647	418	282	195	145	118	**115**
		Drainage (mm)	0	83	170	261	350	445	545
		0-300	423	149	112	**105**	**110**	**112**	**113**
		0-600	562	188	115	**108**	**113**	**109**	**110**
		0-900	638	315	140	111	**119**	**109**	**107**
	SL5	**0-1200**	809	466	230	142	128	112	**108**
		0-1500	961	622	331	191	144	117	**109**
		0-1800	1014	768	445	289	185	161	**153**
		Drainage (mm)	0	86	163	251	344	437	532

Appendix 5.1 The full data set of cumulative drainage as well as the change in the electrical conductivity of the soil water (EC_{sw}, mS m^{-1}) for all the EC_i treatments of both soils

Soil	EC_i (mS m^{-1})	Drainage (mm)	0	199	292	368	620	662	764
		Depth (mm)	EC_{sw} (mS m^{-1})						
Cv	15	**0-300**	142	**80**	68	**54**	**53**	**49**	**46**
		0-600	143	**91**	64	**51**	**50**	**47**	**46**
		0-900	191	97	61	**51**	**50**	**46**	**46**
		0-1200	179	104	60	**51**	**51**	**45**	**47**
		0-1500	169	121	66	53	**52**	**47**	**48**
		0-1800	158	126	78	67	**61**	**55**	**53**
	75	**Drainage (mm)**	0	200	276	345	596	639	757
		0-300	528	134	**99**	**106**	**126**	**118**	**120**
		0-600	519	139	**95**	**99**	**119**	**113**	**119**
		0-900	584	147	**100**	**99**	**119**	**110**	**116**
		0-1200	641	157	105	**101**	**120**	**111**	**115**
		0-1500	607	174	113	106	122	**113**	**116**
		0-1800	544	282	200	147	125	**115**	**117**
	150	**Drainage (mm)**	0	197	295	363	593	650	764
		0-300	823	319	190	**185**	**0**	**302**	**119**
		0-600	913	258	159	**151**	**124**	**215**	**125**
		0-900	920	237	147	**136**	**119**	**180**	**127**
		0-1200	901	228	140	**130**	**118**	**162**	**128**
		0-1500	878	233	137	127	**117**	**149**	**125**
		0-1800	835	333	179	138	120	**144**	**124**
	225	**Drainage (mm)**	0	216	301	382	622	665	781
		0-300	1785	250	**272**	**232**	**269**	**246**	**255**
		0-600	1898	287	261	**225**	**256**	**243**	**252**
		0-900	1812	301	251	**220**	**257**	**248**	**254**
		0-1200	1637	373	271	220	**253**	**246**	**253**
		0-1500	1557	434	298	235	252	**246**	**253**
		0-1800	1492	596	418	278	250	**244**	**251**
	300	**Drainage (mm)**	0	195	290	351	572	612	723
		0-300	2815	456	355	**359**	**390**	**407**	**367**
		0-600	2645	487	356	**369**	**448**	**446**	**388**
		0-900	2342	562	363	356	**431**	**418**	**397**
		0-1200	2070	621	381	360	**426**	**408**	**403**
		0-1500	1949	726	411	369	421	403	**399**
		0-1800	1887	838	579	431	413	397	**397**

Appendix 5.1 Continue

Soil	EC_i (mS m^{-1})	Drainage (mm)	0	207	275	346	541	635	774
		Depth (mm)	EC_{sw} (mS m^{-1})						
Bv	15	0-300	206	61	**52**	**51**	**42**	**51**	**52**
		0-600	212	61	**49**	**54**	**39**	**46**	**48**
		0-900	201	84	58	**58**	**45**	**52**	**47**
		0-1200	188	106	75	65	**47**	**52**	**46**
		0-1500	179	128	93	79	54	**56**	**49**
		0-1800	160	137	103	89	60	**61**	**53**
	75	Drainage (mm)	0	237	312	383	582	679	850
		0-300	580	173	**102**	**111**	**103**	**107**	**102**
		0-600	586	155	**105**	**107**	**101**	**105**	**98**
		0-900	609	170	119	112	**105**	**109**	**98**
		0-1200	666	184	128	113	104	**107**	**96**
		0-1500	623	235	157	125	106	**110**	**99**
		0-1800	636	294	219	175	126	126	109
	150	Drainage (mm)	0	214	286	354	555	646	803
		0-300	1446	158	**161**	**124**	**116**	**133**	**175**
		0-600	1781	155	**142**	**119**	**111**	**126**	**177**
		0-900	1832	170	145	**121**	**111**	**121**	**161**
		0-1200	1710	218	175	138	**113**	**120**	**149**
		0-1500	1561	342	242	169	118	**123**	**143**
		0-1800	1372	452	372	290	162	158	155
	225	Drainage (mm)	0	236	307	381	597	684	855
		0-300	1883	246	**226**	**235**	**224**	**262**	**209**
		0-600	2042	266	229	**223**	**226**	**255**	**211**
		0-900	1778	302	244	224	**223**	**245**	**212**
		0-1200	1731	381	295	235	221	**237**	**210**
		0-1500	1656	526	379	269	225	**237**	**211**
		0-1800	1520	675	560	423	254	259	221
	300	Drainage (mm)	0	232	304	376	555	652	814
		0-300	1891	397	343	**371**	**382**	**422**	**386**
		0-600	1741	376	346	351	**378**	**401**	**365**
		0-900	1694	415	364	350	**372**	**392**	**361**
		0-1200	1828	527	428	366	373	**390**	**365**
		0-1500	1808	695	541	414	371	**389**	**367**
		0-1800	1698	817	697	525	415	416	382