RESPONSE OF CROPS ON SHALLOW WATER TABLE SOILS IRRIGATED WITH DETERIORATING WATER QUALITIES

by

Louis Ehlers

A thesis submitted in accordance with the academic requirements for the degree

Philosphiae Doctor

In the Department of Soil, Crop and Climate Sciences
Faculty of Natural and Agricultural Sciences
University of the Free State
Bloemfontein

November 2007

Promoter:	Prof. A.T.P. Bennie	Ph. D.
Co-promoter:	Prof. L.D. van Rensburg	Ph. D.

TABLE OF CONTENTS

DECLARATION

I declare that the dissertation hereby submitted for the Philosophiae Doctor degree at the University of the Free State, is my own independent work and has not been submitted to any other University. I furthermore cede copyright for the dissertation in favour of the University of the Free State.

Signed:

Louis Ehlers

ACKNOWLEDGEMENTS

The successful completion of this study was only possible with the co-operation of many individuals and institutions, and it is my sincerely desire to express gratitude towards the following persons:

- My heavenly Father whose comfort, encouragement, guidance and mercy is always with me.
- Prof. A.T.P. Bennie, my promoter, for his immeasurable guidance, patience and encouragement throughout the duration of this study.
- Prof. L.D. van Rensburg, my co-promoter, for his valuable contributions and efforts to finalize this thesis.
- Prof. C.C. du Preez, Head of the Department of Soil, Crop and Climate Sciences for his advice and encouragement.
- All the members of the Department of Soil, Crop and Climate Sciences for providing me with their excellent facilities and their assistance during the field experiments, data analysis and writing of this thesis.
- The Water Research Commission (WRC) for being part of the research team responsible for the project titled "*Effect of irrigation water and water table salinity on the growth and water use of selected crops*", as well as the permission granted to use the data for this study.
- Suidwes Landbou, my employer, for the opportunity and support to complete this study.
- The National Research Foundation (NRF) for financial support.
- My parents, family and friends for their love, support and motivation.
- My wife, Suzette, for her interest and endless care. Without her loving support I would not have been able to achieve this goal.

ABSTRACT

This study was undertaken to investigate a number of issues regarding the effect of using saline irrigation water for crop production on soils with shallow water tables. The experiments were conducted in large drainage lysimeters, filled with a yellow sandy soil and a red sandy loam soil in which shallow saline water tables were maintained at a constant depth of 1.2 m. Wheat, beans, peas and maize were grown under controlled conditions using irrigation water with salinities that ranged from 15 to 600 mS m^{-1}. This facility was used to determine the effect of irrigation water and water table salinity on crop yield and water uptake, as well as salt accumulation in the root zone during growing seasons.

The field experiments simulated conditions of adequate water supply to the crops through irrigation in the presence of a shallow saline water table. Except for wheat that gave better yields in the more clayey soil, the growth of the other three crops was similar on both soils for comparative irrigation water salinity treatments. The above-ground biomass of wheat, maize, peas and beans started to decline when irrigated with water of 600, 450, 300 and 150 mS m^{-1}, respectively.

The water use of all four crops, as indicated by evapotranspiration, declined with deteriorating irrigation water salinity. On a relative basis the evapotranspiration of peas, beans, maize and wheat decreased at rates of 0.0007, 0.0005, 0.0004 and 0.0001 mm per unit increase of soil water salinity measured in mS m^{-1}. A decrease in the osmotic potential of the soil water to -300 kPa, which is equivalent to an electrical conductivity of 750 mS m^{-1}, reduced evapotranspiration in comparison to the control by 7, 30, 38 and 53% for wheat, maize, beans and peas, respectively. The water use efficiency of the crops, expressed in above-ground biomass produced per unit mass water used, started to decline only when the threshold EC_e-values were exceeded.

Water uptake from the shallow water tables decreased with an increase in irrigation water salinity for all four crops on both soils. The relative water uptake from the capillary zones above the water tables declined linearly when the soil water salinity in these zones exceeded certain threshold values. These values varied between 57 mS m^{-1} for beans to 279 mS m^{-1} for maize, with an average value of 136 mS m^{-1}. The crops less affected by the increase in salinity, were wheat followed by maize, beans and peas.

Salts accumulated at or just below the capillary fringe in both soils, with maximum accumulation at 700 mm from the soil surface or 500 mm above the water table. Equations were derived from the accumulation of salts in the root zone to calculate the salt accumulation in soils with restricted drainage during a crop growing season. These equations were incorporated in proposed procedures for salinity management on irrigated soils. The procedures made provision for five different conditions: i) where added salts to the root zone accumulate without any possibility for leaching and the mean root zone salinity is lower than the crop EC_e-threshold value; ii) where added salts to the root zone accumulate without any possibility for leaching and the mean root zone salinity is higher than the crop EC_e-threshold value; iii) where added salts can leach naturally from the root zone, but with not enough irrigation water to supply in the crop water demand; iv) where the natural leaching of added salts can be accelerated by irrigating more than the required crop water demand; and v) to irrigate according to the crop water demand in order to utilize rainfall for leaching.

The different salinity management procedures were compared on the two soil types by means of computer simulations for a range of irrigation water qualities and long-term climatic conditions. The simulated results indicated that under conditions with zero drainage, sustainable production could be maintained for only 25 to 40 years if good quality water was used for irrigation. Irrigation water with an ECi > 50 mS m^{-1} resulted in severe soil salinisation and crop losses within 5 to 10 years. On freely drained soils additional leaching was required within 5 years, even with the use of good quality irrigation water. It was clear from the simulated results that an increase in root zone salinity in soils with shallow water tables, necessitate adaptations in the normal approaches to irrigation scheduling and irrigation water management.

Key words: Shallow water table, irrigation water quality, osmotic potential, water use efficiency, soil salinity, capillary rise, salinity management.

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION AND OBJECTIVES

Most irrigation fields throughout the world suffer to some degree from the effects of salt accumulation in soils. From available FAO and UNESCO information, Szabolcs (1985), as cited by Rhoades & Loveday (1990), estimated that 20% of the then 230 million ha of irrigated land in the world is seriously affected by salinity. The total area irrigated increased to 270 million ha in 1990 (FAO, 1990). Backeberg *et al*. (1996) estimated that at least 20% of the 1.3 million ha irrigated land in South Africa was salt-affected in 1990.

The effects of salinity are manifested in loss of stand, reduced rates of plant growth, reduced yields and in severe cases, crop failure. Salinity limits water uptake by plants by reducing the osmotic and thus the total water potential of the soil solution. Certain salts may be specifically toxic to plants or may upset the nutritional balance when present in excessive concentrations. The salt composition of the soil water affects the exchangeable cation composition of the colloids which has an effect on soil permeability and tilth.

The sources of the salts found in saline soils can be the parent material, irrigation water, shallow groundwater or fertilizer and other soil amendments. All irrigation waters contain some salt which over time concentrates in the root zone as the water, but very little of the salt, is extracted by the plant roots. Even with good quality irrigation water the addition of salt to the root zone, unless it is removed through leaching by irrigation or rain in excess of the crop water requirement, will range between 5 000 to 10 000 kg ha^{-1} yr^{-1}.

The salts within the root zone may be redistributed towards the soil surface through the upward capillary flux of water from shallow saline water tables. Shallow water tables develop in irrigated fields, normally in the lower laying downslope positions, where impermeable strata occur below the root zone and where the water application exceeds removal. A major concern in irrigated agriculture is the gradual decline in irrigation water quality because of a growing demand for non-agricultural uses of water. This increase in demand leads to a gradual decrease in the quality of irrigation water due to reduction in streamflow of rivers with increased seepage of salts, re-use and recycling of available water resources.

A prime requirement for salinity control in irrigated fields is that the natural or artificial drainage should be adequate to ensure a nett downward flux of water and salts to ensure, in turn, the optimum development and functioning of roots. The reclamation of saline soils is accomplished through leaching with water of lower salinity, providing that drainage is adequate.

Little in this regard has been studied in South Africa. This study was undertaken to investigate a number of issues regarding the effect of using saline irrigation water for crop production on soils with shallow saline water tables. The specific objectives of this study were to:

1. Quantify the effect of increasing salt content of irrigation water on the growth and yield of selected crops on two different soil types.

2. Determine the relationship between irrigation water with increasing salt contents and the water use of selected crops on two different soil types.

3. Measure the root water uptake from a shallow water table with varying salt contents.

4. Quantify the accumulation of salts during the growing season of selected crops, at a range of irrigation water salinities and in the presence of shallow saline water tables.

5. Develop different root zone salinity management procedures.

6. Compare the different salinity management procedures, calculated with a range of irrigation water qualities and long-term climatic conditions, on two different soil types.

The study focused on cases where a shallow water table is present in the lower part of the potential root zone resulting in conditions of restricted leaching. Irrigation water ranging from low to a high salinity was used to irrigate wheat, beans, peas and maize on a sandy and sandy clay loam soil. Experiments were conducted under controlled conditions in the field in order to achieve the above-mentioned objectives.

A thorough literature study of the issues raised in the objectives is reported in Chapter 2. Large drainage lysimeters, filled with the two soils in which shallow water tables were maintained at a constant depth of 1.2 m, were used for the field experimentation. This facility was used to determine the effect of irrigation water and water table salinity on crop yield and water uptake (Chapter 3) and salt accumulation in the root zone during the growing seasons (Chapter 4). These results were combined in recommending procedures for managing root zone salinity (Chapter 5) and evaluated by means of simulation studies (Chapter 6).

CHAPTER 2

LITREATURE REVIEW

2.1 Introduction

The global demand for food and agriculturally produced raw materials makes the sustainable use of soil and water resources on the earth imperative and urgent. In science and politics the prevalent opinion is that agricultural soil can supply not only the present demands of mankind, but must fulfil all future food requirements of an ever-growing population.

In order to meet those requirements, the further study of and optimal utilization of soil and water resources must be given a high priority. This applies especially to processes that are associated with soil and water degradation. One of the soil degradation processes is salinization, viz. the accumulation of salt, which leads to the degradation of especially heavy-textured soils (Szabolcs, 1989). According to the FAO (1990), salinization of irrigated soils is a major problem. It concluded that of 270 million ha of irrigated land 20% is salt-affected and of the 1500 million ha under dryland agriculture, 2% is salt-affected to varying degrees.

The general feeling is that the importance of irrigation in world agriculture is rapidly increasing, which means that the problem of salinization of irrigated land cannot be ignored. The record of irrigation speaks for itself in terms of increased crop production; but the question remains, how successful was the utilization of irrigation schemes? Past history shows us that irrigation failed in many regions, probably because the technology and knowledge at the time was incapable of dealing with the problems that arose.

One of the biggest problems in irrigated areas is a decline in water quality. Because of the growing demand for water by industrial and mining sectors, the management and conservation of water resources are considered to be very important. The increasing demand for limited water resources must ultimately lead to re-use and recycling of water. In many parts of the world this has already occurred, especially in cases where field drainage and industrial and domestic wastewaters are re-used and recycled for irrigation (Ragab, 2002). The increasing use of marginal water enhances the possibility of salinization of irrigated soils.

Secondary salt accumulation can result in high salinity or sodicity, or both in soils. Salinity is associated with increased water stress and specific ion effects on plants. Sodicity leads to increased swelling and dispersion of the soil colloids and a breakdown in soil structure. However, because soil sodicity does not form part of this study, a detailed discussion of it will not be included.

Letey (1984) concluded that investigations on salinity control could be divided into two categories. Firstly, those that inhibit the toxic effect of a salt without removing it from the soil and secondly, those that try to eradicate the problem by removing the salt from the soil through leaching. It was the latter that was found to be more successful, and in recent years a major effort was devoted to the approach of salt leaching. Salts leached from the soil will eventually end up in the under-ground or surface water resources.

It is clear that salinization of irrigated soils is a major problem and an effort must be made to improve the management of irrigation farming. A proper management proposal should address all the different factors affecting salinity and its' effect on crop growth, with the purpose of controlling groundwater, stream flow and farmland salinization. Modelling the different components involved in secondary salinization can be very useful when it comes to the management of an irrigation farm for purposes of salinity control.

2.2 Irrigation water quality

Water quality plays an important role in several facets of irrigation agriculture. Under specific conditions the selection of the irrigation method, crops to be cultivated, scheduling, fertigation etc. will be determined largely by water quality. Several water quality characteristics need to be considered in the evaluation of its suitability for irrigation. However, the main water quality determinants of concern remain the salinity and sodicity risks posed by its use (Du Plessis, 1998).

Electrical conductivity (EC) is a measure of the ability of water to conduct an electrical current and is expressed in millisiemens per metre (mS m^{-1}). This ability is a result of the presence of ions such as $CO_3^{=}$, HCO_3^-, Cl^-, $SO_4^{=}$ NO_3^-, Na^+, K^+, Ca^{++} and Mg^{++}, all of which carry an electrical charge. Virtually all natural waters contain varying concentrations of these ions originating from the dissolution of minerals in rocks, soils and decomposing plant material. The EC of natural waters is therefore often dependent on the characteristics of the geological formations with which the water was, or is, in contact. The total concentrations, as well as the relative concentrations of these ions influence the electrical conductivity of the irrigation water (EC_i). Consequently, EC_i is directly proportional to the total dissolved solids (TDS) in the water. Since EC_i is much easier to measure routinely, it is used to estimate TDS. According to the Department of Water Affairs and Forestry (1996) the average conversion factor for most waters is as follows:

$$\text{TDS (mg L}^{-1}\text{)} = \text{EC (mS m}^{-1}\text{ at 25 °C)} \times 6.5 \tag{2.1}$$

The exact value of the conversion factor depends on the ionic composition of the water, especially the pH and HCO_3^- concentration. For very accurate measurement of TDS, the conversion factor should be determined for specific conditions.

According to the United States Salinity Laboratory Staff (1969), irrigation water can be divided into four classes on the basis of it's EC:

1. Low salt content (C1): Water with an EC less than 25 mS m^{-1} which holds no danger of salinization on well-drained soils.
2. Medium salt content (C2): Water with an EC between 25 and 75 mS m^{-1} where provision must be made for a reasonable degree of salt leaching and salt sensitive crops must be avoided.
3. High salt content (C3): Water with an EC between 75 and 225 mS m^{-1} which can only be used on a well-drained soil. Leaching is required periodically and salt resistant crops must be used.
4. Very high salt content (C4): Water with an EC above 225 mS m^{-1}. Not suitable for use as irrigation water under normal conditions. Can be used as an emergency measure under extreme conditions on sandy soils only.

Adapted guidelines for South African conditions are given by the Department of Water Affairs and Forestry (1996). There are some limitations in setting such criteria for salinity, but the criteria remain useful for comparing qualities of different water resources. The salinity of South Africa's irrigation water has, historically, been relatively low and compares favourably with the rest of the world when compared with the 90th percentile value of about 320 mS m^{-1} found by the United States Salinity Laboratory (Herold & Bailey, 1996). A deterioration of irrigation water salinity in some regions of South Africa has been reported by Du Plessis & Van Veelen (1991).

Long-term average EC_i-values for the Riet, Vaal and Orange Rivers are given in Table 2.1.

Table 2.1 Long-term average electrical conductivity (EC_i, mS m^{-1}) and sodium adsorption ratio (SAR) values for the Riet, Vaal and Orange Rivers

River	**EC_i (mS m^{-1})**	**SAR**	**Reference**
Lower Riet	136	3.2	Du Preez *et al.* (2000)
Lower Vaal	50-74	<2	Du Preez *et al.* (2000)
Upper Orange	23	<1	Du Preez *et al.* (2000)
Lower Orange	40	<1.5	Volschenk *et al*. (2005)

The sodium adsorption ratio (SAR) is an index of the potential of irrigation water to induce sodic soil conditions. It is calculated from the Na^+, Ca^{++} and Mg^{++} concentrations ($mmol_c$ L^{-1}) in irrigation water as shown in Equation 2.2.

$$\mathrm{SAR} = \frac{\mathrm{Na}^{+}}{\sqrt{\left(\mathrm{Ca}^{++} + \mathrm{Mg}^{++}\right)/2}} \qquad (2.2)$$

An increase in SAR will be the result of either an increase in the Na or a decrease in the Ca and/or Mg content of the irrigation water.

In the long-term (i.e. under conditions of chemical equilibrium) the SAR of irrigation water determines the exchangeable sodium percentage (ESP) of irrigated soils. Since the quantity of cations in irrigation water is normally small, compared to those adsorbed on a soil's cation exchange complex, the ESP over the depth of a soil profile only changes slowly to reach equilibrium with the SAR of irrigation water. Changes in the ESP start in the topsoil and move progressively deeper. While short-term variations in the SAR of irrigation water will affect the overall ESP of the soil profile marginally, the soil surface could be markedly affected (United States Salinity Laboratory Staff, 1969).

Soil permeability is largely determined by texture and mineralogy. It has long been realized that for irrigated soils, both the inherent permeability and hardsetting characteristics of a soil can be modified by irrigation water SAR, due to it's effect on soil ESP and the EC of the infiltrating water. Increasing soil ESP gives rise to more swelling and increasing dispersion of clay minerals, making soil structure unstable and thereby reducing the infiltration rate and hydraulic conductivity of soils. The effect of an increasing SAR in irrigation water on lowering the infiltration rate is mainly a soil surface phenomenon. Agassi *et al*. (1981) drew attention to the fact that infiltration rate was largely determined by the formation of a surface seal which forms under raindrop impact. Depending on the concentration of the SAR constituents in the water and the soil buffering capacity, the ESP of the soil surface may often be determined by the SAR of the last irrigation. The risk of a reduction in the infiltration rate of a soil is, therefore, related to the maximum SAR of the irrigation water.

The SAR of most South African rivers is generally low (Table 2.1), but very high values can be measured in borehole water. This study concentrated on salinity, therefore no further attention will be given to problems associated with sodicity.

A major factor contributing to land degradation is soil and water salinisation. Land and water resources can be salinised by natural or by human activities and there are quite a number of examples all over the world of once fertile farmland becoming highly saline, waterlogged wasteland (Appleton, 1984). Irrigation agriculture is not only at the receiving end of water quality deterioration, but is itself a major contributor to the observed water quality degradation in many rivers (Du Plessis, 1998). Plants selectively extract water from the soil solution, leaving most of the salt behind. Leaching of excess salt from the root zone is thus a prerequisite for sustainable irrigation farming. The salinity of water draining to below the root zone of irrigated crops will therefore always be higher in salts than the applied water. Irrigation drainage seeping back to a river, and drainage water released into the river, is consequently more saline than the irrigation water. When the drainage water percolates through saline underground layers on its way to the river, the salinity load is even higher.

In an assessment of South Africa's water quality situation, the Department of Water Affairs and Forestry (1996) found that the country's water quality is deteriorating in spite of the Department's efforts to control pollution from point sources such as urban, industrial and mining developments. The conclusion was reached that water quality degradation originating from non-point sources, such as irrigation return flow, also plays a major role in the observed deterioration of irrigation water.

Hall & Görgens (1978) indicated that in the Breede River, the mean salinity of the river increased from 103 mg L^{-1} at the Brandvlei Dam to 728 mg L^{-1} down stream, mainly because of irrigation return flow from the irrigated areas during the summer months. The same observation was also made for the Great Fish River at Jordaans Kraal and it was found that the increase in salinity corresponded positively with the increase in irrigated area. Du Preez *et al*. (2000) also ascribed the observed increase in the downstream salinity of the lower Vaal, Harts and Riet Rivers to irrigation activities. They also reported a gradual increase in the salt content of these rivers over time. The same observation was made by Volschenk *et al.* (2005) for the lower Orange River.

2.3 Soil and water table salinity

Shallow water tables can contribute significantly towards plant evaporation because water moves through capillary upflow from the water table into an active plant root zone, thus reducing the amount of supplemental irrigation needed (Ehlers *et al*., 2003). Shallow water tables in or just below the root zone cause rapid salinization of soil layers above it, since leaching is restricted by its presence. As a result crop growth and water uptake can be hampered despite adequate water availability. Soil and water table salinity can therefore affect the capillary contributions from the water table towards evapotranspiration. Many researchers mentioned soil salinization as a potential hazard where subsurface irrigation is practised in arid and semi-arid regions throughout the world (Streutker *et al*., 1981; Meyer *et al*., 1994; Kang *et al*., 2001).

Wallender *et al*. (1979) reported that water tables with salinity levels of 290 mS m^{-1} or higher, gave pronounced yield losses with wheat. They found that, in a soil with a saline water table at a depth of 2.1 m, the average conductivity of the saturation extract below a depth of 0.9 m was 788 mS m^{-1}, compared to 309 mS m^{-1} at shallower depths. They warned against the potential buildup of soil salinity and toxic ions in the root zone of water table soils and emphasized the importance of taking the sensitivity of different crops to salt and specific ions into account, when a long-term management system is developed.

Ayars & Schoneman (1986) referred to work done by Van Shilfgaarde *et al*. (1974), who suggested that crops are capable of using water with a higher salinity than has been indicated by some salt tolerance studies. They found from studies in California and Texas, that certain salt tolerant crops, like lucerne, barley and cotton are capable of extracting significant quantities of water from saline water tables. Cotton extracted up to 60% of its seasonal evapotranspiration from a water table with a salinity of 600 mS m^{-1} and up to 49% from the water table when salinity increased to 1000 mS m^{-1}.

This was confirmed by Blaine & Kite (1984) who investigated irrigation scheduling of cotton in the presence of saline water tables. Soil salinity ranged from 100 to 500 mS m^{-1} near the soil surface and from 1000 to 1200 mS m^{-1} at a depth of 1 m. They concluded that cotton plants can tolerate high levels of soil water salinity in the lower part of the root zone, when water with a low salinity is available to the plant in the upper part of the root zone. Most of the water uptake occurred from soil layers where the soil water quality was the best, regardless of the depth of the water table.

When irrigation is reduced to the crop water requirement minus precipitation and uptake from a shallow water table, rapid salinization of the root zone is very likely. Leaching will be required, probably just before the rainy season, when water tables are supposed to be at their deepest.

2.4 Effect of soil and water salinity on crop growth

2.4.1 Crop salt-tolerance

Excess salinity within the root zone reduces the growth rate of established plants, thus a general reduction in growth is observed. The hypothesis is that excess salt reduces plant growth, primarily because it increases the energy required to take up water from the soil and for making the biochemical adjustments necessary for survival. This energy is diverted from the processes that lead to growth and yield, such as cell enlargement and the synthesis of metabolites and structural compounds (Maas, 1984).

Typically, growth is suppressed when a threshold value of salinity is exceeded. This threshold value depends on the crop, external environmental factors such as temperature, relative humidity, wind speed, and the water-supplying potential of the root zone. Beyond the threshold value the suppression of growth increases linearly as salinity increases until the plant dies. The salt tolerance of crops can be expressed as follows (Maas & Hoffman, 1977):

$$Y_r = 100 - b\ (EC_e - a) \tag{2.3}$$

where Y_r = the percentage of the yield of the crop grown under saline conditions relative to that obtained under non saline conditions

a = the threshold electrical conductivity (mS m^{-1}) of the saturated soil paste at which yield decreases start

b = the percentage yield loss per unit increase in the electrical conductivity of the soil extract in excess of the threshold value

EC_e = electrical conductivity of the soil extract (mS m^{-1})

The salt tolerance rating of selected crops based on their threshold value (a, mS m^{-1}) and slope of yield decline (b, % mS m^{-1}) are given in Table 2.2.

Table 2.2 Salt tolerance of some agronomic crops (After Maas, 1986)

		Electical conductivity of saturated soil extract		
Common name	**Botanical name**	**Threshold mS m^{-1}**	**Slope % per mS m^{-1}**	**Rating ***
Bean	*Phaseolus vulgaris*	100	0.190	S
Cotton	*Gossypium hirsutum*	770	0.052	T
Maize	*Zea mays*	170	0.120	MS
Pea	*Pisum sativum*	-	-	S
Peanut	*Arachis hypogaea*	320	0.290	MS
Potato	*Solanum tuberosum*	170	0.120	MS
Wheat	*Triticum aestivum*	600	0.071	MT
* S = Sensitive, MS = Medium Sensitive, MT = Medium Tolerant, T = Tolerant				

According to Maas (1986) it should be recognized that the salt tolerance data presented in Table 2.2 cannot provide a fully accurate, quantitative measure of crop yield losses to be expected from salinity for every situation, since actual response to salinity varies with growth conditions such as climate, irrigation management, agronomic management and crop response to saline conditions.

Improvement in diagnosis can be achieved by using salinity of the soil solution (EC_{sw}) rather than EC_e, since salinity of the saturation extract does not account for the increase in salinity of the soil water between irrigations due to soil water depletion (Rhoades *et al*., 1981). The use of soil water-based salinities necessitates the conversion of crop salt tolerance data from EC_e to EC_{sw}, since instrumental techniques have become available to facilitate the measuring of EC_{sw} directly in the field.

Crop salt tolerance also depends on the method of irrigation and its frequency. The available crop salt tolerance data apply mostly to furrow and flood irrigation with conventional irrigation management. Sprinkler irrigated crops are potentially subjected to additional damage by foliar salt uptake and burn from water contact with the foliage. Susceptibility to foliar salt injury depends on leaf characteristics and rate of absorption. The degree of foliar injury depends not only on the salinity and salt composition of the irrigation water but also upon atmospheric conditions, the size of sprinkler droplets, crop type and growth stage. The tolerance of crops to foliar-induced salt damage does not generally coincide with that of root-induced damage. Some of the available data are summarized in Table 2.3.

Table 2.3 Relative susceptibility of crops to foliar injury from saline sprinkling waters (After Maas, 1985)

Na^+ or Cl^- concentrations causing foliar injury ($mmol_c\ L^{-1}$)			
<5	**5-10**	**10-20**	**>20**
Almond Apricot Citrus Plum	Grape Pepper Potato Tomato	Alfalfa Barley Cucumber Safflower Sesame Sorghum Maize	Cauliflower Cotton Sugarbeet Sunflower

Besides the above-mentioned effects, salinity also adversely influences crop establishment. In fact, obtaining a good stand of plants is often the most limiting factor to crop production in saline areas. Once an acceptable stand is established, management risks are generally substantially reduced. The problem of reduced seed germination and seedling establishment is due in part to the generally lower salt tolerance of seedlings compared to established plants. Additionally, the problem is enhanced because the seeds or small seedlings are exposed to excessive soil surface salinity in the seed bed, due to water evaporation (Miyomoto *et al*., 1985). Salt concentrations in crop beds vary markedly with depth and time (Bernstein & Francois, 1973).

2.4.2 Osmotic effect

Under irrigated field conditions, soil water salinity or the osmotic component of total soil water potential, is seldom uniform with depth throughout the root zone. Between irrigations, as water is used by the crop and lost by evaporation, the total soil water potential of the root zone decreases because of reductions in both the matric potential with soil drying and the osmotic potential as salt is concentrated in the reduced volume of soil water. Thus, the salinity level varies both in time and depth, depending on the degree to which water is depleted between irrigations and the degree of salt leaching (Rhoades, 1972; Rhoades & Merrill, 1976).

Crop yields have been shown to be closely correlated with the average soil water potential of the root zone over time (Bresler, 1987). Plant roots preferentially absorb water from regions of high total potential, i.e. of low matric plus osmotic stress (Shalhevet & Bernstein, 1968). Thus water is used from the upper, less saline root zone, until the total water stress becomes greater in the upper rather than in the lower part of the root zone and at such time water will be used from the lower root zone (Wadleich & Ayers, 1945).

Osmotic induced plant water stress sets in when the difference between the osmotic potential of the soil water and that of the plant's cells declines. To survive, the plant must adjust osmotically, by building up even higher internal solute concentrations. This can be achieved by absorption of ions from the soil, or synthesis of organic compounds, or both.

Salt-accumulating halophytes are adapted by absorbing salt from the soil and using it as a major internal osmoticum (Flowers *et al*., 1977). However, salt in plant cells can be dangerous. Substantial evidence (Greenway & Munns, 1980; Wyn Jones, 1981; Munns *et al*., 1983) indicates that high salt concentrations in the cytoplasm damages enzymes and organelles. Salt taken up from the soil apparently serves as an osmoticum in the large fraction of the total cell volume, the vacuole. In the cytoplasm, the function of osmoregulation is served mainly by organic solutes synthesized by the plant (Wyn Jones & Gorham, 1983). Thus, organic osmolytes are used to a large extent in only a small fraction of the total cell volume. The tonoplast must transport salt into the vacuole, build up a high concentration of the salt there, and prevent any substantial leakage of organic osmolytes from the cytoplasm into the vacuole. Non-halophytic plants are unable to absorb major quantities of external ions for osmoregulation. To survive in a saline medium, these plants must synthesize organic osmolytes to a greater extent, by utilizing more metabolic energy than plants that use inorganic salts absorbed from the soil as a major osmoticum. Plants vary greatly in the adjustment of their energy economy to the presence of salt (Schwarz & Gale, 1981). Respiration rates usually increase at moderate salinities depending on the salt tolerance of the plant. Salt tolerance data assumes that crops respond primarily to the osmotic potential of the soil solution. As water becomes limiting, plants experience stresses from low matric potential, as well as low osmotic potential. However, the effects of specific ions or elements must also be considered although this is generally of secondary importance.

2.4.3 Specific ion effect and nutrition

A universal feature of salt-affected soils is the presence of high concentrations or chemical activities of certain ionic species like sodium and chloride (Epstein & Rains, 1987; Szabolcs, 1989). The ratios of these ions to others may be quite high and may cause deficiencies of nutrient elements present at much lower concentrations. In short-term experiments with barley seedlings, Aslam *et al*. (1984), found that the presence of $SO_4^{=}$, and to a greater extent, Cl^-, decreased the rate of NO_3^- uptake by plants with 83% at a 0.2 M NaCl concentration.

Studies by Ball *et al*. (1987) and Cramer *et al*. (1988) showed that salt-induced potassium and calcium deficiency occurred in saline environments where sodium dominates. Maas & Grieve (1987) compared the effects of exposing maize (*Zea mays*) to osmotic solutions salinised at various Na:Ca ratios and indicated that at a high ratio of 35:1 the plants suffered from calcium deficiency. At a lower ratio of 5.7:1 and less, no calcium deficiency occurred.

2.4.4 Specific ion effect and toxicity

Certain salt constituents are specifically toxic to some crops. Boron is toxic to certain crops when present in the soil solution at concentrations of only a few milligrams per litre. In some woody crops, Na^+ and Cl^- may accumulate in the tissue to toxic levels. These crops have little ability to exclude Na^+ or Cl^- from their leaves and being long-lived, they often suffer toxicities at even moderate soil salinities.

In experiments conducted by Grattan & Maas (1988), leaf injury to soybean plants caused by salinity, was identified as phosphate toxicity. The extent of such leaf injury depended on the concentration of phosphate, the Ca:Na ratio and the crop variety.

2.5 Salt accumulation in soils

2.5.1 Origin of salinity in irrigated areas

It is generally accepted that salinization of irrigated soils is the result of several processes. Inadequate drainage is probably the most important one. In many irrigated areas in the world the water table has raised, due to the degree of excessive irrigation that exceeds the drainage from the soil. High water tables gave rise to problems of salinity and waterlogging in most of the irrigation schemes. This secondary salinization results from human activities that change the hydrologic balance of the soil between water applied (irrigation or rainfall) and water used by the plant (transpiration) and evaporation from the soil. An important source of salt added to irrigated soils, is irrigation water and capillary rise from water tables. The accumulation of salt in the soil will depend on soil type (texture, depth, internal drainage and salt content), quality of irrigation water, type of irrigation system (flood or sprinkle) and management practices (irrigation scheduling and leaching fraction) (Du Preez *et al.*, 2000).

2.5.2 Factors involved in salt accumulation

2.5.2.1 Irrigation water quality

Irrigation water contains a mixture of soluble salts, and the concentration of these salts determines the quality of the irrigation water. Soils irrigated with poor quality water will have a similar mixture of salt, usually at a higher concentration than the applied irrigation water. Irrigation water with a salt content of 500 mg kg^{-1} or mg L^{-1} contains 0.5 tons of salt per 1000 m^3. Crops require from 6000 to 10 000 m^3 of water per hectare each year. One hectare of land will then receive 3 to 5 tons of salt. Because the amount of salt removed by crops is negligible, salt will accumulate in the soil without adequate drainage.

When poor quality water is used for irrigation three management options should be considered: i) selection of appropriately salt-tolerant crops; ii) improvement in water management, and in some cases the adoption of advanced irrigation technology; and iii) maintenance of soil physical properties to assure soil tilth and adequate soil permeability to meet crop water and leaching requirements (Oster, 1994).

2.5.2.2 Capillary rise

The total amount and number of irrigations can be reduced in the presence of root accessible water tables. It is reported by Ghamarnia *et al.* (2004), that 20% to 40% of the evapotranspiration demands of different crops can be met by capillary upflow from water tables at depths of 0.7 to 1.5 metres. Capillary upflow can be defined as the movement of water from a water table into an active plant root zone.

Ehlers *et al.* (2003) found that the successful use of water tables to supplement the water supply to crops, depends on several factors including water table depth, soil physical properties, soil and water table salinity and plant root distribution. A soil with a high unsaturated hydraulic conductivity was able to supply water to root systems at higher rates and heights above the water table. They indicated that the height of capillary rise will increase with an increase in the silt-plus-clay content of the soil. The upward flux at a specific height above the water table was higher for higher silt-plus-clay percentages.

In Figure 2.1 relationships between water table depth and the contribution from the water table as a percentage of evapotranspiration (ET) are illustrated for three soils with different textures. When water table depth increases, the contribution of the water table to ET will decrease. This effect of water table depth will also be influenced by its salinity level (Sepaskhah & Karimi-Goghari, 2005). Ghamarnia *et al.* (2004) reported that under high irrigation water salinity levels for wheat, the contribution from the water table as a percentage of ET declined from 43% to 28% when the water table salinity level rose from 200 to 800 mS m^{-1}.

Water tables can reduce the irrigation requirements of cotton and wheat by 50%, but utilizing it can cause salinization problems especially at high water table salinity levels (Streutker *et al*., 1981).

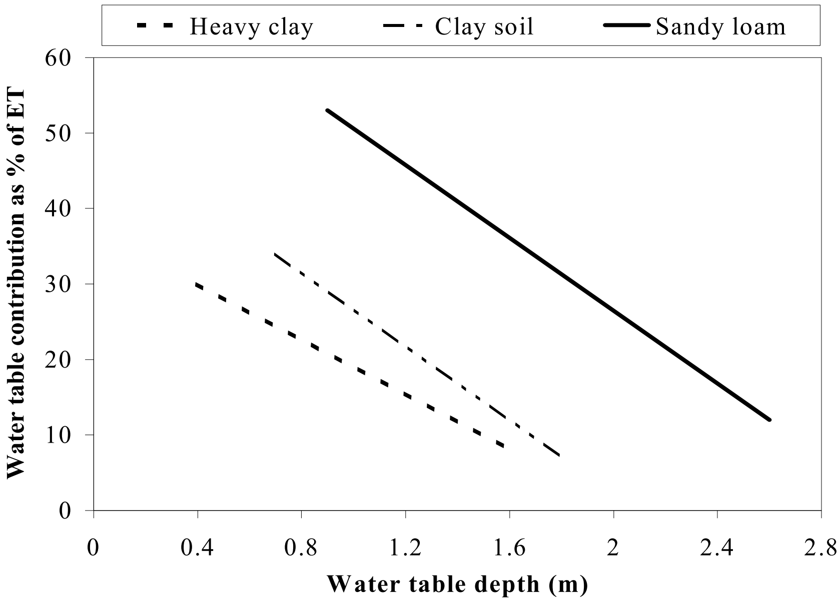


Figure 2.1 Water uptake from water tables, as affected by water table depth and soil texture (Grismer & Gates, 1988).

2.6 Salt removal from soils

2.6.1 Salt balance

Salts accumulate in the irrigated root zone when they are left behind as the soil water is used by plants during transpiration or lost by evaporation. By drying the upper soil relative to deeper layers, evapotranspiration also creates the potential for an upward flow of water into the root zone. The root zone and the soil surface may become salinised by this process, especially where shallow saline water tables are present. On freely drained soils, however, during periods of excessive rainfall or irrigation, a fraction of infiltrated water can pass through the root zone leaching soluble salts into the deeper subsoil. A salt balance (Equation 2.4) may therefore be obtained by adding the various inputs to and subtracting the outputs of salt from the soil water salinity (S_{sw}) of the root zone (Rhoades, 1974):

$$\Delta S_{sw} = V_{iw} C_{iw} + V_{gw} C_{gw} + S_m + S_f - V_{dw} C_{dw} - S_p - S_c \qquad (2.4)$$

where

V_{iw} = volume of irrigation water with a salt concentration C_{iw}

V_{gw} = volume of upward flux from the water table with a salt concentration C_{gw}

V_{dw} = volume of drainage water with a salt concentration C_{dw}

S_m = amount of salt added from weathering of soil minerals or salt deposits

S_f = amount of soluble salt added through applied chemicals

S_p = amount of salts precipitating in the soil

S_c = amount of salts removed by the harvested vegetation

Equation 2.4 indicates that when the additions of salts exceed the losses, the salt content in the root zone will increase and *vice versa*.

2.6.2 Salt movement in soil

According to miscible displacement theory, salt will move in the soil by two processes, namely convection and diffusion. Convection is the simultaneous movement of water plus the dissolved salts by mass flow through the larger water filled pores. This creates a gradient between the typically lower salt concentration of the macro pores and the higher salt concentration of the micro pores. As a result, salt ions tend to diffuse from the stagnant micro pores into the mass flow stream through the macro pores. Equation 2.5 describes the process:

$$q_s = q_c + q_d \tag{2.5}$$

where q_s is the total solute flux, q_c the convective solute flux, and q_d the diffusive solute flux, all with units of g cm^{-2} h^{-1}. These two components must be considered separately because of different physical and chemical processes (Wagenet, 1984).

2.6.2.1 Convection

According to Jury *et al.* (1991) the bulk flow or convective transport of solute q_c may be written as:

$$q_c = J_w \, . \, C_l \tag{2.6}$$

where J_w is the water flux and C_l the solute concentration. Equation 2.6 only takes the mean pore water velocity over many soil pores into consideration. It does not represent the actual flow paths, which must curve around solid particles and air space. These differential pore flow velocities must be considered and is often referred to as hydrodynamic dispersion. Equation 2.7 can then describe the solute convection.

$$\text{Total convection} = J_w \, . \, C_l + J_{lh} \tag{2.7}$$

where J_{lh} is the hydrodynamic dispersion flux.

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

2.6.2.2 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.

Nye & Tinker (1977) concluded that the process of solute diffusion could be calculated from Fick's first law:

$$F = - D_w \, . \, dC / dx \tag{2.8}$$

Equation 2.8 applies to steady state conditions where the concentration gradient remains constant over F which is the flux, dC / dx is the concentration gradient across a section and D_s the diffusion coefficient relating F to dC / dx in a liquid, which can be measured experimentally.

Rewriting Equation 2.8 for unsaturated soil conditions gives Equation 2.9:

$$F = -D_s(\theta) \, . \, dC / d\,x \tag{2.9}$$

where θ is the volumetric soil water content and $-D_s$ the diffusion coefficient of the solute in the soil solution which is a function of θ.

Since air as well as solid particles forms barriers to liquid diffusion, a liquid tortuosity factor, describing the increased path length and decreased cross-sectional area of the diffusing solute in soil, the diffusion coefficient (D_s) can be estimated with Equation 2.10.

$$D_s = -D_w \, . \, \theta \, . \, f \tag{2.10}$$

where f is the tortuosity factor.

It is clear that salt movement and accumulation in soil is extremely dependent on soil water content and movement. Therefore, the factors that influence the amount of soil water flux will also play an important role in the movement of salt. Soil water flux can be determined by using a Darcian approach, the water budget or chloride mass balance approach. A summary of the different approaches can be found in Herald (1999).

2.6.3 Leaching of salts

Leaching is by far the most effective procedure for removing salts from the root zone of soils. Leaching is mostly accomplished by ponding fresh water on the soil surface, or by a high frequency of heavy irrigations, and allowing it to infiltrate. Leaching is only effective when the saline drainage water is removed through subsurface drains or transferred into the deeper subsoil with sufficient natural drainage. Leaching during the summer months is, as a rule, less effective, because large quantities of water are lost through evaporation. The actual choice will, however, depend on the availability of water and other considerations. In some parts of India, for example, leaching is best accomplished during the summer months because this is the time when the water table is deepest and the soil is dry. This is also the only time when large quantities of fresh water can be diverted for reclamation purposes.

2.6.3.1 Quantity of water for leaching

It is important to have a reliable estimate of the quantity of water required to accomplish salt leaching. The initial salt content of the soil, desired level of soil salinity after leaching, depth to which reclamation is desired and soil characteristics are major factors that determine the amount of water needed for reclamation. A useful rule of thumb is that a unit depth of water will remove nearly 80 percent of salts from a unit soil depth. Thus 300 mm water passing through the soil will remove approximately 80 percent of the salts present in the upper 300 mm of soil. For more reliable estimates, however, it is desirable to conduct salt leaching tests on a limited area and prepare leaching curves. The leaching curves displayed in Figure 2.2 for three soils in Iraq relate the ratio of the actual salt content to initial salt content in the soil (S_a/S_b) to the depth of drainage water per unit depth of soil (D_w/D_s). These curves illustrate the effect of soil type and the quantity of water required to achieve the same degree of leaching.

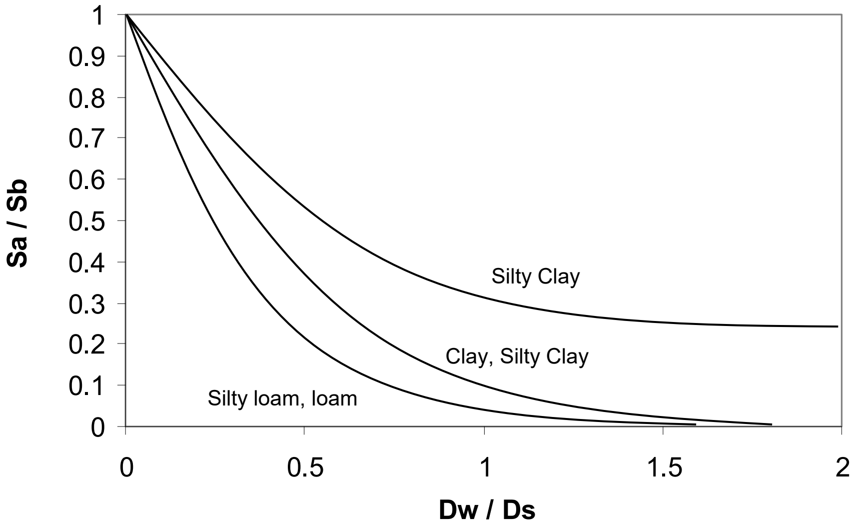


Figure 2.2 The ratio of the required salinity (S_a, mg L^{-1}) and initial salinity (S_b, mg L^{-1}) and its relationship with the ratio between the amount of drainage (D_w, mm) and soil depth (D_s, mm) (Dieleman, 1963).

2.6.3.2 Water application method

Results from several laboratory experiments (Nielsen & Biggar, 1961; Miller *et al.,* 1965) and some field trials (Nielsen *et al*., 1966; Oster *et al*., 1972) have shown that the amount of salts removed per unit depth of water leached can be increased appreciably by leaching at soil water contents below saturation, i.e. under unsaturated conditions. Unsaturated conditions during leaching can be obtained in practice by intermittent ponding or by irrigation at a rate less than the infiltration rate of the soil. Nielsen *et al.* (1966) for example, showed that 250 mm of sprinkler irrigation reduced the salinity of the upper 600 mm of soil to the same degree as 750 mm of ponded water.

Finally, secondary salinisation will have to be controlled or prevented through irrigation management and leaching. Modelling can be very useful in managing secondary salinisation.

2.7 Root zone salinity management

Rhoades and Loveday (1990) emphasized the need for appropriate practices that prevent the development of excessive salinisation in irrigated land. According to them management need not necessarily aim to control salinity at the lowest possible level, but rather to keep it within limits commensurate with sustained productivity. Crop, soil and irrigation practices can be modified to achieve these limits, but it is important to maintain a check on the efficacy of the control practices with a system of monitoring soil salinity and drainage adequacy.

2.7.1 Crop management

Crops and different cultivars of the same crop vary considerably in their tolerance to salinity (Maas & Hoffman, 1977; Maas, 1986), and therefore crops with higher salt tolerances can be selected that produce satisfactorily under the particular conditions of salinity in the root zone. It is important to consider the crop’s salt tolerance especially during seedling development, for this is often considered to be the most sensitive growth stage (Shannon, 1982). Salt present in the seedbed reduces the rate of germination (Shannon & Francois, 1977; Dikgwatlhe, 2006), and the stand may suffer as a consequence. Seeding density may be increased to compensate for the loss of stand in order to increase the crop yield under saline conditions.

2.7.2 Drainage management

From Equation 2.4 it is evident that the change in salt content of the root zone depends on the direction of the net salt flux. The only practical way to reduce the salt concentration in the root zone is to leach salts out of the root zone with water of a lower salinity than the soil solution. As mentioned in Section 2.6.3 the salinity level of the root zone in a freely drained soil will be a function of the irrigation water salinity and the amount with which irrigation exceeds plant water uptake. However, water that percolates deeper than the root zone does not contribute towards production for that specific season and could therefore be regarded as a net loss of water for crop production. Managing the amount of drainage water that percolates out of the root zone is an important aspect that determines irrigation efficiency and consequently the sustainability of any irrigation scheme. Under conditions of low soil salinity, percolation should be managed with the minimized leaching approach where the aim is to make the maximum use of applied irrigation water through transpiration.

Under conditions of high soil salinity, removing salts out of the root zone through drainage water is probably the single most important factor that must be considered for sustainable production. In this case, percolation can be regarded as productive, assuming that the drainage system (either natural or artificial) is able to cope with water percolating beneath the root zone. In the absence of adequate drainage, the groundwater will eventually rise to levels that allow salts to accumulate in the soil and the root zone to become waterlogged.

2.7.3 Water table management

Shallow water tables can contribute significantly towards evapotranspiration and are recognized as an important water resource in agriculture (Meyer *et al*., 1994). Research conducted by Ehlers *et al*. (2003) indicated irrigation water savings of 30 to 65% in the presence of shallow water tables at depths ranging from 1 to 1.5 m from the soil surface. However, when irrigation is reduced to the crop water requirement minus precipitation and uptake from a shallow water table, rapid salinisation of the root zone is very likely (Streutker *et al*., 1981; Kang *et al*., 2001). When root zone salinity under these conditions exceeds the threshold values of the cultivated crops, artificial drainage of the soil becomes essential. Leaching will be required, probably just before the rainy season, when water tables are supposed to be at their deepest.

2.8 Conclusions

Major factors contributing towards land degradation is soil and irrigation water salinisation. Assessments of South Africa’s water quality situation revealed that the river water quality is gradually deteriorating in spite of efforts to control pollution from point sources such as urban, industrial and mining developments, as well as non-point sources such as irrigation return flows.

Soil and irrigation water salinity affects agricultural crops through loss of stand, reduced rates of plant growth, reduced yields, and in severe cases, total crop failure. Salinity limits water uptake by plants by reducing the osmotic potential and thus the total potential of the soil water. Additionally, certain salts may be specifically toxic to plants or may upset nutritional balances if they are present in excessive amounts or proportions.

The salt composition of the soil water influences the composition of cations on the exchange complex of the soil colloids, and jointly, salinity levels and exchangeable cation composition influence soil permeability and tilth.

Shallow water tables typically develop in irrigated lands usually in down-slope positions, when applied water and rainfall exceeds losses from the root zone. Shallow water tables are recognized as an important energy-efficient water resource for agriculture. Unfortunately, the upflow of the soil solution from a saline water table causes rapid salinisation of soil layers above the water table because of restricted leaching. Thus, a prime requirement for salinity control in irrigation projects is that leaching through natural or artificial drainage is adequate to ensure that the nett flux of water and salt is deeper than the root zone. Additionally, the water table should be deep enough to provide adequate root development and aeration, but at the same time reduce the amount of required supplementary irrigation.

The best means of managing and controlling soil and water salinity is through efficient irrigation scheduling combined with adequate but minimum leaching and drainage which is maintained over time.

CHAPTER 3

EFFECT OF IRRIGATION WATER SALINITY ON CROP YIELD AND WATER UPTAKE ON TWO APEDAL SOILS WITH SHALLOW WATER TABLES

3.1 Introduction

Shallow water tables can contribute significantly towards evapotranspiration by plants through the capillary supply of water into the active root zone, thus reducing the required amount of irrigation (Wallender *et al.,* 1979; Ehlers *et al.*, 2003; Ghamarnia *et al.,* 2004). Unfortunately, if the water table is saline, salts will move with the water into the root zone with rapid salinization of it, due to restricted leaching (Hillel, 1998). As a result crop growth and water uptake can be hampered despite adequate water availability. Soil and water table salinity are therefore important factors affecting the capillary contributions from water tables towards evapotranspiration.

The aim of this chapter is to quantify the effect of an increase in irrigation water salinity on the growth, yield and water uptake characteristics of four crops on two apedal soils in the presence of a water table at a constant 1.2 m depth.

3.2 Materials and methods

3.2.1 Experimental site

All the experiments were conducted at the Field Research Facility of the Department of Soil, Crop and Climate Sciences, University of the Free State at Kenilworth near Bloemfontein (29°01'00"S, 26°08'50"E). This research was conducted on the lysimeter unit constructed in 1999 by Ehlers *et al*. (2003) for investigating the contribution of root accessible water tables towards the irrigation requirements of crops. A detailed description of the experimental site and the procedures can be found in the above-mentioned report. However, the layout of the lysimeters and an illustration of a vertical section through a lysimeter with a constant water table height control mechanism are shown in Plate 3.1.

The area of the experimental site is 70 m by 35 m. In the center of this site 30 round plastic lysimeters (1.8 m diameter and 1.8 m deep), were buried in the soil in two parallel rows of 15 each, with their rims 50 mm above the bordering soil surface. A 100 mm layer of gravel (10 mm in diameter) was placed on the bottom of each lysimeter and covered with a plastic mesh. The one row of lysimeters was filled with a homogenous yellow sandy soil (Soil A) and the other with a red sandy loam soil (Soil B) to the same level as the soil in the surrounding field. An underground access chamber (1.8 m wide, 2 m deep and 30 m long), allowed access to the inner walls of the lysimeters. On the access chamber side, an opening at 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 treatments. Each lysimeter was also equipped with two neutron probe access tubes.

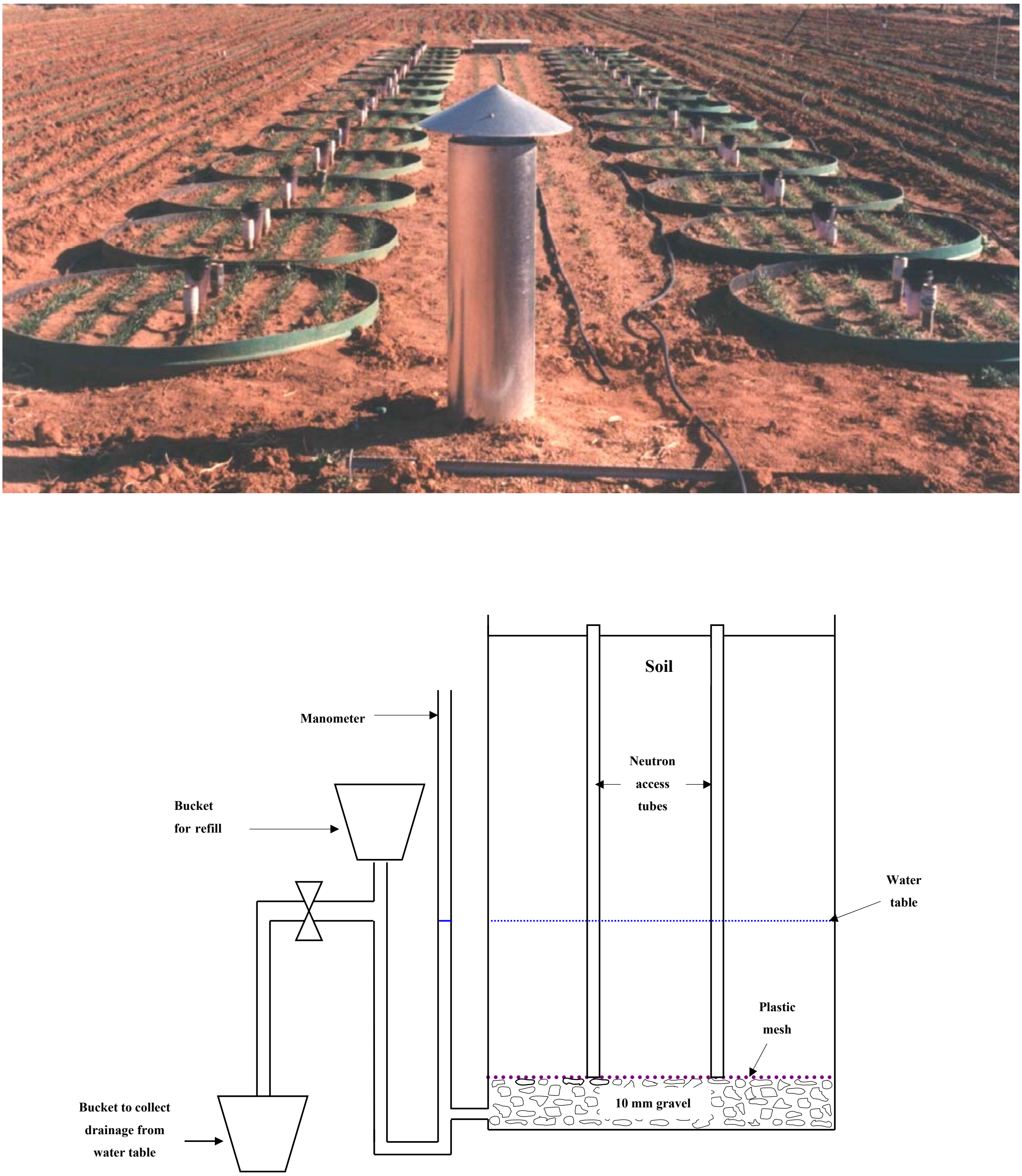


Plate 3.1 Layout of the lysimeters and an illustration of a vertical section through a container with a manually controlled constant water table height control mechanism.

For this experiment, five 2 500 litre reservoirs, one for each treatment, used for the purpose of mixing of the different salinity classes of irrigation water, were mounted aboveground on a 1 m high stand at the eastern end of the two parallel rows of lysimeters. Each of the reservoirs was connected to the individual lysimeters, randomly allocated to those specific treatments, with a 20 mm polyethylene pipe, which was used for irrigation. A tap from each reservoir was installed below-ground for recharging of the water tables. A movable shelter (30 m long, 10 m wide and 4 m high) was constructed to cover the lysimeter unit when rainfall events occurred to prevent any dilution of the soil solutions in the lysimeters by rainwater.

3.2.2 Soil characteristics

The soils that were used in this study were a yellow sandy Clovelly Setlagole soil from the Sand-Vet region (Soil A) and a red sandy loam Bainsvlei Amalia soil from the Bloemfontein region (Soil B) according to the Soil Classification Working Group (1991). Particle size analyses, using standard procedures (The Non-affiliated Soil Analysis Work Committee, 1990), were carried out on both soils. The particle size distribution for the different layers of the two soils that were packed into the lysimeters is presented in Table 3.1.

3.2.3 Treatments

Five irrigation water salinity treatments, replicated three times, were randomly allocated to the lysimeters for each soil type. Before planting of the first crop, wheat, the lysimeters of each treatment were leached with the appropriate irrigation water salinity until the electrical conductivity (EC) of the leachate outflow from the bottom of the lysimeter had the same value as the irrigation water. In each of the replicated lysimeters of each treatment, a water table was established at a depth of 1.2 m from the surface using the appropriate water salinity. The water tables were kept at a constant height by adding water of the same quality used for irrigation, to the bottom of the lysimeters daily. The planned treatments that were chosen for the different crops 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 prepare the irrigation water for the different treatments. The correct amounts of these salts needed to give the required electrical conductivity (EC) and sodium adsorption ratio (SAR) values in the irrigation water were determined through experimentation in the laboratory. Theoretically, the total dissolved solids (TDS) values were obtained by using the relationship TDS (mg L^{-1}) = EC (mS m^{-1}) x 6.5 as reported by the Department of Water Affairs and Forestry (1996).

Table 3.1 Particle size distribution of Soil A and Soil B for the different depths at which they were packed in the lysimeters

Soil	**Soil type**		**Depth (mm)**	**Coarse Sand (%)**	**Medium sand (%)**	**Fine sand (%)**	**Silt (%)**	**Clay (%)**
	Form	**Family**						
Soil A	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
Soil B	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

Table 3.2 Planned electrical conductivity (EC_i, mS m^{-1}) and sodium adsorption ratio (SAR) of the irrigation water to be used for the different treatments and crops

Wheat		**Beans**		**Peas**		**Maize**	
EC_i	**SAR**	**EC_i**	**SAR**	**EC_i**	**SAR**	**EC_i**	**SAR**
15*	0.26	15*	0.26	15*	0.26	15*	0.26
150	3	150	3	75	3	150	3
300	3	300	3	150	3	300	3
450	3	450	3	225	3	450	3
600	5	600	5	300	3	600	5

*Control

It was pointed out earlier in this study, that the factor of 6.5 might differ in terms of ionic composition and concentration, but provides a good basis for further laboratory experimentation. Salt solutions were made up in the laboratory, making sure that the SAR and cation and anion ratios remain within a certain range. These ranges were decided upon by studying the present and future trends of ionic composition of the waters of the lower Vaal, Riet and Harts Rivers, which were identified as the worst case scenarios in a previous research project by Du Preez *et al*. (2000). After various laboratory attempts, a reliable linear EC vs TDS relationship was found, namely: TDS (mg L^{-1}) = EC (mS m^{-1}) x

9.528 with a $R^2 = 0.99$. This equation was verified later in the lysimeters study (Section 4.3.3) where the value of the constant was determined as 7.568 for the soil water and 7.831 for the irrigation water. This discrepancy can probably be ascribed to the fact that the laboratory mixtures consisted of made up solutions without soil and the lysimeters values were determined by analysing the soil water extracted with the suction cups.

Table 3.3 gives the amount of the different salts that were used to prepare the irrigation water salinity treatments and final SAR-values for the different crops. Calcium (Ca^{++}) and magnesium (Mg^{++}) was used in a ratio, on a mass basis, ranging between 1.2 and 1.6, whereas the sulphate ($SO_4^{=}$) and chloride (Cl^-) ratio ranged from 1.3 to 1.4. These ratios are based on the long-term average values of the lower Vaal and Riet Rivers (Du Preez *et al*., 2000).

3.2.4 Agronomic practices

All the agronomic practices were managed with the objective of creating optimal conditions for crop growth, allowing for maximum root water uptake and yield. Some of these practices for the different crops are given in Table 3.4. The area surrounding the lysimeters was treated in a manner identical to the lysimeters. The cultivars that were selected are widely used throughout the central parts of South Africa. Crops were planted on the recommended planting dates.

3.2.5 Grain and biomass yields

The experiment was conducted four times with the following cropping order: wheat (*Triticum aestivum* L.), beans (*Phaseolus vulgaris* L.), peas (*Pisum sativum* L.) and maize (*Zea mays* L.). The above-ground biomass for the different crops of each lysimeter was harvested when the crops were dry, by cutting just above the soil surface. After drying at 70°C for three days in a ventilated oven, it was weighed and threshed to determine seed mass. It was decided to express the seed, dry matter and total biomass yield in kg $lysimeter^{-1}$. The plants grew over the edges of the lysimeters and it is virtually impossible to determine the actual area of the plant canopy in each of the lysimeters and it would therefore be incorrect to convert it to mass per hectare based on the area of the lysimeter.

Table 3.3 The amounts of different salts that were used to prepare the irrigation water quality treatments for the different crops

Parameter	**Wheat**				**Beans**				**Peas**				**Maize**			
EC (mS m^{-1})	150	300	450	600	150	300	450	600	75	150	225	300	150	300	450	600
SAR	3.0	5.0	5.0	5.0	3.0	5.0	5.0	5.0	1.8	3.0	3.0	5.0	3.0	5.0	5.0	5.0
TDS (mg L^{-1})	988	2003	3554	5107	988	2003	3554	5107	494	988	1229	2003	988	2003	3554	5107
NaCl (mg L^{-1})	360	790	1140	1415	360	790	1140	1415	120	360	400	790	360	790	1140	1415
$CaCl_2$ (mg L^{-1})	100	235	500	825	100	235	500	825	0	100	153	235	100	235	500	825
$MgSO_4$ (mg L^{-1})	297	620	1190	1740	297	620	1190	1740	108	297	375	620	297	620	1190	1740
Na_2SO_4 (mg L^{-1})	0	50	20	45	0	50	20	45	0	0	20	50	0	50	20	45
KCl (mg L^{-1})	105	187	533	750	105	187	533	750	175	105	120	187	105	187	533	750
$MgCl_2$ (mg L^{-1})	45	40	90	250	45	40	90	250	10	45	80	40	45	40	90	250
Ca:Mg *	1:1.31	1:1.31	1:1.32	1:1.31	1:1.31	1:1.31	1:1.32	1:1.31	1:1.32	1:1.31	1:1.3	1:1.31	1:1.31	1:1.31	1:1.32	1:1.31
SO_4:Cl *	1:1.33	1:1.32	1:1.33	1:1.32	1:1.33	1:1.32	1:1.33	1:1.32	1:1.33	1:1.33	1:1.31	1:1.32	1:1.33	1:1.32	1:1.33	1:1.32

* Mass basis

Table 3.4 Some of the agronomic practices used for wheat, beans, peas and maize

Practice	**Wheat**			**Beans**			**Peas**			**Maize**		
Planting date	3 July 2003			9 January 2004			21 July 2004			17 December 2004		
Harvesting date	25 November 2003			20 April 2004			17 November 2004			17 May 2005		
Cultivar	SST 806			TEEBUS			SOLARA			PAN 6335		
Sowing density	120 kg ha^{-1}			200 000 seeds ha^{-1}			100 kg ha^{-1}			50 000 plants ha^{-1}		
Fertilizer	**N**	**P**	**K**	**N**	**P**	**K**	**N**	**P**	**K**	**N**	**P**	**K**
Pre planting (kg ha^{-1})	82	41	20	89	30	40	27	40	53	217	49	50
Post planting (kg ha^{-1})	103	-	-	-	-	-	20	-	-	50	-	-
Pest control	**-**			-			-			DECUS (300 ml ha^{-1})		

3.2.6 Soil water balance

For the calculation of evapotranspiration the following components of the soil water balance (Equation 3.1) were measured weekly, throughout the growing season for each of the lysimeters.

$$ET = I \pm \Delta W + Q - D \tag{3.1}$$

where ET = Evapotranspiration (mm).

I = Irrigation (mm).

ΔW = Change in soil water content (mm) measured with a neutron probe at 200 mm intervals, using a (+) for a decrease and a (-) for an increase.

Q = Uptake from the water table (mm) measured as the cumulative volume of water needed to recharge the water table to a constant height divided by the area of the lysimeter.

D = Drainage to the water table (mm) measured as the volume of water from the overflow system in the manometer divided by the area of the lysimeter.

Due to special measures taken the rainfall and runoff components of the soil water balance were taken as zero.

3.2.7 Irrigation scheduling

Irrigation water was applied weekly. The amount of irrigation water applied to each lysimeter of the different treatments, was based on the principle of refilling the 0-600 mm soil layer with the difference between the drained upper limit (DUL) and the soil water content (mm) measured with a neutron probe. The DUL for the 0-600 mm layer is 80 mm for soil A and 100 mm for soil B. The root water uptake from the 600-1200 mm layer was recharged by capillary rise from the water table. For both soils the height of rapid capillary rise exceeds 600 mm (Ehlers *et al*., 2003). The amount of water irrigated, given as mm and litre, as well as the time of application, expressed as days after planting (DAP), for all the crops and treatments are presented in Appendix 3.1. A summary of the total amount of irrigation water applied to all the soils, crops and treatments is given in Table 3.5.

Table 3.5 The total amount of irrigation water applied to the different soils, crops and EC_i treatments

Soil	Wheat			Beans		
	EC_i (mS m^{-1})	**mm**	**litre**	**EC_i (mS m^{-1})**	**mm**	**litre**
A	15*	266	676	15*	401	1020
	150	283	720	150	330	840
	300	345	879	300	271	690
	450	331	842	450	173	441
	600	395	1005	600	173	441
B	15*	246	625	15*	397	1012
	150	306	780	150	314	800
	300	305	775	300	267	681
	450	285	726	450	173	441
	600	273	695	600	181	461
Soil	**Peas**			**Maize**		
	EC_i (mS m^{-1})	**mm**	**litre**	**EC_i (mS m^{-1})**	**mm**	**litre**
A	15*	451	1146	15*	390	993
	75	485	1233	150	352	896
	150	433	1103	300	270	687
	225	405	1031	450	258	657
	300	430	1095	600	233	594
B	15*	461	1174	15*	348	886
	75	444	1131	150	337	857
	150	382	973	300	254	647
	225	377	960	450	246	627
	300	365	928	600	259	660

*Control

3.2.8 Electrical conductivity of the soil water

The procedure for obtaining soil water samples by using suction cups, installed at different depths, is described in detail in Section 4.2. The electrical conductivity (EC_{sw}, mS m^{-1}) of these samples were measured and assumed to be an indication of EC_e.

3.3 Results and discussion

3.3.1 Crop yields

3.3.1.1 Actual crop yields as affected by irrigation water salinity

The seed and total biomass yield data for the individual lysimeters for the different soils and crops are presented in Appendix 3.2. A summary of the mean seed and total biomass yield of the replications for each of the treatments, soils and crops is given in Table 3.6.

Wheat

From Table 3.6 it is evident that the mean wheat seed yield of 1.366 kg lysimeter^{-1} on Soil A was significantly lower compared to the 1.551 kg lysimeter^{-1} on Soil B. This can be ascribed to the higher buffer capacity of the more clayey Soil B causing the salinity effect to be less dominant. Despite the significant difference in seed yield between the two soil types there were no significant differences between the treatments on both soils, except for the biomass yield of the 600 mS m^{-1} treatment on Soil A which was statistically lower than the control. It is clear that a wider range of EC_i treatments would have given a yield decline. The same observations were made in a glasshouse experiment conducted by Dikgwatlhe (2006) where the maximum EC_i treatment was 1200 mS m^{-1}.

Beans

There was a significant decrease in seed yield with an increase in irrigation water salinity (Table 3.6). The seed and total biomass yield of the control treatment was statistically the highest on both soils with no significant differences between the two soil types. The very low yields obtained with the 450 mS m^{-1} and 600 mS m^{-1} treatments were caused by the premature death of the plants due to the rapid accumulation of salt in the soil profile, following the wheat crop.

It is very unfortunate that, in the original planning of the experiment, no provision was made for removal of the salts that accumulated during the wheat experiment. As a result the mean electrical conductivity of the soil water (EC_{sw}, mS m^{-1}) in the lysimeters of the different treatments was much higher than that of the irrigation water (EC_i, mS m^{-1}), as indicated in Table 3.7.

Table 3.6 Mean seed yield (kg lysimeter^{-1}), total biomass yield (BM, kg lysimeter^{-1}) and harvest index (HI) for all the crops and EC_i treatments on both soils

	Wheat				**Beans**				**Peas**				**Maize**			
Soil	**EC_i (mS m^{-1})**	**Seed**	**BM**	**HI**	**EC_i (mS m^{-1})**	**Seed**	**BM**	**HI**	**EC_i (mS m^{-1})**	**Seed**	**BM**	**HI**	**EC_i (mS m^{-1})**	**Seed**	**BM**	**HI**
A	15*	1.445	3.945 a	0.37	15*	1.379 a	3.005 a	0.46	15*	1.207 a	2.838 a	0.43	15*	3.729 a	7.873 a	0.47
	150	1.383	3.660 ab	0.38	150	0.810 b	1.915 b	0.42	75	1.171 a	2.644 ab	0.44	150	3.396 a	7.610 a	0.45
	300	1.377	3.708 ab	0.37	300	0.304 c	0.810 c	0.38	150	1.091 ab	2.393 bc	0.46	300	2.694 b	6.571 a	0.41
	450	1.373	3.375 ab	0.41	450	0.006 d	0.017 d	0.35	225	1.008 b	2.209 c	0.46	450	1.922 c	4.700 b	0.41
	600	1.252	3.212 b	0.39	600	0.000 e	0.000 d	0.00	300	0.656 c	1.620 d	0.40	600	1.085 d	3.454 b	0.31
	LSD 0.05	***ns***	***0.574***	**-**		***0.197***	***0.309***	**-**		***0.214***	***0.400***	**-**		***0.659***	***1.275***	**-**
B	15*	1.535	3.980	0.39	15*	1.393 a	2.977 a	0.48	15*	1.165 a	2.574 a	0.45	15*	3.211 a	6.720 a	0.48
	150	1.573	4.027	0.39	150	0.499 b	1.491 b	0.33	75	1.179 a	2.597 a	0.45	150	3.140 a	7.461 a	0.42
	300	1.589	3.972	0.40	300	0.255 c	0.889 c	0.29	150	1.012 a	2.326 a	0.44	300	2.585 ab	6.114 ab	0.42
	450	1.475	3.729	0.40	450	0.082 d	0.289 d	0.28	225	0.953 ab	2.131 a	0.45	450	1.933 bc	4.879 bc	0.40
	600	1.583	3.718	0.43	600	0.021 e	0.097 d	0.22	300	0.680 b	1.513 b	0.45	600	1.156 c	3.755 c	0.31
	LSD 0.05	***ns***	***ns***	-		***0.1***	***0.213***	**-**		***0.285***	***0.492***	**-**		***0.879***	***1.432***	**-**

*Control

Table 3.7 Mean electrical conductivity of the soil water (EC_{sw}, mS m^{-1}) of the EC_i treatments at the start of the bean growing season

Soil	**Ec_i mS m^{-1}**	**EC_{sw} (mS m^{-1})**
A	15*	143
	150	485
	300	806
	450	1158
	600	1346
B	15*	111
	150	455
	300	714
	450	1245
	600	1460

*Control

The mean EC_{sw} values for the beginning of the bean experiment given in Table 3.7 were calculated using the suction cup values presented in Appendix 4.1. The mean over depth was calculated for each lysimeter where after the arithmetic mean for the three replications in each treatment was calculated. It is evident from the calculated EC_{sw} values that the beans were grown at much higher salinity levels than was envisaged. This explains the rapid decline in plant growth and yield observed up to EC_{sw} values of 600 to 700 mS m^{-1} and premature death of the crop at EC_{sw} values higher than 1100 mS m^{-1}.

Peas

Pro-active leaching of the soil profiles to the respective treatment values resulted in good germination and plant establishment on both soils. As shown in Table 3.6 there was no significant difference between the mean seed yield of 1.027 kg $lysimeter^{-1}$ on Soil A and 0.938 kg $lysimeter^{-1}$ on Soil B. On both soils there was only a slight decrease in the seed and total biomass yield with an increase in irrigation water salinity, except for the 300 mS m^{-1} treatment that was significantly lower than all the other treatments.

Maize

Once again, pro-active leaching of the soil profiles resulted in good germination and plant establishment. There was no significant difference between the mean seed yield of 2.564 kg $lysimeter^{-1}$ on Soil A and 2.405 kg $lysimeter^{-1}$ on Soil B (Table 3.6). However, there was a significant decrease in seed and total biomass yield with an increase in irrigation water salinity, especially with the 450 mS m^{-1} and 600 mS m^{-1} treatments.

3.3.1.2 Relative crop yields as affected by irrigation water salinity

In the previous section it was evident that there was a decreasing trend in seed and total biomass yield with an increase in irrigation water salinity. In order to compare the effect of irrigation water salinity on the growth of the different crops, the relationship between the relative biomass yield (BM_{rel}) and irrigation water salinity (EC_i) was plotted for each of the crops on both soils. The relationships between BM_{rel} and EC_i are illustrated in Figures 3.1 to 3.4 for wheat, beans, peas and maize respectively.

The fitting of the polynomial functions was found to be very good for all the crops on both soils, except for wheat, where the slope is almost zero. Furthermore it is evident that with the irrigation water treatments that were used for wheat, there was only a slight decrease in seed yield compared to the control. However, during glasshouse experiments conducted by Dikgwatlhe (2006), irrigation water salinity treatments of up to 1200 mS m^{-1} were used which resulted in a 96% reduction of total biomass yield. In the case of beans a strong (R^2 = 0.97) relationship was found but it has already been mentioned that the plants were prematurely killed as a result of rapid salt accumulation in the lysimeters to EC_{sw} values in excess of 1000 mS m^{-1} following the wheat trial.

3.3.2 Evapotranspiration and water use efficiency

The mean cumulative evapotranspiration (ET, mm) and water use efficiency (WUE, g seed kg water used^{-1}) results for all the soils, crops and treatments are summarized in Table 3.8. An example of a water balance sheet for the control treatment of maize on Soil A until 26 days after planting is presented in Appendix 3.3. The data sheets are available on request from the Department of Soil, Crop and Climate Sciences at the University of the Free State, Bloemfontein. The mean daily evapotranspiration of the crops over the growing season for all treatments is displayed in Figures 3.5 to 3.12.

Wheat

As expected, there was a significant decrease in cumulative ET with an increase in irrigation water salinity on both soils. There was no significant difference between the average cumulative ET of 584 mm on Soil A compared to the 606 mm on Soil B. The mean daily evapotranspiration over the growing season for all the treatments of wheat is illustrated in Figure 3.5 for Soil A and Figure 3.6 for Soil B. From the two figures it is evident that the period of maximum uptake rate corresponds with 103 to 131 days after planting on both soils, with a maximum daily uptake of 9.3 mm day^{-1} for the control treatment of Soil A and 9.2 mm day^{-1} for both the control and 150 mS m^{-1} treatments of Soil B. There was a decline in the daily ET on both soils with an increase in irrigation water salinity.

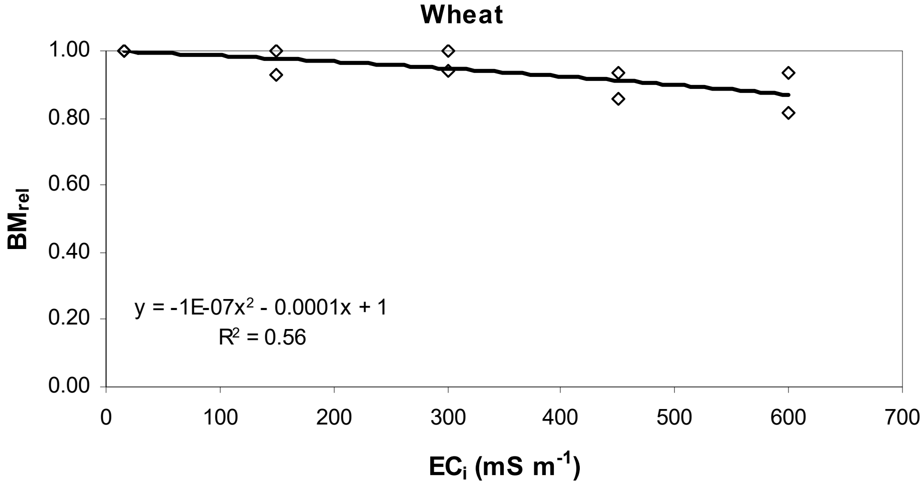


Figure 3.1 The relationship between the relative biomass yield (BM_{rel}) and irrigation water salinity (EC_i, mS m^{-1}) of wheat on both soils.

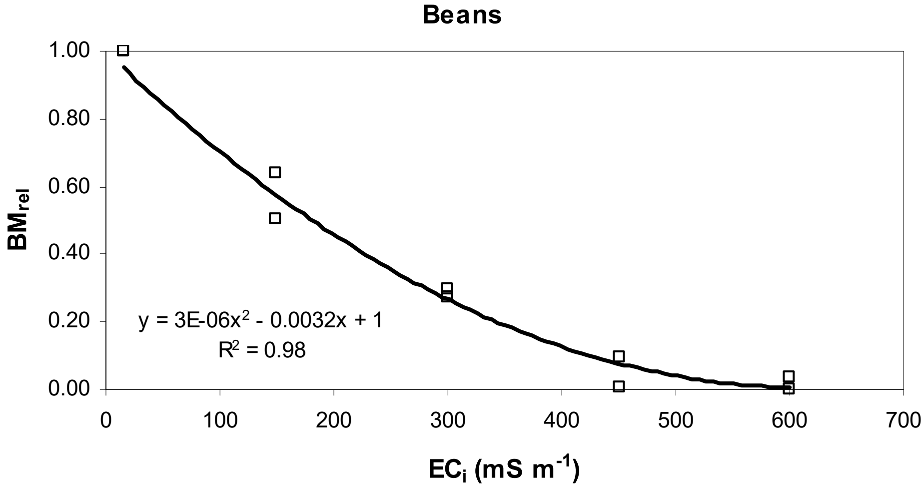


Figure 3.2 The relationship between the relative biomass yield (BM_{rel}) and irrigation water salinity (EC_i, mS m^{-1}) of beans on both soils.

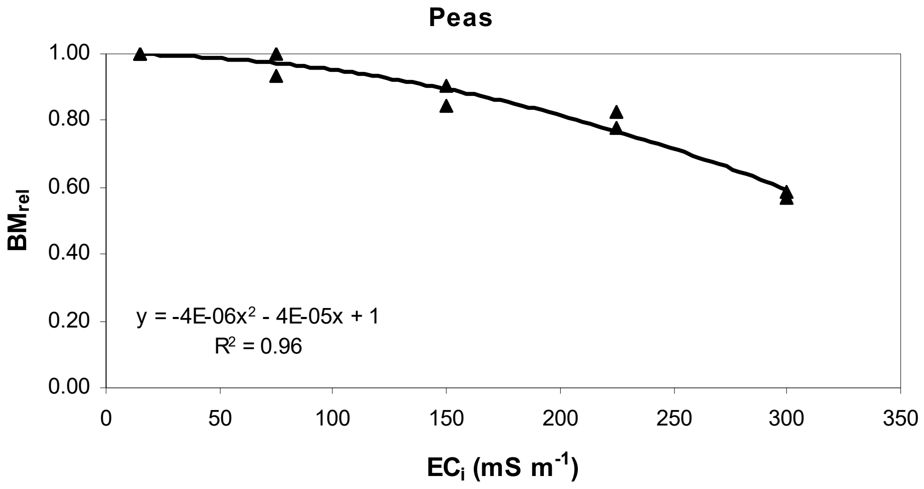


Figure 3.3 The relationship between the relative biomass yield (BM_{rel}) and irrigation water salinity (EC_i, mS m^{-1}) of peas on both soils.

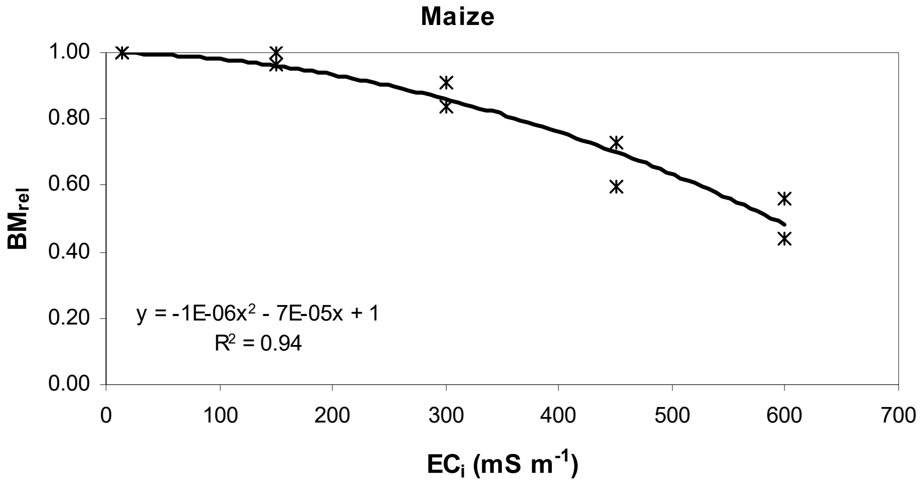


Figure 3.4 The relationship between the relative biomass yield (BM_{rel}) and irrigation water salinity (EC_i, mS m^{-1}) of maize on both soils.

Table 3.8 Mean evapotranspiration (ET, mm) and water use efficiency (WUE, g kg^{-1}) for all the crops and EC_i treatments on both soils

	Wheat				Beans				Peas				Maize			
	EC_i	ET	WUE (g kg^{-1})		EC_i	ET	WUE (g kg^{-1})		EC_i	ET	WUE (g kg^{-1})		EC_i	ET	WUE (g kg^{-1})	
Soil	**(mS m^{-1})**	**(mm)**	**Seed**	**Total BM**	**(mS m^{-1})**	**(mm)**	**Seed**	**Total BM**	**(mS m^{-1})**	**(mm)**	**Seed**	**Total BM**	**(mS m^{-1})**	**(mm)**	**Seed**	**Total BM**
A	15*	637 a	0.892	2.435	15*	533 a	1.017 a	2.215 a	15*	699 a	0.679 ab	1.596	15*	800 a	1.833 a	3.869 ab
	150	599 b	0.906	2.400	150	370 b	0.860 a	2.034 a	75	697 a	0.660 ab	1.490	150	727 a	1.834 a	4.111 ab
	300	582 c	0.929	2.502	300	295 c	0.405 b	1.079 b	150	577 b	0.743 ab	1.631	300	591 b	1.789 a	4.365 a
	450	565 d	0.954	2.346	450	177 d	0.012 c	0.038 c	225	515 c	0.768 a	1.684	450	483 c	1.565 a	3.827 ab
	600	535 e	0.920	2.359	600	175 d	0.000 c	0.000 c	300	440 d	0.586 b	1.447	600	381 d	1.120 b	3.564 b
	LSD $_{0.05}$	***13.1***	***ns***	***ns***		***69.9***	***0.154***	***0.266***		***43.1***	***0.177***	***ns***		***68.8***	***0.315***	***0.623***
B	15*	645 a	0.934 a	2.424	15*	569 a	2.448 a	5.232 a	15*	711 a	0.644	1.423	15*	778 a	1.621 a	3.393
	150	651 a	0.949 a	2.430	150	375 b	1.331 b	3.976 b	75	687 a	0.674	1.486	150	761 a	1.622 a	3.855
	300	616 b	1.013 ab	2.532	300	312 c	0.816 c	2.850 c	150	586 b	0.679	1.560	300	639 ab	1.591 a	3.762
	450	574 c	1.010 ab	2.554	450	212 d	0.385 d	1.363 d	225	544 c	0.688	1.540	450	501 b	1.515 a	3.825
	600	544 d	1.143 b	2.685	600	199 d	0.106 e	0.485 e	300	427 d	0.625	1.391	600	461 b	0.984 b	3.197
	LSD $_{0.05}$	***17.0***	***0.131***	***ns***		***35.7***	***0.225***	***0.689***		***34.5***	***ns***	***ns***		***200***	***0.250***	***ns***

*Control

There were no significant differences in the water use efficiencies (WUE_{seed}) between treatments, except for the 600 mS m^{-1} treatment of Soil B that was significantly higher than the control and 150 mS m^{-1} treatments. This is an indication that the wheat crop can tolerate irrigation water salinity with EC_i values up to 600 mS m^{-1}, without a decline in WUE. Glasshouse experiments conducted by Dikgwatlhe (2006) showed a rapid decline in yield, water use and WUE beyond 600 mS m^{-1}.

Beans

There was a significant decrease in cumulative ET with an increase in irrigation water salinity on both soils. The control treatment used significantly more water than all the other treatments, whereas the 150 mS m^{-1} and 300 mS m^{-1} treatments used more water than the 450 mS m^{-1} and 600 mS m^{-1} on both soils. The mean daily ET over the growing season for all the treatments of beans is illustrated in Figure 3.7 for Soil A and in Figure 3.8 for Soil B. The figures indicate that the plants of the 450 mS m^{-1} and 600 mS m^{-1} treatments started dying from 40 days after planting, after which only evaporation from the soil surface occurred. Peak uptake rates occurred 52 days after planting and ranged from 4.7 to 8.2 mm day^{-1} on Soil A and 4.2 to 8.5 mm day^{-1} on Soil B.

The WUE decreased significantly with an increase in irrigation water salinity on both soils. The premature death of the plants, especially for the 450 mS m^{-1} and 600 mS m^{-1} treatments, is an indication that beans are unable to withstand EC_{sw} values higher than 1000 mS m^{-1}, for reasons explained in Section 3.3.1.1.

Peas

A significant decrease in cumulative ET with an increase in irrigation water salinity was found with peas on both soils. The control and 75 mS m^{-1} treatments used more water than all the other treatments with no significant difference in water use between the two soils. The mean daily ET during the growing season for all the treatments of Soils A and B is illustrated in Figures 3.9 and 3.10 respectively. The figures illustrate two interesting phases. In the vegetative phase towards day 70 after planting, the ET rates of all the treatments were relatively low with no differences between the treatments. However, during the next phase from 70 to 100 days after planting, the ET rates increased drastically, with significant differences, especially between the control and the 225 mS m^{-1} and 300 mS m^{-1} treatments.

From this it is evident that the plants of the higher EC_i treatments experienced water stress which accelerated its growth phases. These treatments reached maturity two weeks before the control. Peak uptake rates occurred 76 days after planting and ranged from 5.6 to 12.0 mm day^{-1} on Soil A and 5.6 to 11.0 mm day^{-1} on Soil B with no significant differences between the two soil types.

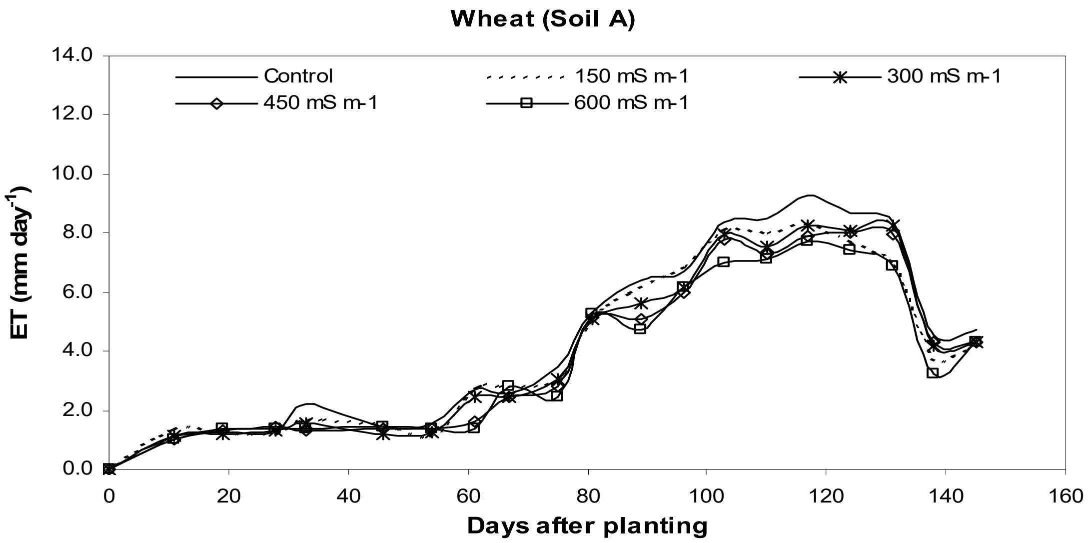


Figure 3.5 Mean wheat daily evapotranspiration (ET, mm day^{-1}) over the growing season for all the treatments of Soil A.

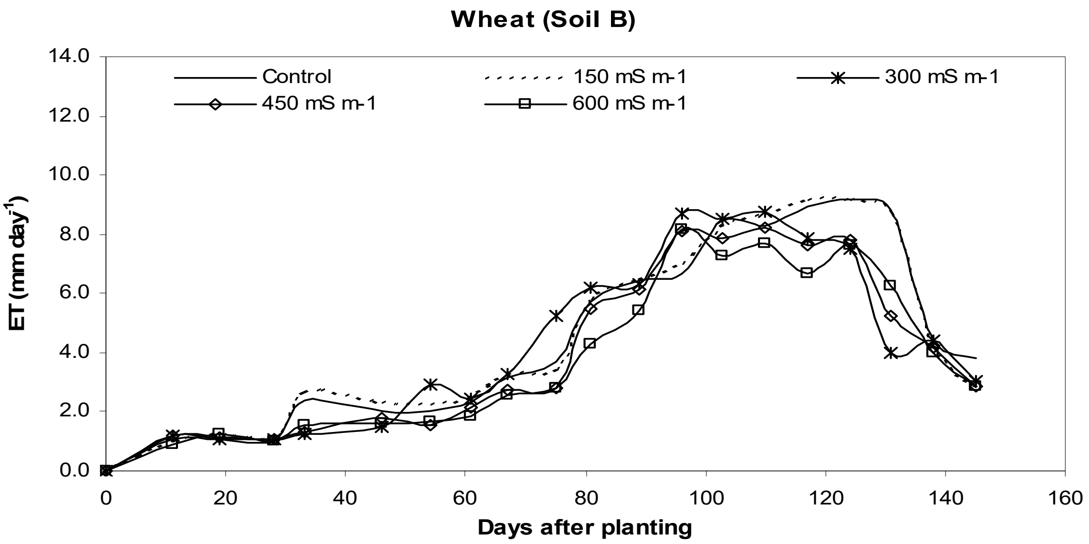


Figure 3.6 Mean wheat daily evapotranspiration (ET, mm day^{-1}) over the growing season for all the treatments of Soil B.

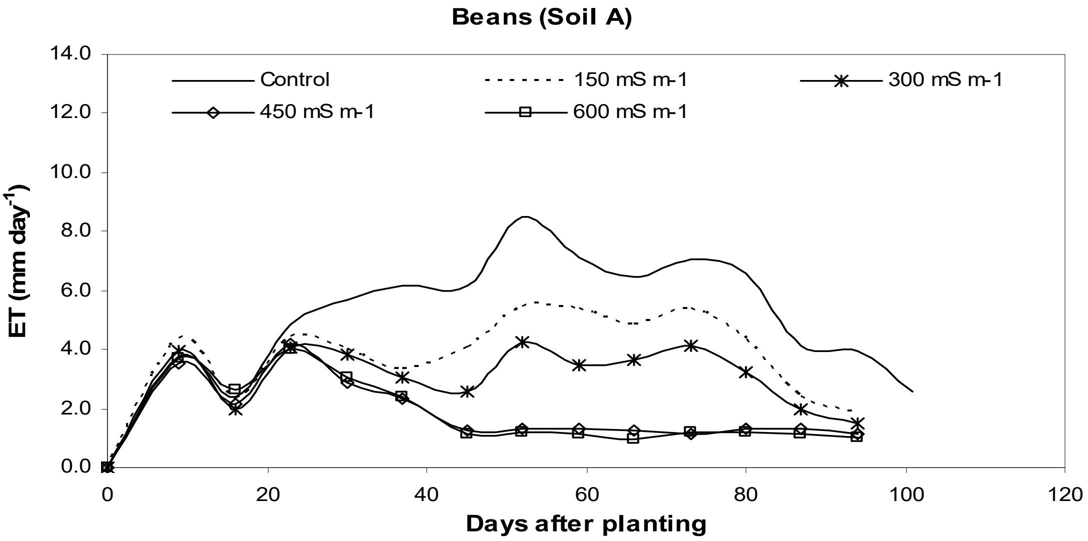


Figure 3.7 Mean bean daily evapotranspiration (ET, mm day^{-1}) over the growing season for all the treatments of Soil A.

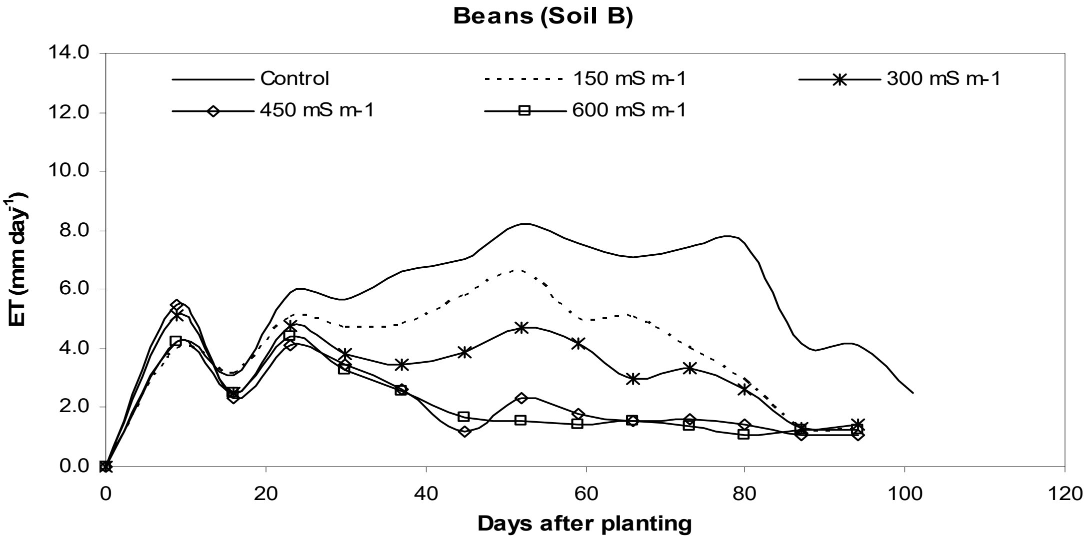


Figure 3.8 Mean bean daily evapotranspiration (ET, mm day^{-1}) over the growing season for all the treatments of Soil B.

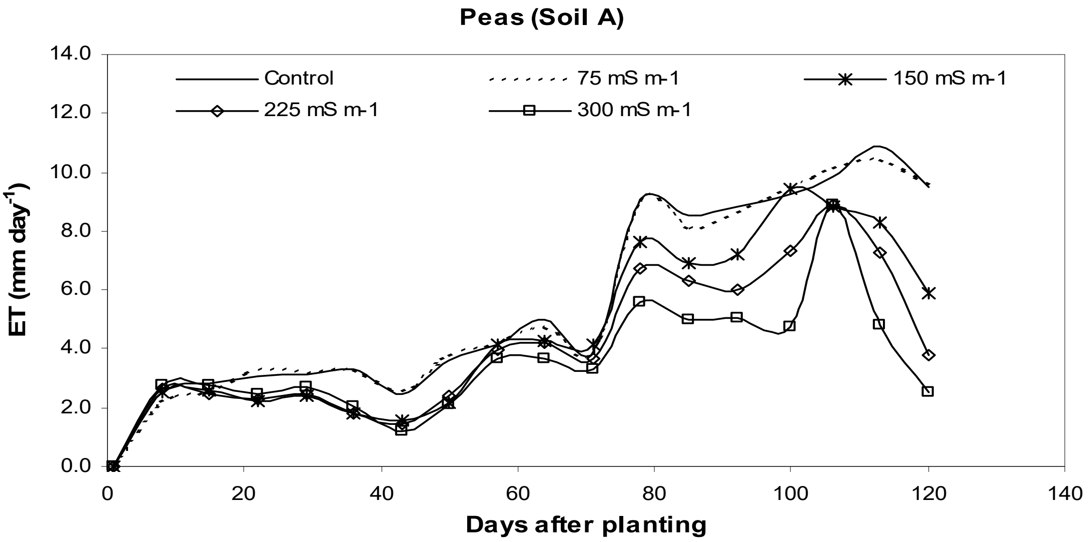


Figure 3.9 Mean pea daily evapotranspiration (ET, mm day^{-1}) over the growing season for all the treatments of Soil A.

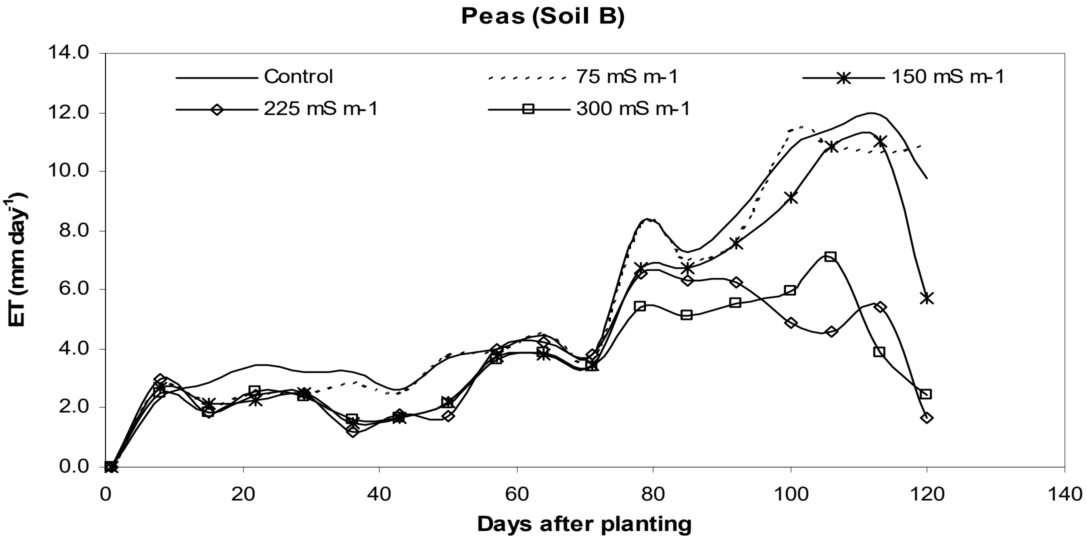


Figure 3.10 Mean pea daily evapotranspiration (ET, mm day^{-1}) over the growing season for all the treatments of Soil B.

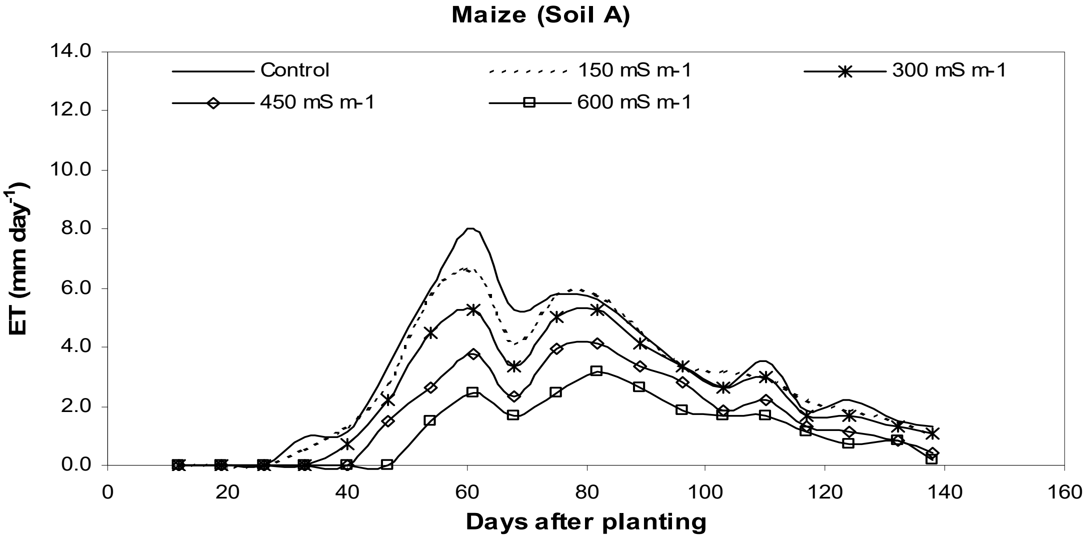


Figure 3.11 Mean maize daily evapotranspiration (ET, mm day^{-1}) over the growing season for all the treatments of Soil A.

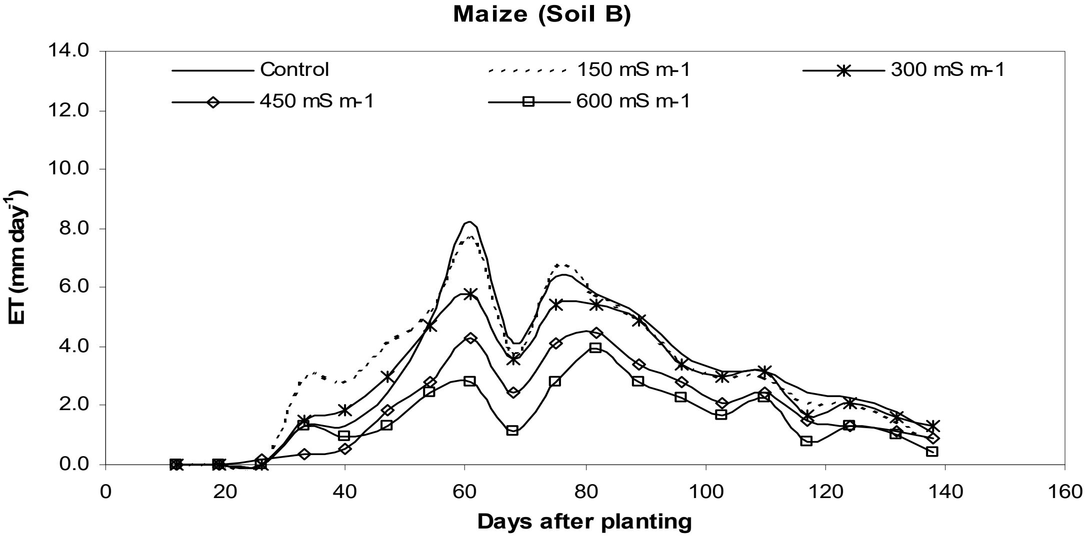


Figure 3.12 Mean maize daily evapotranspiration (ET, mm day^{-1}) over the growing season for all the treatments of Soil B.

As shown in Table 3.8 there were no significant differences in the WUE on both soils, except for the 300 mS m^{-1} treatment of Soil A, which was significantly lower. This is an indication that despite a decrease in ET and yield, the WUE of peas will only be reduced when irrigating with water with an EC of more than 300 mS m^{-1}.

Maize

The same trend that emerged for the previous crops, where the cumulative ET decreased with an increase in irrigation water salinity, was also evident for maize. Once again the control and 150 mS m^{-1} treatments used significantly more water than all the other treatments on both soils. Comparing the water uptake rates during the growing season, as illustrated in Figures 3.11 and 3.12 for Soils A and B respectively, it is evident that there were no significant difference between the two soil types. Peak uptake rates ranged from 3.2 to 8.0 mm day^{-1} on Soil A and from 3.9 to 8.2 mm day^{-1} on Soil B.

Table 3.8 indicates that the WUE$_{seed}$ of only the 600 mS m^{-1} treatment was significantly lower than all the other treatments on both soils. This is an indication that within the salinity range of 150 to 450 mS m^{-1}, despite a reduction in ET and yield the WUE values were the same, whereas for the 600 mS m^{-1} salinity class, the reduction in WUE$_{seed}$ was statistically significant. The same trend for the WUE$_{BM}$ was also found for the 600 mS m^{-1} treatment on the more sandy Soil A. In the case of the more clayey Soil B, the WUE$_{BM}$ for the 600 mS m^{-1} was also lower than all the other treatments, although it was not statistically different.

3.3.3 Water table uptake

The mean seasonal uptake from the water tables, expressed in cumulative uptake (mm) and as a percentage of the ET, for the different crops and treatments on both soils, is summarized in Table 3.9. The cumulative uptake from the water tables over the growing season is also illustrated in Figures 3.13 and 3.14 for wheat, Figures 3.15 and 3.16 for beans, Figures 3.17 and 3.18 for peas and Figures 3.19 and 3.20 for maize.

Wheat

As expected there was a significant decrease in cumulative uptake from the water tables with an increase in irrigation water salinity on both soils. The control treatment on both soils used significantly more water from the water tables than all the other treatments. Cumulative uptake from the water tables, expressed as a function of days after planting (as illustrated in Figure 3.13 for soil A and Figure 3.14 for Soil B), indicates the effect of irrigation water salinity on water table uptake. Significant differences in water table uptake started 80 days after planting on Soil A and around 110 days after planting on Soil B. Uptake from the water tables, expressed as a percentage of ET, ranged between 35 and 46% on Soil A and was significantly lower than the 49 to 54% on the more clayey Soil B.

Water table uptake on Soil A commenced 61 days after planting, whereas water table uptake on Soil B started at 33 days after planting. The reason for this difference is the higher capillary fringe on the more clayey Soil B (Ehlers *et al*., 2003).

Beans

From Table 3.9 it is evident that significantly more water was taken up from the water tables by the control treatments on both soils. A very drastic decrease occurred in the uptake of water from the water tables, due to the sharp increase in salinity, resulting from the accumulation of salts during the preceding wheat experiment. The decrease will be more gradual when the EC_i values are replaced with the calculated EC_{sw} values from Table 3.7. Inspection of Figures 3.15 and 3.16 shows that in the case of the 450 and 600 mS m^{-1} treatments where the plants died, very little water was supplied from the water table of both soils for evaporation.

Peas

Uptake from the water tables decreased significantly with an increase in irrigation water salinity. However, there were no significant differences between the control, 75 mS m^{-1} and 150 mS m^{-1} treatments, which were significantly higher than the 225 mS m^{-1} and 300 mS m^{-1} treatments on both soils. Water table depletion data expressed as a percentage of the ET indicates that there was only a slight difference between the two soils, ranging from 18 to 32% on Soil A and from 21 to 38% on Soil B. As indicated in Figures 3.17 and 3.18, water table uptake commenced on day 57 after planting, on both soils. It is also evident that the difference in cumulative water table uptake between the different treatments on Soil A is greater than for the same treatments on Soil B. Once again this can be ascribed to the higher clay content of Soil B which exhibits a better buffering capacity against salinity than Soil A.

Maize

The results in Table 3.9 reveal that the cumulative water uptake from the water tables of the control and 150 mS m^{-1} treatments were significantly higher than all the other treatments on both soils. However, in the case of Soil B there was no significant difference in water table uptake between the 300, 450 and 600 mS m^{-1} treatments. Comparing the uptake from the water tables, expressed as a percentage of the ET, it is evident that there is no difference between the two soil types and values ranged from 41 to 57%.

Table 3.9 Average cumulative evapotranspiration (ET) and uptake from the water tables (WT) for the different crops and EC_i treatments on both soils

	Wheat				Beans				Peas				Maize			
	EC_i	**ET**	**Uptake from WT**		**EC_i**	**ET**	**Uptake from WT**		**EC_i**	**ET**	**Uptake from WT**		**EC_i**	**ET**	**Uptake from WT**	
Soil	**(mS m^{-1})**	**(mm)**	**Cum (mm)**	**% of ET**	**(mS m^{-1})**	**(mm)**	**Cum (mm)**	**% of ET**	**(mS m^{-1})**	**(mm)**	**Cum (mm)**	**% of ET**	**(mS m^{-1})**	**(mm)**	**Cum (mm)**	**% of ET**
A	15*	637 a	293 a	46	15*	533 a	124 a	23	15*	699 a	221 a	32	15*	800 a	399 a	50
	150	599 b	271 b	45	150	370 b	38 b	10	75	697 a	202 a	29	150	727 a	375 a	51
	300	582 c	255 c	44	300	295 c	18 b	6	150	577 b	182 ab	32	300	591 b	317 b	54
	450	565 d	218 d	39	450	177 d	8 b	4	225	515 c	150 b	29	450	483 c	227 c	47
	600	535 e	186 e	35	600	175 d	0 b	0	300	440 d	77 c	18	600	381 d	155 d	41
	LSD $_{0.05}$	***13.05***	***12.4***	**-**		***69.9***	***55.2***	**-**		***43.1***	***46.1***	**-**		***68.8***	***50.5***	**-**
B	15*	645 a	349 a	54	15*	569 a	160 a	28	15*	711 a	220 ab	31	15*	778 a	401 a	51
	150	651 a	314 b	48	150	375 b	65 b	17	75	687 a	243 a	35	150	761 a	417 a	55
	300	616 b	303 bc	49	300	312 c	33 bc	10	150	586 b	223 ab	38	300	639 ab	367 ab	57
	450	574 c	287 cd	50	450	212 d	16 c	7	225	544 c	192 b	35	450	501 b	258 ab	51
	600	544 d	267 d	49	600	199 d	5 c	3	300	427 d	92 c	21	600	461 b	204 b	44
	LSD $_{0.05}$	***17.0***	***22.9***	**-**		***35.7***	***43.0***	**-**		***34.5***	***36.3***	**-**		***200***	***163***	**-**

*Control

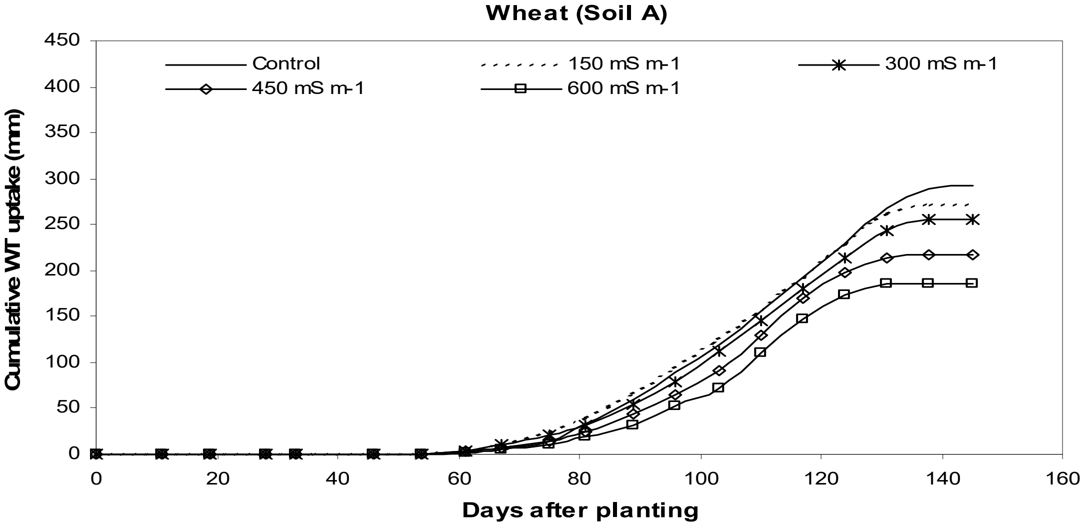


Figure 3.13 Cumulative water table uptake as a function of days after planting for all the treatments of the wheat crop on Soil A.

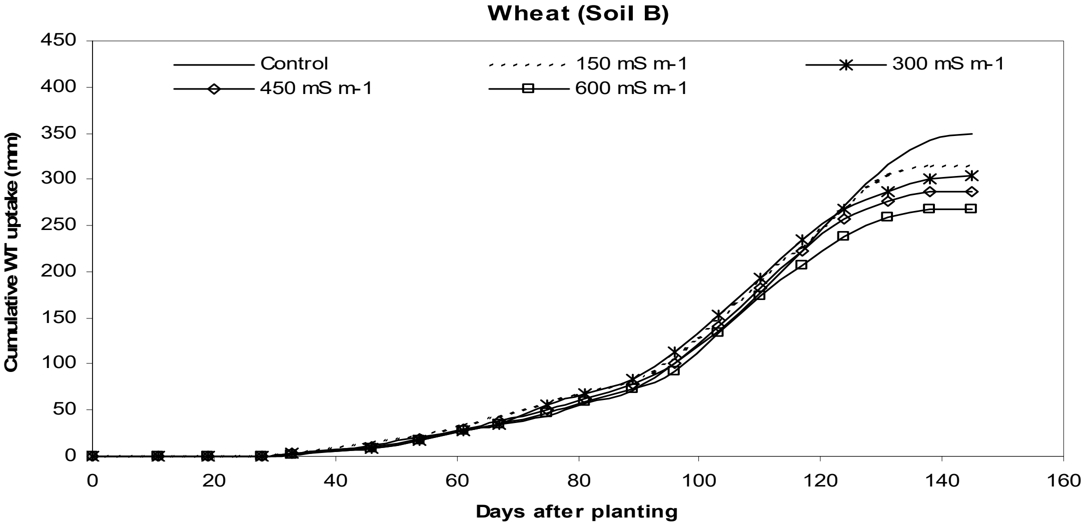


Figure 3.14 Cumulative water table uptake as a function of days after planting for all the treatments of the wheat crop on Soil B.

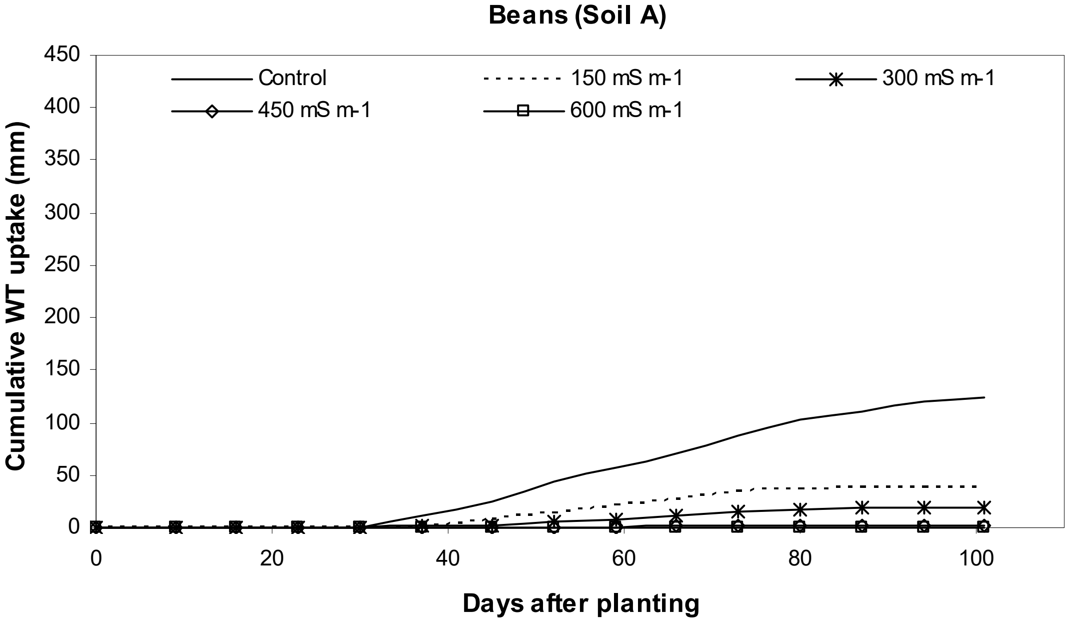


Figure 3.15 Cumulative water table uptake as a function of days after planting for all the treatments of beans on Soil A.

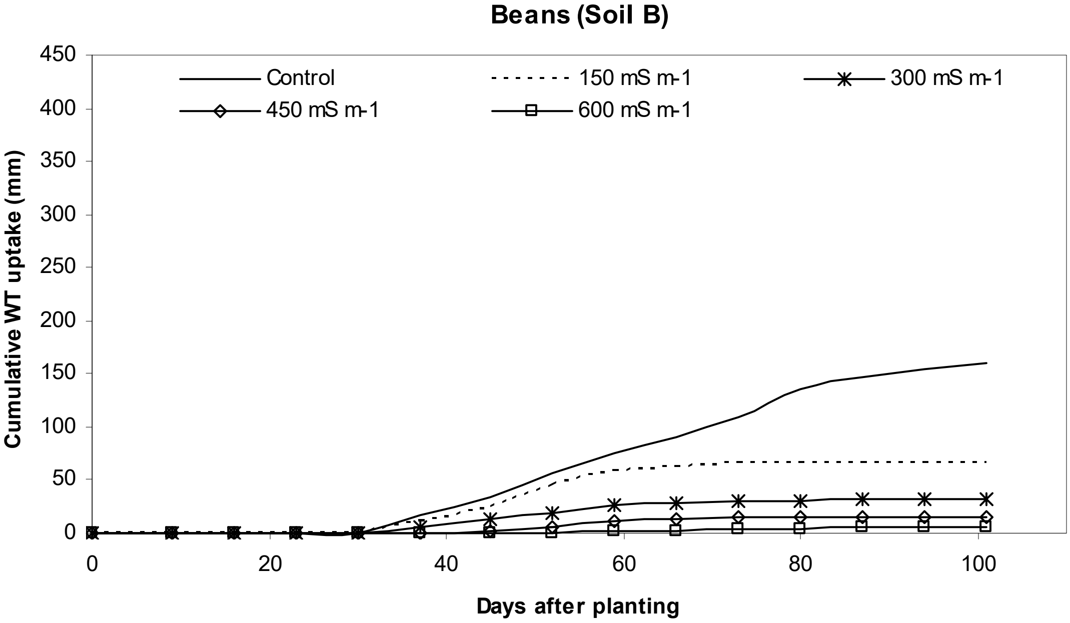


Figure 3.16 Cumulative water table uptake as a function of days after planting for all the treatments of beans on Soil B.

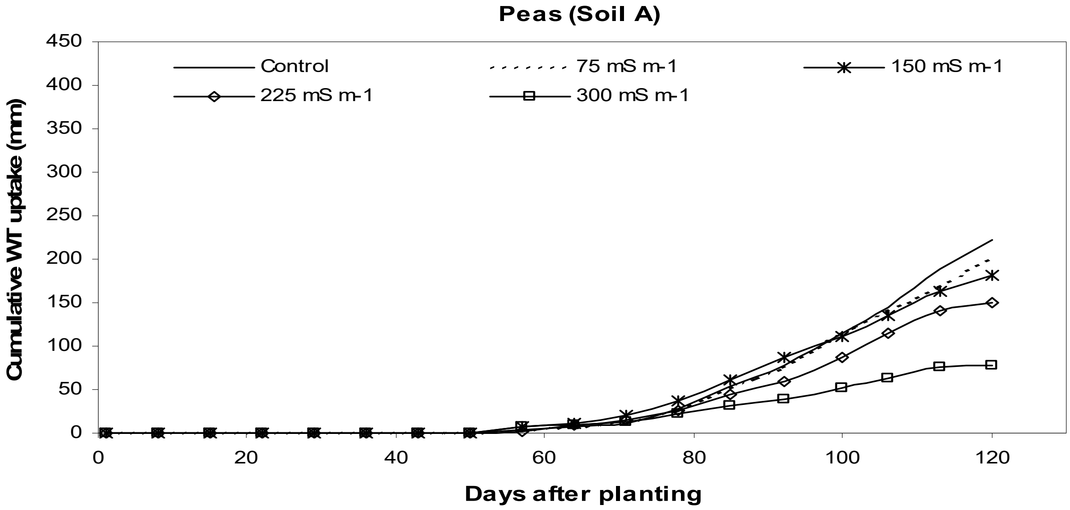


Figure 3.17 Cumulative water table uptake as a function of days after planting for all the treatments of peas on Soil A.

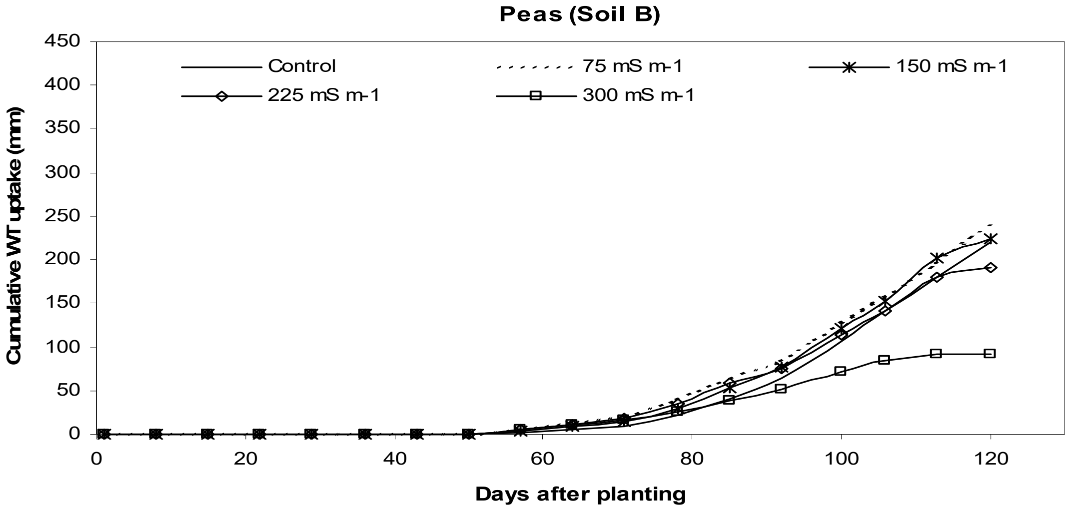


Figure 3.18 Cumulative water table uptake as a function of days after planting for all the treatments of peas on Soil B.

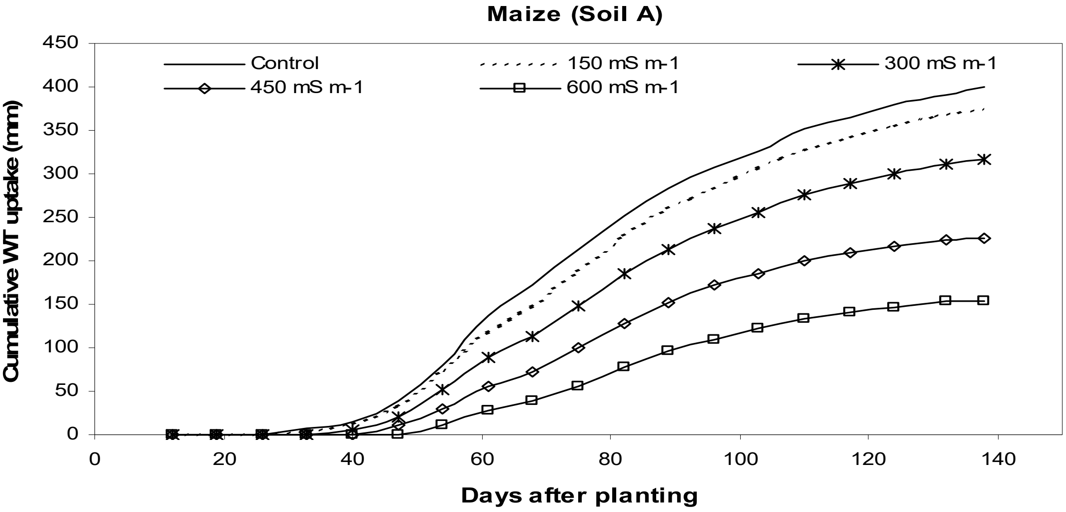


Figure 3.19 Cumulative water table uptake as a function of days after planting for all the treatments of maize on Soil A.

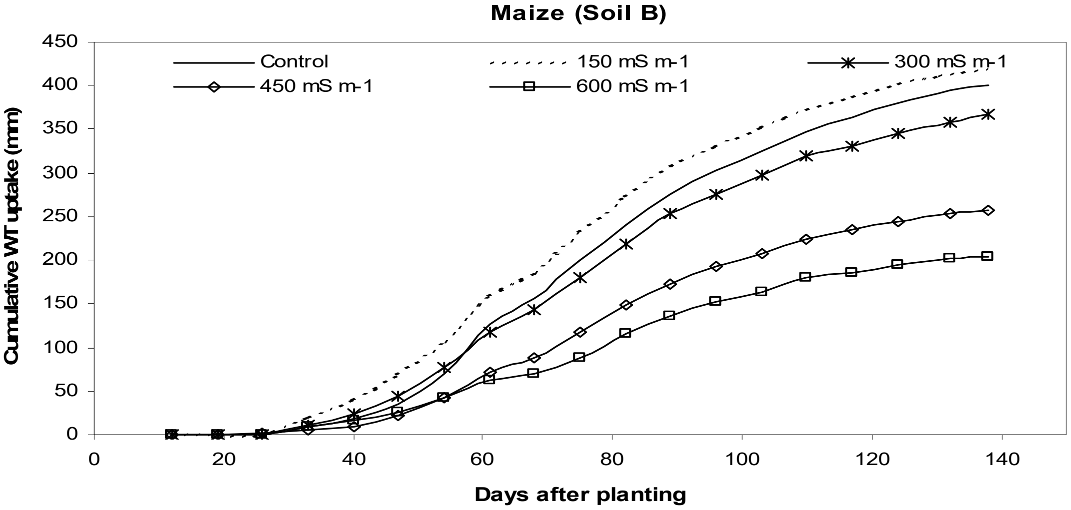


Figure 3.20 Cumulative water table uptake as a function of days after planting for all the treatments of maize on Soil B.

Figures 3.19 and 3.20 indicate that uptake from the water tables commenced around 33 and 54 days after planting for Soil B and Soil A respectively. They also illustrate that the control treatment on Soil A maintained a higher cumulative water table uptake throughout the growing season, and in the case of Soil B, the 150 mS m^{-1} treatment. Although the cumulative water table uptake of the 300 mS m^{-1} treatments were lower than the control treatments, the uptake from the water tables expressed as a percentage of ET was much higher on both soils.

3.3.4 Comparison of the salt tolerance of the different crops

3.3.4.1 Relationship between relative cumulative evapotranspiration and soil water salinity

Salinity affects the water stress of plants through its effect on the osmotic potential of the soil water. An increase in salinity results in a decrease of the osmotic potential and therefore also the water availability to the plants. Stewart *et al*. (1977) demonstrated, according to Katerji *et al*. (2003), that the relationship between yield and evapotranspiration of maize was the same for drought and salinity conditions. An increase in water stress reduces stomatal conductance, leaf growth and photosynthesis (West *et al*., 1986).

To compare crop salt tolerance, the relationship between the relative cumulative ET (Cum ET_{rel}) and soil water salinity (EC_{sw}) for the different crops is given in Figure 3.21, where the regression analysis is based on the means of all treatments on both soils and the 100% cumulative ET was taken as the cumulative ET of the control treatment. In this figure the osmotic potential is also indicated and it was calculated by using the equation of Jurinak & Suarez (1996): Ψ_0 (-kPa) = EC_{sw} (mS m^{-1}) x 0.40. The soil water salinity (EC_{sw}) was taken as the average EC_{sw} of the root zone between the beginning and end of the growing season of each crop, as given in Table 3.10.

This method is based on the hypothesis that crop salt tolerance is experimentally determined as the fractional reduction in cumulative ET resulting from osmotic induced water stress imposed on a crop during its growing season. According to the analysis, the decline in ET as a result of decreasing osmotic potential as indicated by slopes of the linear regression lines, is expressed as wheat < maize < beans < peas.

These results support Maas's (1986) classification based on growth and yield, namely that wheat is moderately salt tolerant, maize moderately salt sensitive and beans and peas salt sensitive.

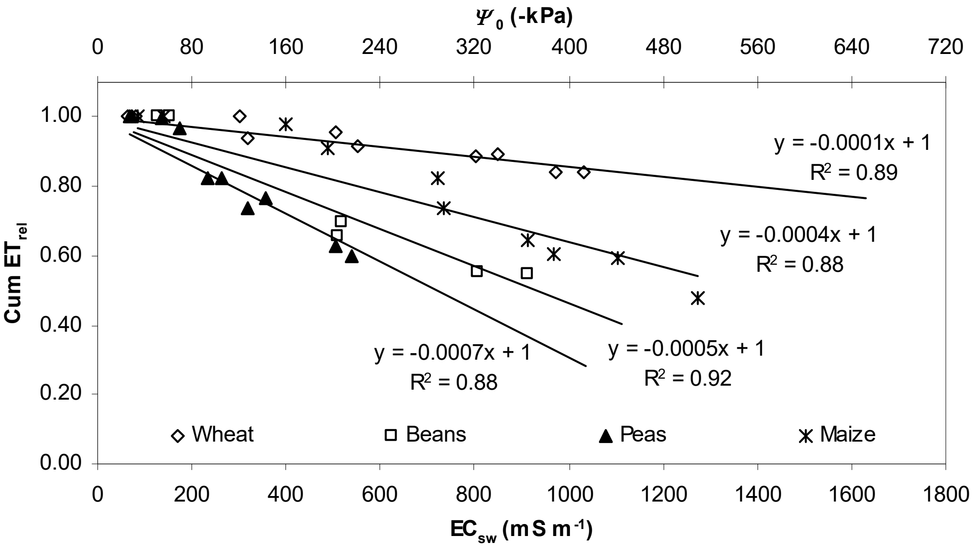


Figure 3.21 The relationship between the relative cumulative ET (Cum ET_{rel}) and soil water salinity (EC_{sw}, mS m^{-1}) as affected by osmotic potential (Ψ_0, -kPa) for all the crops on both soils.

Table 3.10 Mean soil water salinity of the root zone at the beginning (EC_{sw} in) and end (EC_{sw} end) of the growing season of all the treatments and crops for both soils

Soil	Wheat				Beans			
	EC_i (mS m^{-1})	EC_{sw} in	EC_{sw} end	Mean	EC_i (mS m^{-1})	EC_{sw} in	EC_{sw} end	Mean
A	15*	15	143	79	15*	143	159	151
	150	150	485	318	150	485	544	515
	300	300	806	553	300	806	835	821
	450	450	1158	804	450	1158	1492	1325
	600	600	1346	973	600	1346	1889	1617
B	15*	15	111	63	15*	111	143	127
	150	150	455	303	150	455	562	508
	300	300	714	507	300	714	1111	913
	450	450	1245	847	450	1245	1520	1382
	600	600	1460	1030	600	1460	1701	1580

Soil	Peas				Maize			
	EC_i (mS m^{-1})	EC_{sw} in	EC_{sw} end	Mean	EC_i (mS m^{-1})	EC_{sw} in	EC_{sw} end	Mean
A	15*	54	92	73	15*	77	200	139
	75	117	157	137	150	209	769	489
	150	124	404	264	300	368	1101	734
	225	251	383	317	450	503	1433	968
	300	397	611	504	600	692	1852	1272
B	15*	53	82	68	15*	69	100	84
	75	109	239	174	150	209	592	400
	150	155	311	233	300	355	1088	721
	225	221	491	356	450	521	1303	912
	300	382	693	537	600	686	1523	1105

*Control

3.3.4.2 Relationship between the relative biomass yield and soil water salinity

For this regression analyses, only the saline treatments with relative biomass yields of less than 0.95 were used, in order to avoid the effect of the non-saline treatments on the threshold value and the slope of the linear function. For the regression analysis of beans the relative biomass yield of 1 was included because the initial EC_{sw} of 139 to 150 mS m^{-1} (Table 3.10) was already in the same order as the reported threshold value of 100 mS m^{-1} (Rhoades & Loveday, 1990). The results of the linear regression analysis, i.e. the threshold EC_{sw} (mS m^{-1}) and the slope (relative yield reduction per mS m^{-1}) is given in Table 3.11. The biomass yield response of the different crops to soil salinity as characterized by linear functions are illustrated in Figures 3.22 to 3.25.

Table 3.11 Threshold EC_{sw} (mS m^{-1}) and slope (relative yield reduction per mS m^{-1}) according to the regression analysis of the relationship between relative biomass yield and soil water salinity (EC_{sw}) of the saline treatments

Crop	**Threshold EC_{sw} (mS m^{-1})**			***b***		
	Dikgwatlhe***	**Field**	**R & L****	**Dikgwatlhe*****	**Field**	**R & L****
Wheat	331	*	860	-0.0004	-0.00011	-0.0003
Beans	202	82	100	-0.0009	-0.00086	-0.0019
Peas	*	105	-	-0.0004	-0.00096	-
Maize	*	499	170	-0.0008	-0.00073	-0.0012

* Negative value

** Rhoades & Loveday (1990)

*** Dikgwatlhe (2006)

No threshold value could be calculated for wheat because the EC_{sw} of the treatments, with the exception of treatment 5, were less than the threshold value of 860 mS m^{-1} reported by Rhoades & Loveday (1990). The threshold value of 499 mS m^{-1} for maize in this study was higher compared to the threshold EC_e-values reported by Rhoades & Loveday (1990) of 170 mS m^{-1} and 130 mS m^{-1} by Katerji *et al*. (2003).

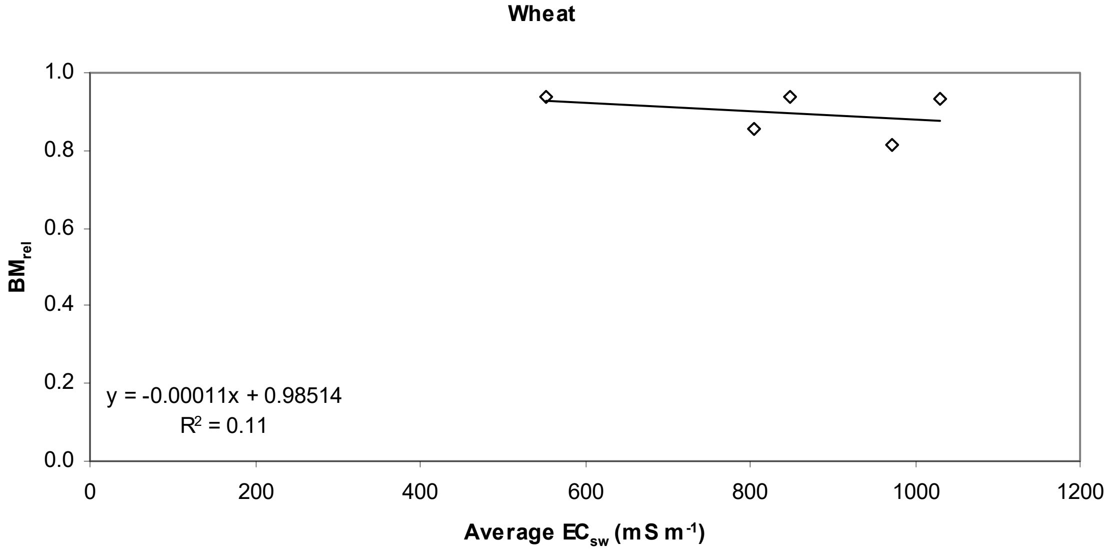


Figure 3.22 The relationship between the relative biomass yield (BM_{rel}) and mean seasonal soil water salinity (EC_{sw}) for wheat on both soils.

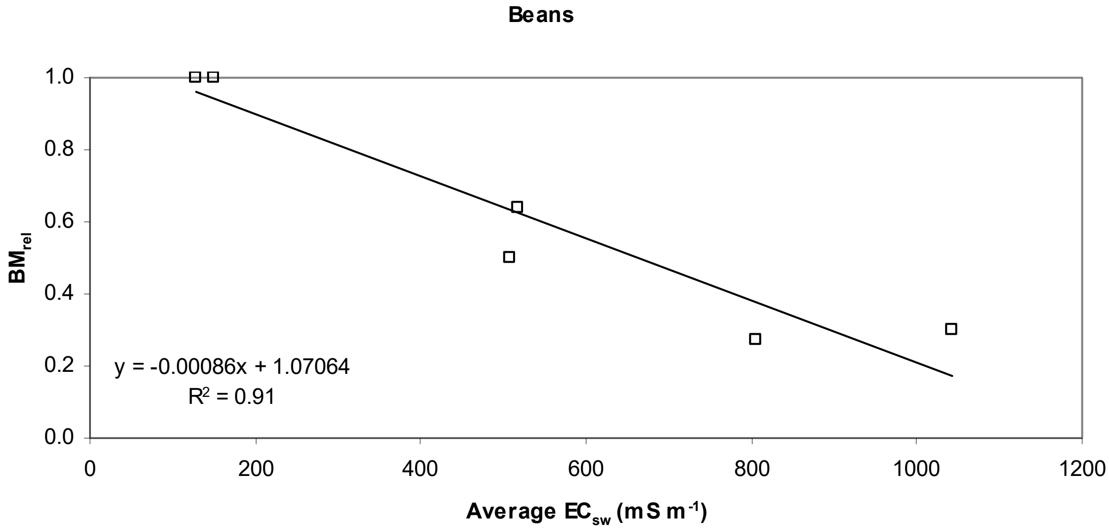


Figure 3.23 The relationship between the relative biomass yield (BM_{rel}) and mean seasonal soil water salinity (EC_{sw}) for beans on both soils.

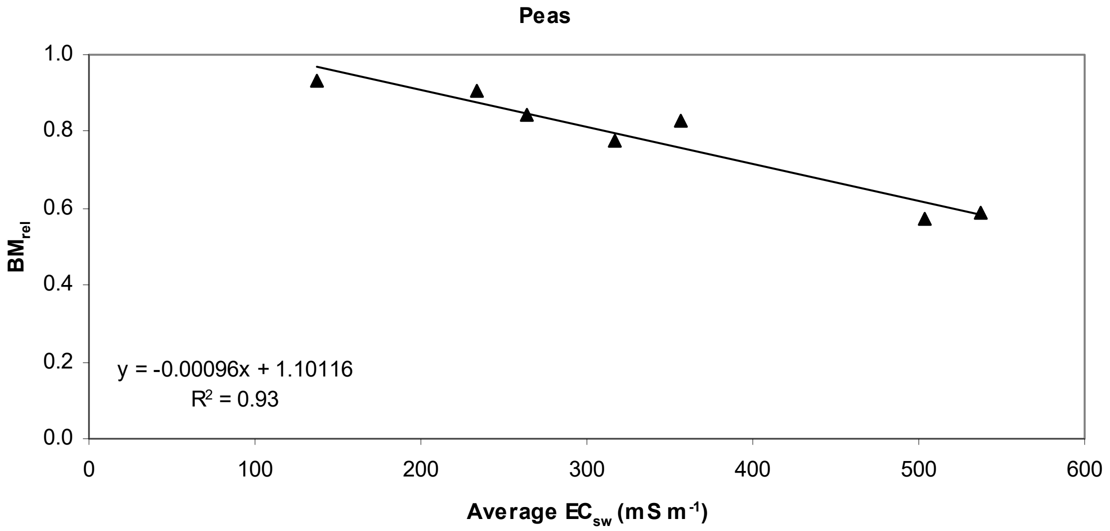


Figure 3.24 The relationship between the relative biomass yield (BM_{rel}) and mean seasonal soil water salinity (EC_{sw}) for peas on both soils.

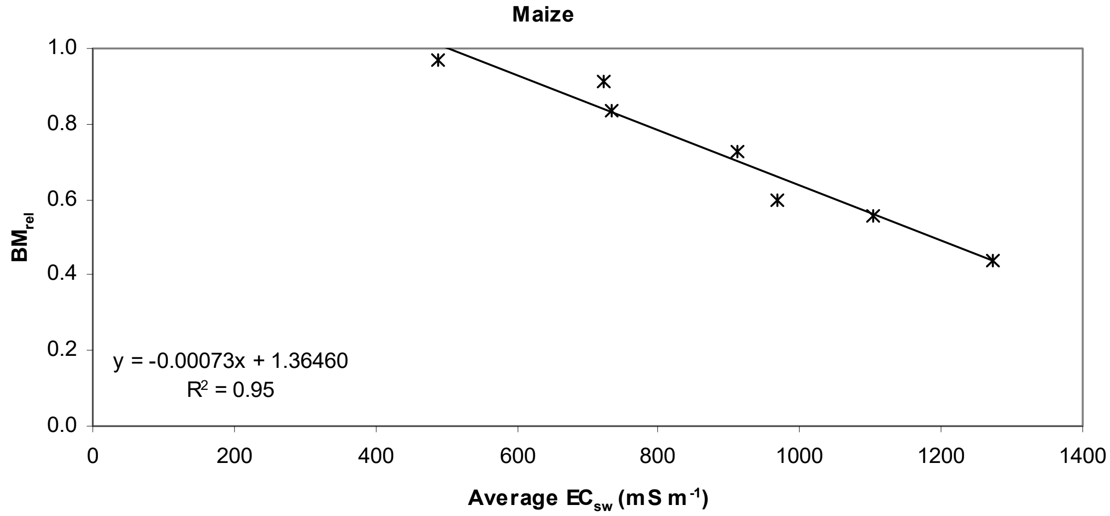


Figure 3.25 The relationship between the relative biomass yield (BM_{rel}) and mean seasonal soil water salinity (EC_{sw}) for maize on both soils.

According to Maas (1990), the parameters in Table 3.11 can be used to estimate the relative yield (Y_r) with Equation 3.2 for soil salinities exceeding the threshold value of any crop.

$$Y_r = 1 - b\,(EC_{sw} - a) \tag{3.2}$$

where a = Salinity threshold value mS m^{-1}

b = Slope per mS m^{-1}

EC_{sw} = Mean electrical conductivity of the soil water taken from the root zone higher Than the threshold value (mS m^{-1})

The salt tolerance of the crops in terms of biomass production can be classified as wheat > maize > beans = peas.

3.3.4.3 Effect of soil water salinity on the water production functions of crops

Decreasing osmotic potential, due to higher salt contents, results in a lower total soil water potential (matric plus osmotic). The corresponding potential difference decrease between the root xylem and surrounding soil solution results in less water being taken up under conditions of normally adequate water supply. The reduction in water uptake was correlated to the reduction in yield by using the relationship of Stewart *et al*. (1977):

$$1 - \frac{Ya}{Ym} = \beta \left[1 - \left(\frac{ETa}{ETm}\right)\right] \tag{3.3}$$

where Y_a = actual crop biomass yield (t ha^{-1}) of a treatment

Y_m = biomass yield (t ha^{-1})of the control treatment with no water stress

ET_a = actual crop evapotranspiration (mm) of a treatment

ET_m = potential crop evapotranspiration (mm) of the control treatment

β = slope of relative yield and relative evapotranspiration

Taking Y_m and ET_m as the biomass yield and evapotranspiration of the control treatments, the analysis of the results gives a linear relationship between relative evapotranspiration and relative yield as illustrated by Figure 3.26 for the combined data of all the crops and both soils. This is a clear indication that the relative decrease in growth of all the crops was directly proportional to the relative decrease in ET caused by the decreasing osmotic potential with increased salinity. Hence, this proves that, irrespective of the differences in salt tolerance of the different crops, in all cases the reduction in growth was proportionally related to the increase in plant water stress induced by lower water uptake.

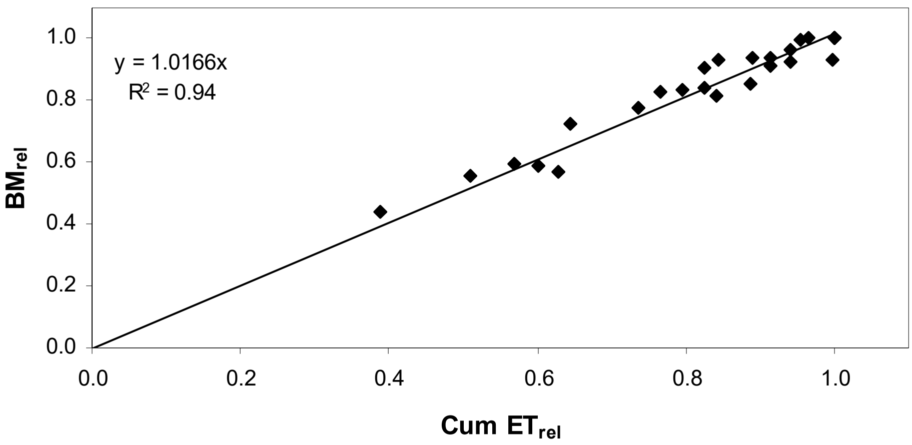


Figure 3.26 Relationship between the relative biomass yield (BM_{rel}) and the relative cumulative ET (Cum ET_{rel}) for all the crops and soils combined.

3.3.4.4 Effect of soil water salinity on water table uptake of crops

The uptake of water from the water tables (WT) is presented in Table 3.9 for the different crops and soils. The mean EC_{sw} of the three replications, of the WT (1200 – 1800 mm) depth and the capillary zone above the WT (600 – 1200 mm) is presented in Tables 3.12 and 3.13 respectively.

To illustrate the effect of water table salinity on water uptake, the mean of the initial and end EC_{sw} of the capillary zone (Table 3.13), from which most of the water from the WT is extracted, was plotted against the relative water table uptake (control taken as 1) in Figure 3.27, using the data of both soils for the different crops.

An increase in salinity or a decline in osmotic potential of the capillary zone affected the four crops in the order: wheat < maize < beans < peas. The threshold EC_{sw}-values, above which water uptake started to decrease, varied between 57 mS m^{-1} for beans to 279 mS m^{-1} for maize with an average value of 136 mS m^{-1} or an osmotic potential of –54 kPa.

Water uptake from non-saline water tables can be estimated with a high degree of accuracy with the application of the models SWB (Jovanovic *et al.*, 2004) and SWAMP (Bennie *et al.*, 1998). To model the water uptake from saline water tables, the decrease in osmotic potential will reduce the potential difference between the root and the surrounding soil solution. A preliminary analysis has shown that the decrease in osmotic potential alone does not explain all of the measured decline in water table uptake associated with an increase in salinity of the capillary zone. A possible explanation is that the measured EC_{sw} of the capillary zone does not represent the osmotic potential in the rhizosphere surrounding the roots. Salts are transported into the rhizosphere through mass flow, due to rapid water uptake by the roots from the wet soil. This causes an accumulation of salts in the rhizosphere, and if the removal of salts away from the roots through diffusion is slower than the addition through mass flow, the nett effect will be a higher degree of salinity in the rhizosphere. The osmotic potential in the rhizosphere will then be lower than the EC_{sw} value measured for the bulk soil.

An alternative is to follow an empirical approach, for estimating the water table uptake under saline conditions. This approach will be discussed in Section 5.2.9.

Table 3.12 Electrical conductivity of the soil water (EC_{sw}, mS m^{-1}) of the water table (1200 – 1800 mm) for the different crops, EC_i treatments and soils

Soil	**Wheat**				**Beans**			
	EC_i (mS m^{-1})	**EC_{sw} in**	**EC_{sw} end**	**Mean**	**EC_i (mS m^{-1})**	**EC_{sw} in**	**EC_{sw} end**	**Mean**
A	15*	15	91	53	15*	91	103	97
	150	150	190	170	150	190	227	208
	300	300	400	350	300	400	619	509
	450	450	590	520	450	590	1167	879
	600	600	1168	884	600	1168	1580	1374
B	15*	15	70	43	15*	70	64	67
	150	150	211	181	150	211	696	454
	300	300	343	321	300	343	428	385
	450	450	597	524	450	597	839	718
	600	600	735	668	600	735	1151	943
Soil		**Peas**			**Maize**			
	EC_i (mS m^{-1})	**EC_{sw} in**	**EC_{sw} end**	**Mean**	**EC_i (mS m^{-1})**	**EC_{sw} in**	**EC_{sw} end**	**Mean**
A	15*	75	72	74	15*	89	78	83
	75	122	117	120	150	265	212	238
	150	115	178	147	300	497	414	456
	225	240	262	251	450	536	419	477
	300	384	436	410	600	830	808	819
B	15*	74	52	63	15*	69	50	59
	75	157	133	145	150	221	223	222
	150	216	184	200	300	340	356	348
	225	272	279	276	450	486	558	522
	300	457	430	444	600	715	664	690

*Control

Table 3.13 Electrical conductivity of the soil water (EC_{sw}, mS m^{-1}), of the capillary zone above the water table (600-1200 mm), for the different crops, EC_i treatments and soils

Soil	**Wheat**				**Beans**			
	EC_i (mS m^{-1})	**EC_{sw} in**	**EC_{sw} end**	**Mean**	**EC_i (mS m^{-1})**	**EC_{sw} in**	**EC_{sw} end**	**Mean**
A	15*	15	169	92	15*	169	187	178
	150	150	616	383	150	616	667	641
	300	300	1040	670	300	1040	855	947
	450	450	1555	1003	450	1555	1329	1442
	600	600	1716	1158	600	1716	1485	1601
B	15*	15	132	74	15*	132	157	144
	150	150	578	364	150	578	649	613
	300	300	989	644	300	989	1386	1188
	450	450	1521	986	450	1521	1466	1493
	600	600	1917	1259	600	1917	1852	1885
Soil	**Peas**				**Maize**			
	EC_i (mS m^{-1})	**EC_{sw} in**	**EC_{sw} end**	**Mean**	**EC_i (mS m^{-1})**	**EC_{sw} in**	**EC_{sw} end**	**Mean**
A	15*	50	107	78	15*	80	124	102
	75	115	254	184	150	193	592	393
	150	125	470	298	300	325	1200	763
	225	255	415	335	450	500	1399	950
	300	407	669	538	600	582	1633	1107
B	15*	50	86	68	15*	85	100	92
	75	100	231	165	150	211	420	316
	150	121	283	202	300	367	1004	685
	225	212	420	316	450	507	1085	796
	300	368	657	513	600	741	1307	1024

*Control

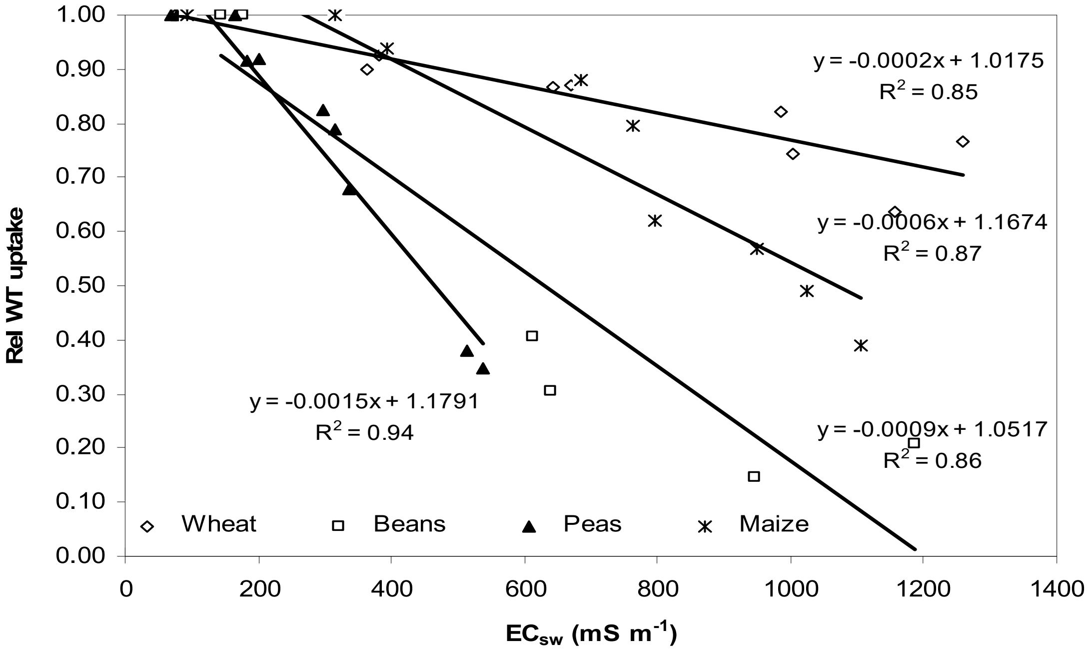


Figure 3.27 Relative water uptake from the capillary zones of water tables with different salinity levels by the experimental crops.

3.4 Conclusions

The experiments simulated conditions of adequate water supply to crops under irrigation, and a shallow water table at 1200 mm depth. Although similar conditions are common in irrigated fields, it is also ideal for rapid build-up of salts in the root zone, especially when saline irrigation water is used. The main treatments comprised irrigation with water ranging from low to high salinity. Accumulation of salt in the root zone was so high within one growing season, that the salt had to be removed through leaching, before starting the next experiment.

Positive results were obtained by correlating growth and water uptake of the crops with the electrical conductivity of the irrigation water (EC_i), but the results could be better explained in terms of the electrical conductivity of the soil water (EC_{sw}). Samples of the soil water were extracted with suction cups at the beginning and end of each growing season.

The highest EC_i treatment of 600 mS m^{-1} was selected on the basis of what was predicted to be the worst-case scenario for South African rivers. The growth of wheat only started to be affected by EC_i values of 600 mS m^{-1}. The threshold values for EC_i, given in the discussion of the results, should be interpreted with caution because of the rapid increase in the salt content of the soil water (EC_{sw}). For wheat, peas and maize the results represent the effect of a first growing season with restricted drainage. Beans were planted after wheat as a second season crop without leaching of the salts that accumulated with the wheat crop. This build up of salts caused serious inhibition of growth of the beans because of the high EC_{sw} values.

With the exception of wheat, which gave better yields on the more clayey Soil B, the growth and water uptake of all the other crops were similar on both soils, for comparable treatments. The growth of wheat, maize, peas and beans started to decline when irrigating with water of 600, 450, 300 and 150 mS m^{-1}, respectively. It should be emphasised that the value for beans represents a second season crop, and would be higher for a first season crop. The cumulative seasonal ET and maximum daily ET of all the crops, declined with increasing salt content of the irrigation water with a corresponding increase in EC_{sw} and a decrease in osmotic potential. The water use efficiency of the crops, expressed in biomass produced per unit mass water used, seems to be unaffected by moderate salt content of the soil and started to decline only when the threshold values were exceeded.

Water uptake from the shallow water tables decreased with an increase in EC_i for all the crops and on both soils, due probably to a decrease in the osmotic potential. The relative decline in plant water uptake from a water table at a depth of 1200 mm declined linearly when the osmotic potential decreased below –50 kPa. The decline was most rapid for peas followed by beans > maize > wheat.

By using the mean of the initial and end EC_{sw}, also averaged over depth, instead of EC_i, it was possible to compare these results with the EC_e-values published in literature. The cumulative seasonal ET, expressed relative to the control for all treatments, decreases linearly with increasing salinity of the soil water. The effect on the crops was wheat < maize < beans < peas. The decrease in relative biomass production was directly related to a relative decrease in cumulative ET on a 1:1 basis. A decrease in osmotic potential to –300 kPa (EC_{sw} = 750 mS m^{-1}) reduced ET and biomass produced by 7%, 30%, 38% and 53% for wheat, maize, beans and peas respectively.

The threshold EC_{sw}-values above which relative plant growth starts to decline linearly deviate slightly from the EC_e-values reported in the literature. The value for maize is higher and that of beans is very similar, and no values could be found against which to compare peas. The salt accumulation during the wheat experiment was insufficient to derive a threshold value. The threshold value for wheat as reported by Dikgwatlhe (2006) was lower than that reported in the literature.

In conclusion, it can be stated, that this part of the study confirmed the findings of researchers such as Maas (1990), Rhoades & Loveday (1990) and Katerji *et al.* (2003), namely, that the effects of salinity and water stress on plant growth are similar. The increase in the salinity of the soil water of the root zone, and the corresponding decrease in osmotic potential and also total water potential, decreases the potential difference between the soil solution and the root xylem. This smaller driving force results in less water being taken up by the plants, with a corresponding decline in growth, even under conditions of adequate water supply, as was the case in these experiments. Saline irrigation water can, within one growing season and in the presence of a shallow water table and restricted salt leaching, increase the salinity of the soil water in the root zone several fold. The quantification of this aspect will be the objective of the next chapter.

CHAPTER 4

SALT ACCUMULATION IN THE ROOT ZONE DURING THE GROWING SEASON OF CROPS IN THE PRESENCE OF SHALLOW WATER TABLES

4.1 Introduction

Irrigation, irrespective of the water quality, will result in the accumulation of salts in the soil profile when little or no leaching takes place, especially in the presence of shallow water tables. Crops are sensitive to soil salinity and yield is reduced when crops are grown on salt-affected soils (Chapter 3). The salt content of irrigation water and the cropping history determines the long term salt distribution in a soil profile. Although true equilibrium conditions are seldom reached in practice, due to changes in irrigation management, fluctuating irrigation water salinity and variable rainfall, quasi-equilibrium soil salinity profiles are mostly attained within two irrigation seasons. The salt content of the root zone normally increases with depth. Near the soil surface the salt content will be similar to that of the irrigation water. Plant roots actively absorb water and leave most of the salts behind, resulting in a gradual increase in salt concentration throughout the soil profile, between irrigation applications. When more water than the crop water requirement is applied with each irrigation event, the accumulated salt can be leached deeper into the soil profile where it is again concentrated until it is progressively leached from the root zone. However, in the presence of a shallow saline water table where leaching is restricted, upflow of the soil solution causes rapid salinisation of soil layers above the water table.

The objective in this chapter is to quantify the accumulation of salts during the growing season of selected crops, for a range of irrigation water salinities and in the presence of shallow saline water tables.

4.2 Materials and methods

The lysimeter unit used for obtaining data for this study is described in Section 3.2.1. Six ceramic suction cups were installed in each lysimeter by inserting the cups horizontally into the soil from the access chamber side of the lysimeters (Plate 4.1). The installation depths were 300, 500, 700, 900, 1100 and 1500 mm from the soil surface. The outlet of each cup was connected to a vacuum system operating at a suction of 50 kPa. Samples of the soil solution were collected for chemical analysis in glass bottle traps from all the depths, at the beginning and end of the growing seasons of beans, peas and maize. The lysimeters were saturated with the corresponding irrigation water before suction commenced.

Before planting of the wheat experiment, which was the first crop, the lysimeters of each treatment were leached with the appropriate irrigation water salinity until the EC of the leachate (EC_d, mS m^{-1})

corresponded with the EC of the irrigation water. The first suction cup samples were taken after the bean crop was planted. These values were taken to represent the end of the wheat growing season and the beginning of the bean growing season. At the end of the dry bean, pea and maize growing seasons the free water tables were drained from each of the lysimeters. Thereafter the lysimeters for every treatment were leached with the appropriate irrigation water salinity until the EC_d of the outflow from the bottom corresponded with the EC of the applied irrigation water.

Plate 4.1 Ceramic cups installed from the access chamber side of the lysimeters at different depths from the soil surface.

The water samples from the suction cups were analyzed for electrical conductivity of the soil water (EC_{sw}, mS m^{-1}). In addition, dissolved calcium (Ca^{++}, mg L^{-1}), magnesium (Mg^{++}, mg L^{-1}), sodium (Na^{+}, mg L^{-1}), potassium (K^{+}, mg L^{-1}), chloride (Cl^{-}, mg L^{-1}) and sulphate ($SO_4^{=}$, mg L^{-1}) were analyzed to calculate the total dissolved solids (TDS) and sodium adsorption ratio (SAR) of the soil water.

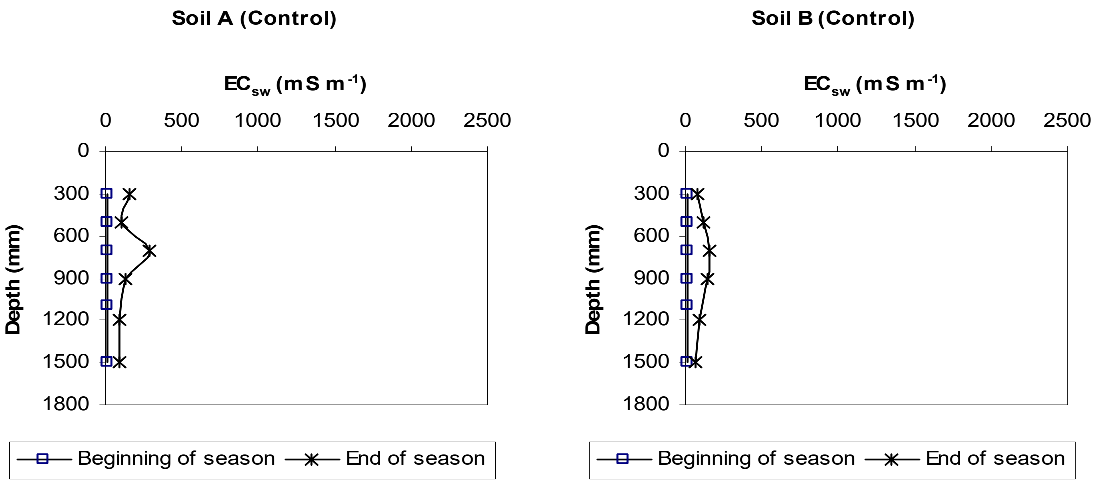
4.3 Results and discussion

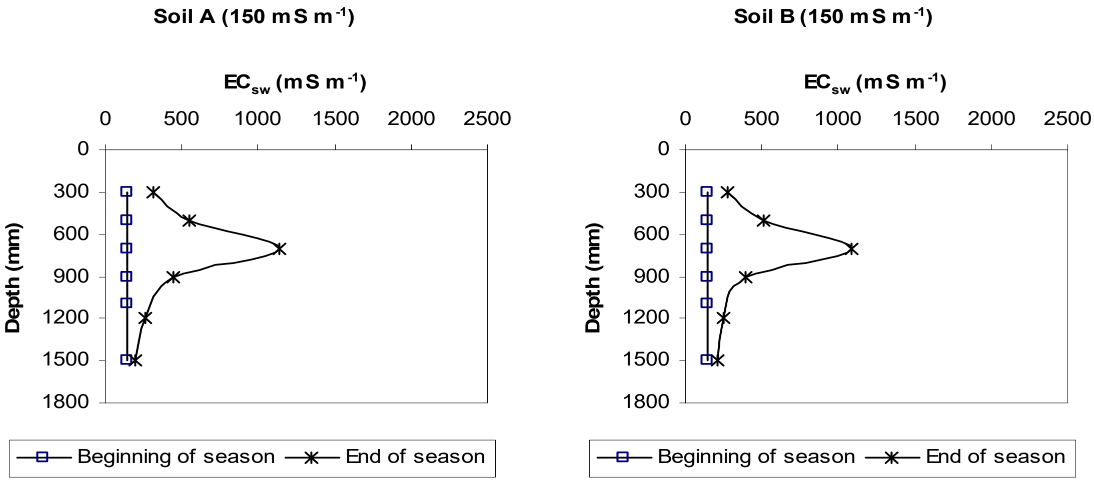
4.3.1 Soil water salinity profiles at beginning and end of growing season

The EC_{sw} values, for the beginning and end of the growing seasons of all the treatments and soils for the beans, peas and maize experiments, are given in Appendix 4.1. Figures 4.1 to 4.4 represent the EC_{sw}, as measured with the suction cups at different depths in the soil profile of all the treatments of both soils, at the beginning and end of the growing season of beans, peas and maize. The values given for the end of the wheat growing season (Figure 4.1) are the same as for the beginning of the bean growing season.

Wheat

Unfortunately it was not possible to obtain soil solution samples at the beginning of the wheat growing season. As previously mentioned, the lysimeters were leached with the corresponding irrigation water salinity before the wheat was planted. Therefore in Figure 4.1 the EC_{sw} at different depths, for the beginning of the season, was set equal to the EC_i of the treatment. The difference between the two lines in each graph represents the salt accumulation at different depths during the growing season. It is evident that on both soils the salt content of the soil extract increased with an increase in depth from the soil surface, reaching a maximum at a depth of 700 mm. The salt contents then gradually decreased from 700 mm to a depth of 1800 mm. As would be expected there was an increase in EC_{sw} -values with an increase in EC_i. For Soil A the salinity of the topsoil, 300 mm from the soil surface, increased from 162 mS m^{-1} in the control treatment to 840 mS m^{-1} in the 600 mS m^{-1} treatment. For Soil B the increase ranged from 78 mS m^{-1} in the control to 880 mS m^{-1} in the 600 mS m^{-1} treatment.





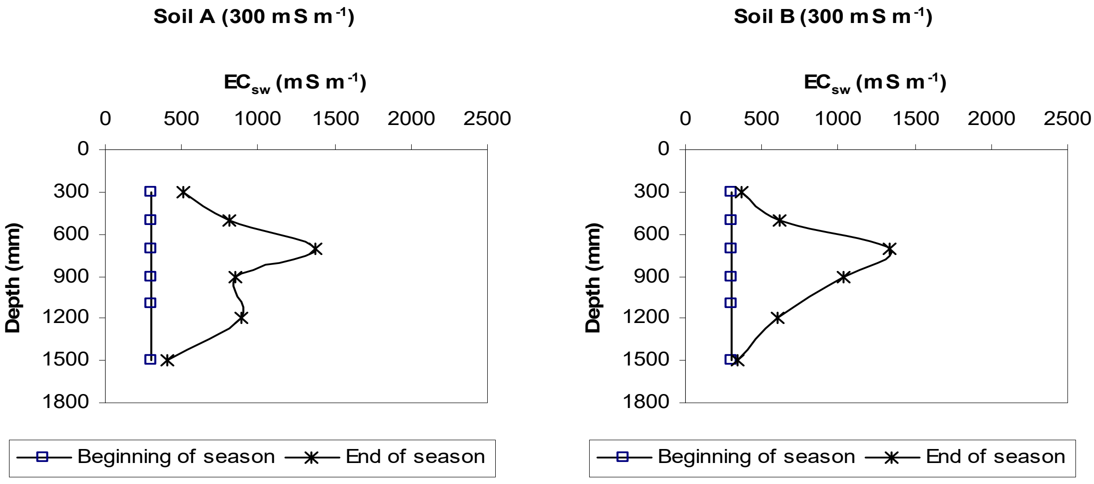


Figure 4.1 continue

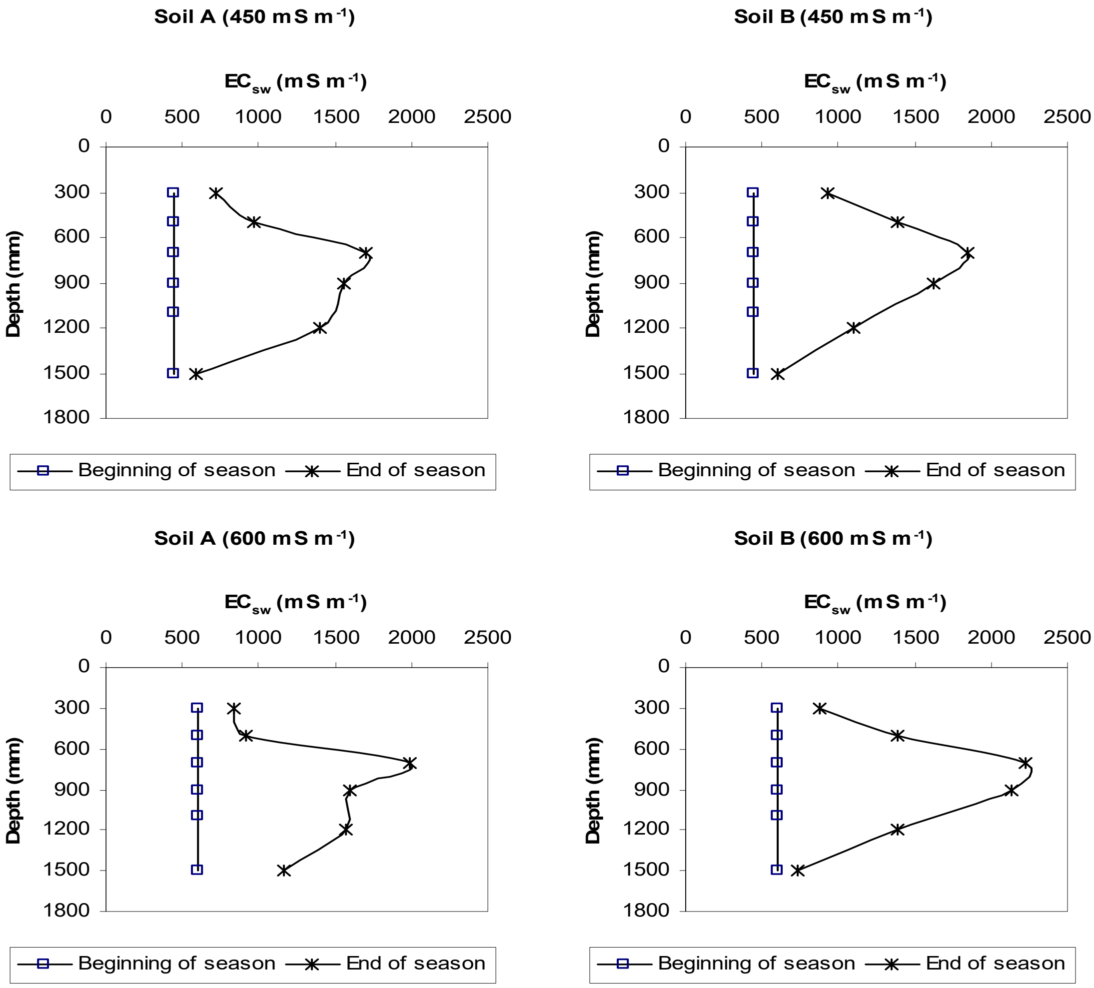
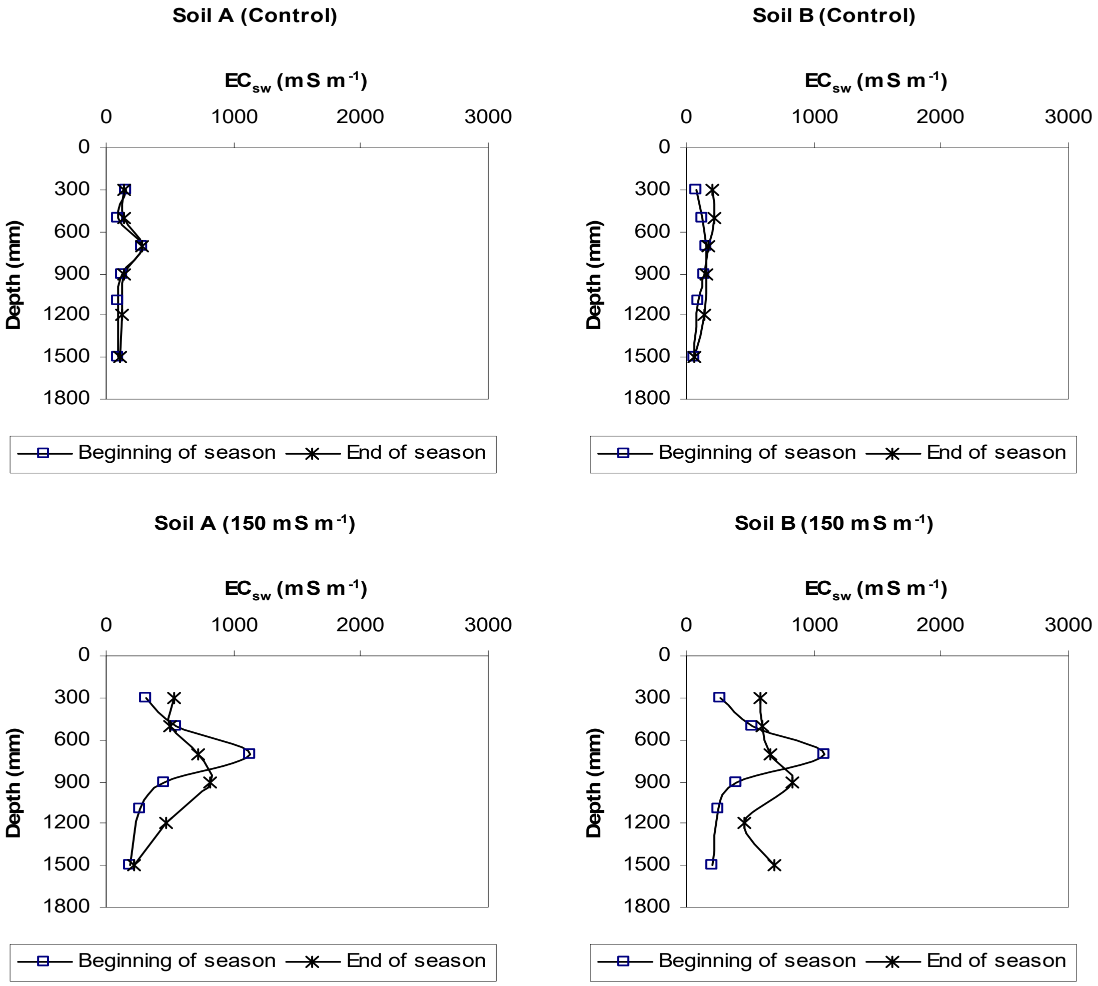


Figure 4.1 Soil water salinity profiles at the beginning and end of the wheat growing season for all the EC_i treatments of both soils.

Beans

The salinity levels in both soils were already high at the beginning of the season due to rapid accumulation of salts during the irrigation of wheat. Salts accumulated rapidly in the soil profile of the lysimeters because it is a closed system, where drainage is artificially kept at zero. As explained in the experimental procedure (Section 4.2) the excess salts in the lysimeters were not removed through leaching at the end of the wheat growing season because the accumulation was not expected to be so pronounced. Consequently the additional salt accumulation, as indicated in Figure 4.2, was directly related to the salinity level of the added irrigation water, as surface or sub-surface irrigation. As explained in Section 3.3.1, the high salinity levels in the top soil negatively affected the germination and establishment of beans. As illustrated in Figure 4.2 little salt accumulated in the control treatments. However, in all the saline irrigation water treatments, the salinity of the top soil increased further towards the end of the growing season. The EC_{sw} of the 150 mS m^{-1} treatment, for example, increased from 321 mS m^{-1} to 528 mS m^{-1} on Soil A and from 271 mS m^{-1} to 580 mS m^{-1} on Soil B.

Downward movement of salts can be observed in all the treatments applied to Soil A and in the 150, 450 and 600 mS m^{-1} treatments of Soil B (Figure 4.2).



Soil A (Control)

Soil B (Control)

Soil A (150 mS m^{-1})

Soil B (150 mS m^{-1})

Figure 4.2 continue

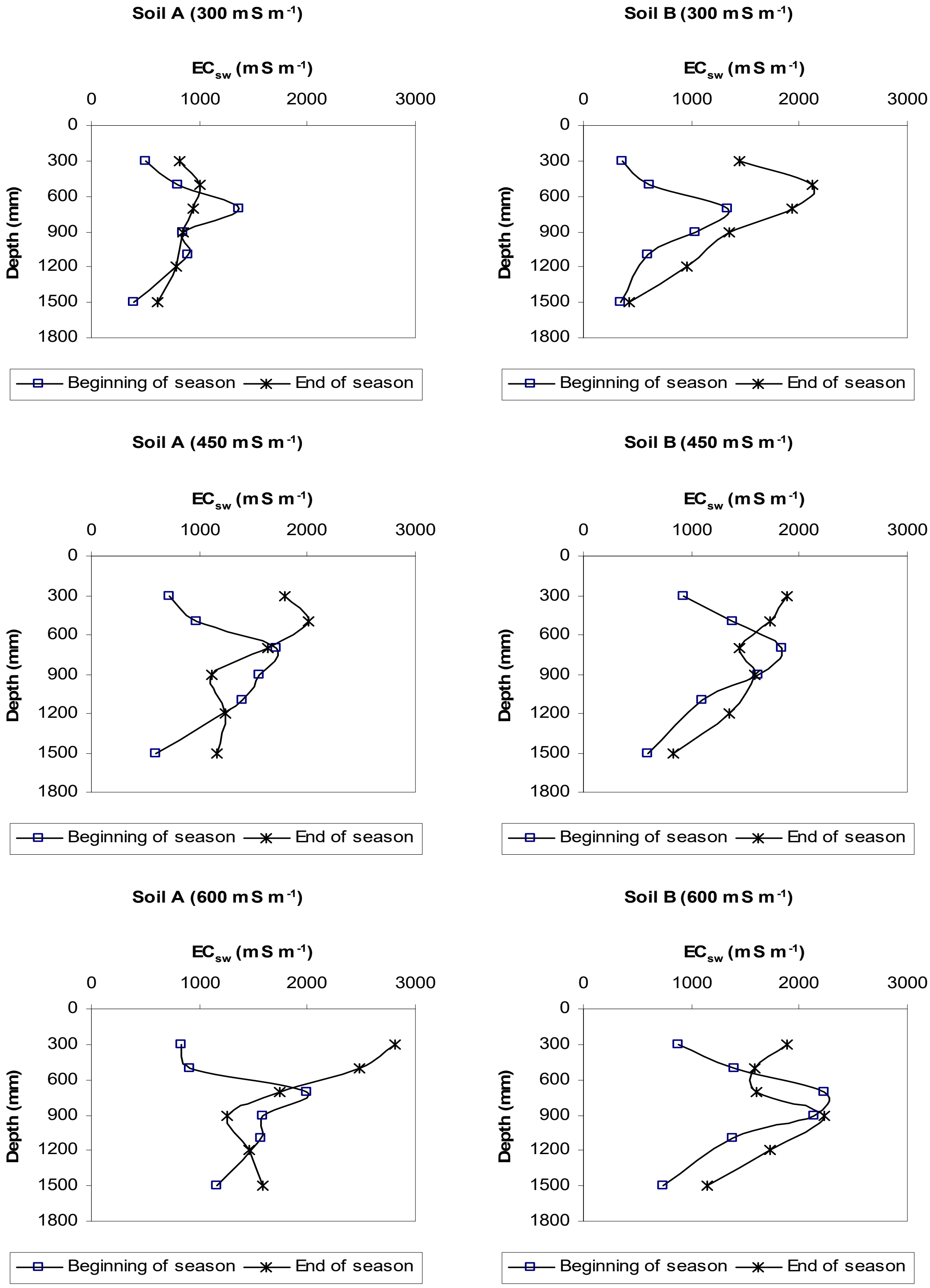


Figure 4.2 Soil water salinity profiles at the beginning and end of the bean growing season for all the EC$_i$ treatments of both soils.

Peas

Due to the rapid accumulation of salts during the irrigation of the previous crops, viz. wheat and beans, the soils were leached before planting with water salinities similar to the selected EC$_i$ levels for the pea treatments. Figure 4.3 illustrates the salinity levels at the beginning (i.e. after leaching) and the end of the growing season for all the treatments of both soils. As was observed with the previous crops, the EC$_{sw}$ increased with an increase in irrigation water salinity. The quantity of salts accumulated, as indicated by the difference in EC$_{sw}$ between the beginning and end of season values at different depths, increased with the increasing salinity of the irrigation water.

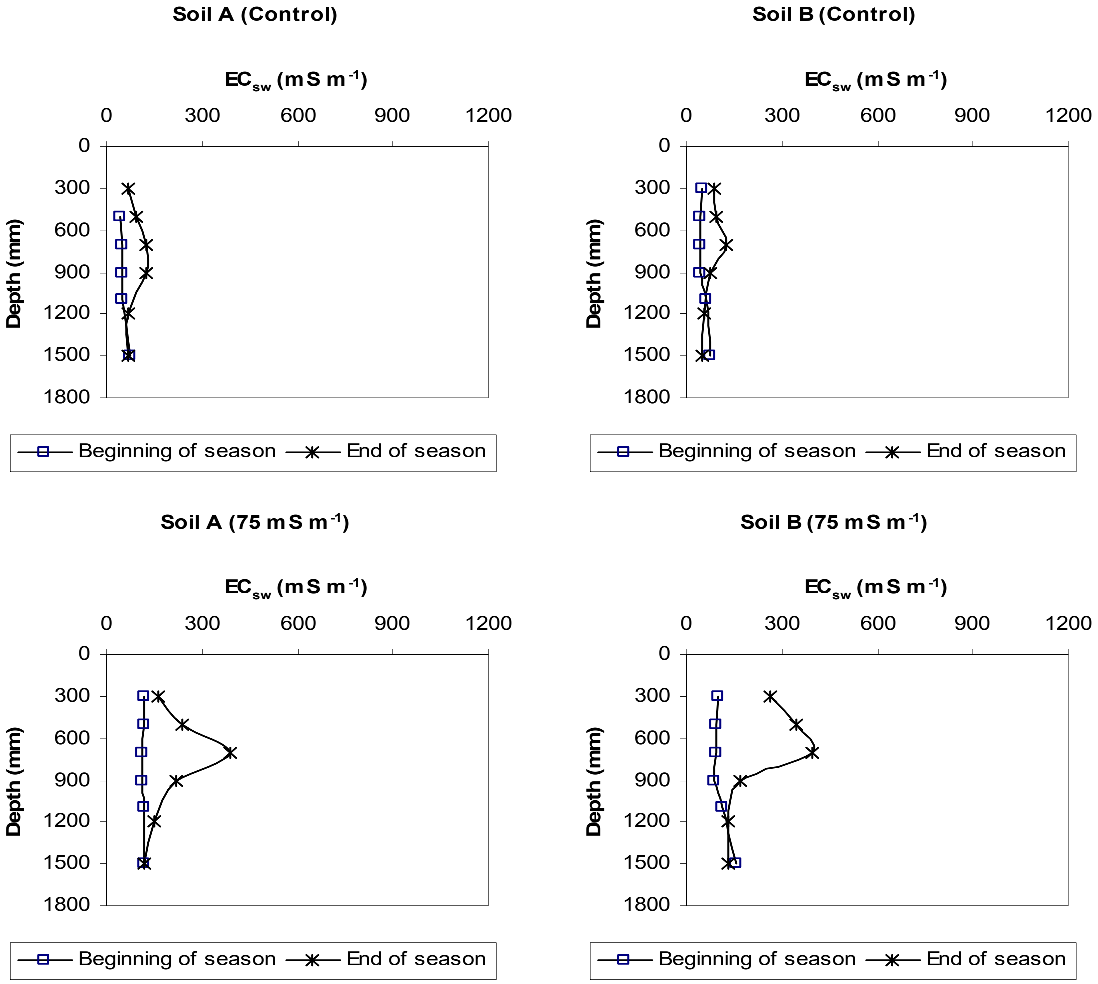


Figure 4.3 continue

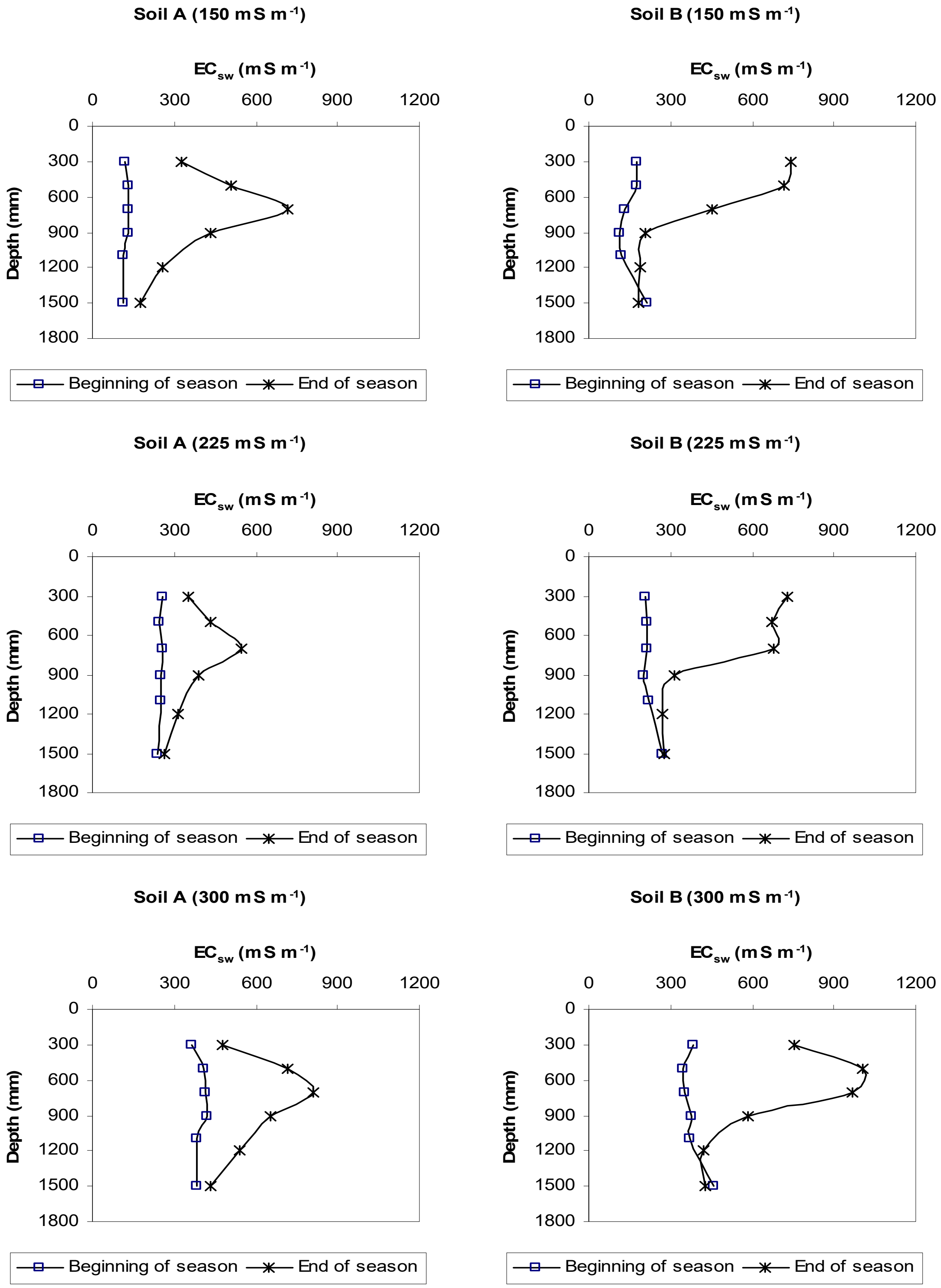


Figure 4.3 Soil water salinity profiles at the beginning and end of the pea growing season for all the EC_i treatments of both soils.

Maize

The salinity levels at the beginning (after leaching) and end of the maize growing season are illustrated in Figure 4.4 for all the treatments of both soils. As was found with the previous crops, there was a rapid increase in salt content of the soils with an increase in irrigation water salinity. For Soil A, EC_{sw}-values increased from 70 to 174 mS m^{-1} and from 708 to 2088 mS m^{-1} in the topsoil of the control and 600 mS m^{-1} treatments respectively. In the case of Soil B the corresponding increases were from 61 to 139 mS m^{-1} and from 663 to 2670 mS m^{-1}.

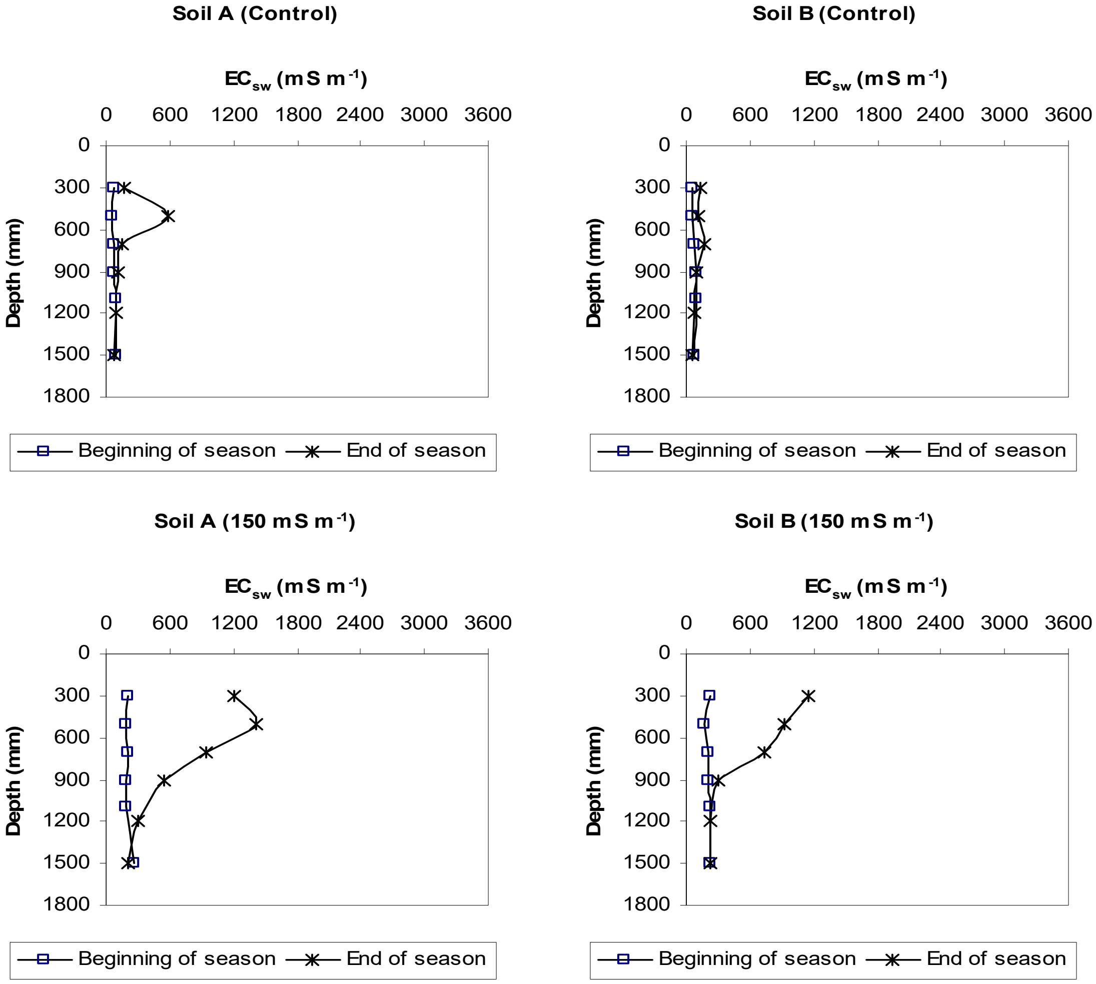


Figure 4.4 continue

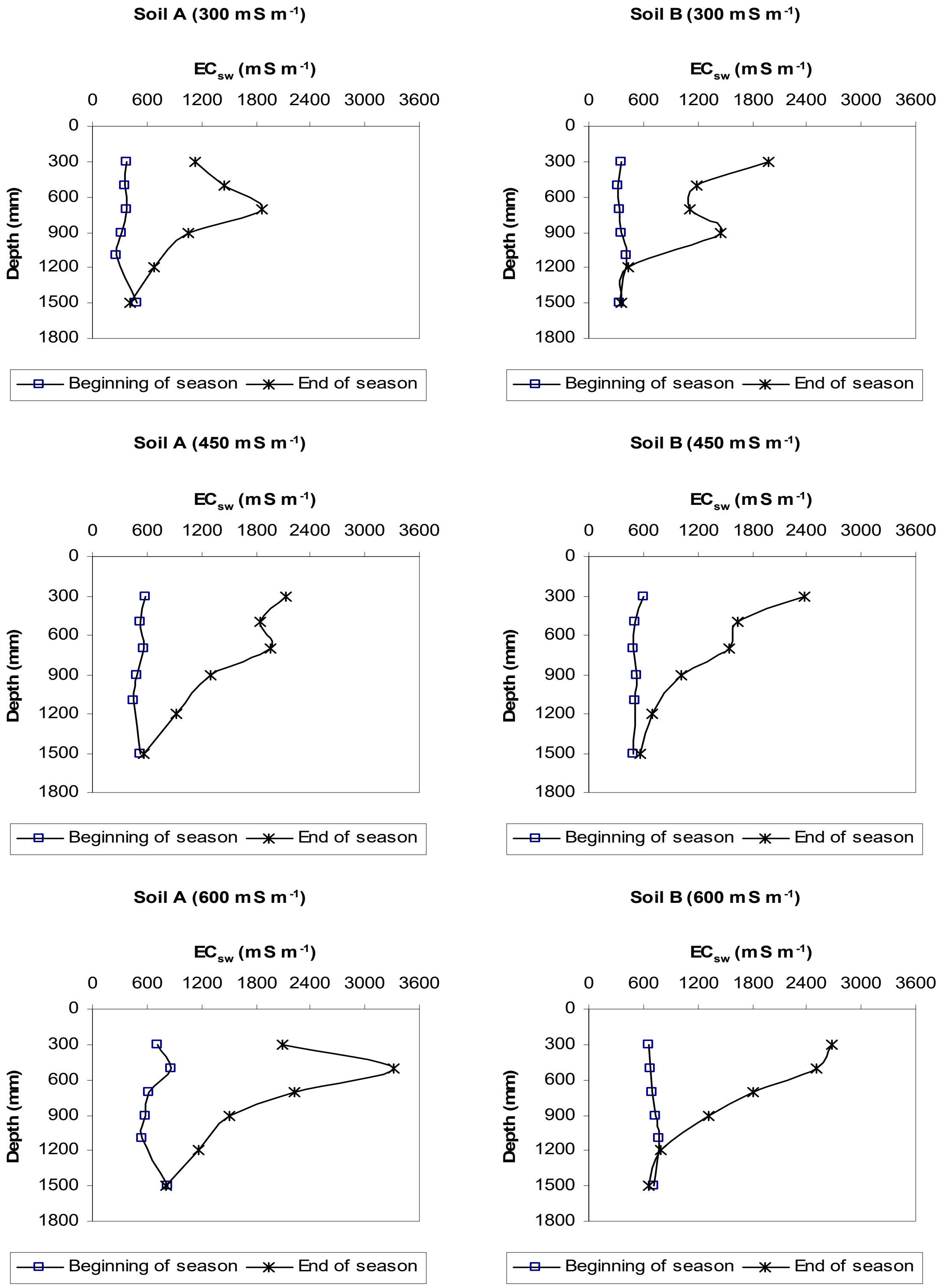


Figure 4.4 Soil water salinity profiles at the beginning and end of the maize growing season for all the EC_i treatments of both soils.

4.3.2 Effect of capillary zone on salt distribution through the soil profile

According to Streutker *et al*. (1981), upflow of the soil solution from saline water tables under field conditions on the Vaalharts Irrigation Scheme causes rapid salinisation of soil layers above the water table in the capillary zone, where leaching is restricted. Ehlers *et al.* (2003) gave Equation 4.1 for the relationship between the height of capillary rise above a water table, and the silt-plus-clay contents of different soils.

$$Z_a = -0.3463\,(S+C\%)^2 + 24.525\,(S+C\%) + 484.47 \tag{4.1}$$

where Z_a = height of capillary rise above a water table (mm)
$(S+C\%)$ = silt-plus-clay content of the soil (%)

Using the average silt-plus-clay contents of 8.25% and 16% for Soils A and B respectively, Equation 4.1 was used to calculate the top of the capillary fringe for both soils, as 536 mm and 412 mm from the soil surface for Soil A and B respectively.

Figures 4.5 to 4.8 present salt distribution profiles at the end of the growing season of wheat, beans, peas and maize for all the treatments of both soils. The depth of the water table (1200 mm) is indicated by a solid line, where the capillary fringe (Cap fringe) is indicated by a dashed line. All the figures indicate that salts accumulated at or just below the capillary fringe in both soils. This is also the zone where most of the water is taken up by plant roots, causing the concentration of ions to increase. The figures also indicate that in both soils, salt accumulated at a depth of around 700 mm from the soil surface, which is a little deeper than the calculated depth of the capillary fringe in both soils. This is caused by the leaching of salts with irrigation water, since irrigation scheduling is managed in such a way to refill only the 0 to 600 mm soil layers as explained in Chapter 3. The statement by Streutker *et al.* (1981) that upflow from a water table will transport soluble salts to the capillary fringe causing rapid salinisation of the soil layers above the water table is therefore verified.

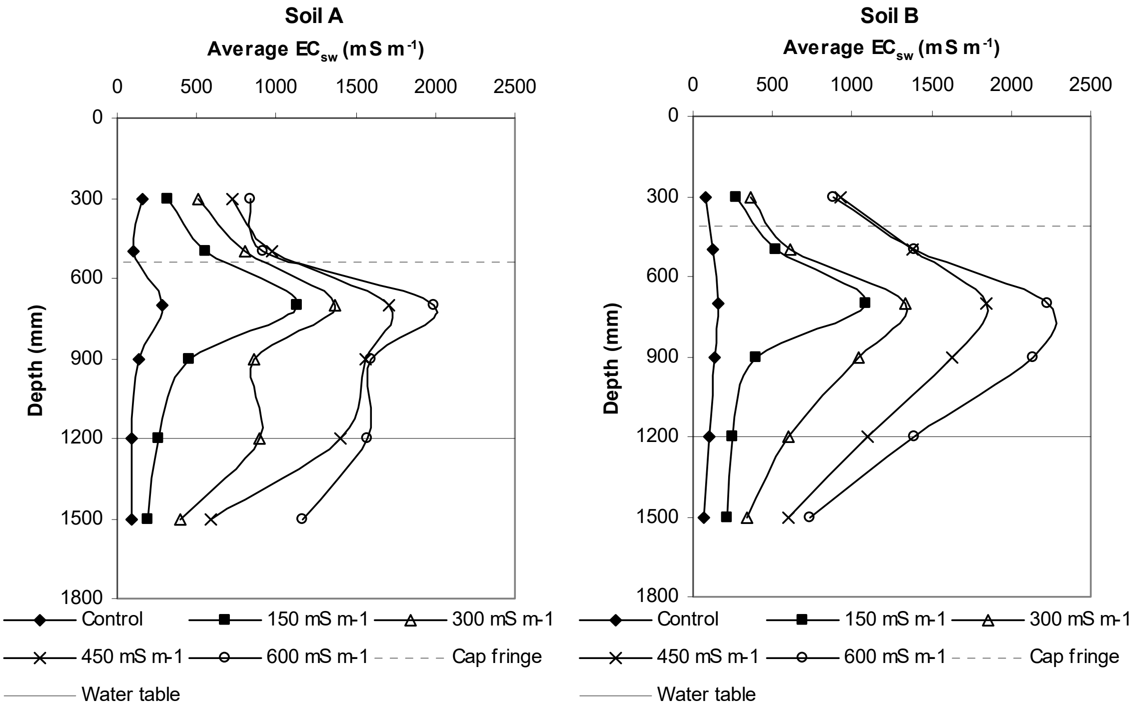


Figure 4.5 Salt distribution profiles (EC_{sw}, mS m^{-1}) at the end of the wheat growing season for all the EC_i treatments of Soil A and B.

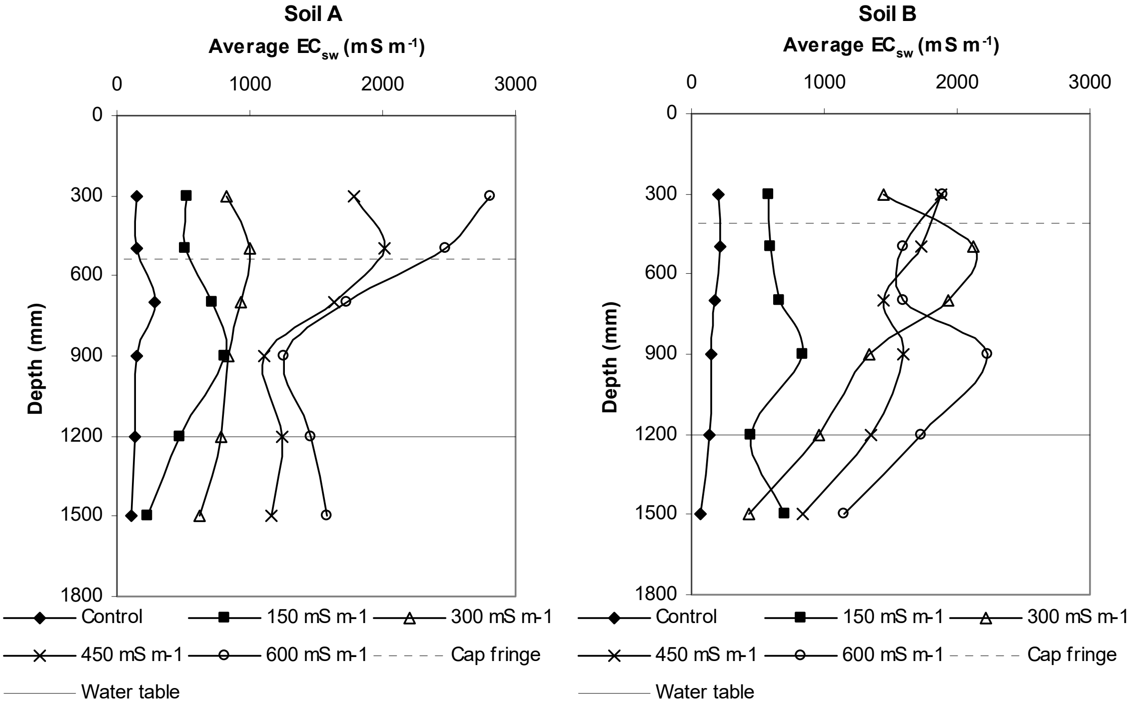


Figure 4.6 Salt distribution profiles (EC_{sw}, mS m^{-1}) at the end of the bean growing season for all the EC_i treatments of Soil A and B.

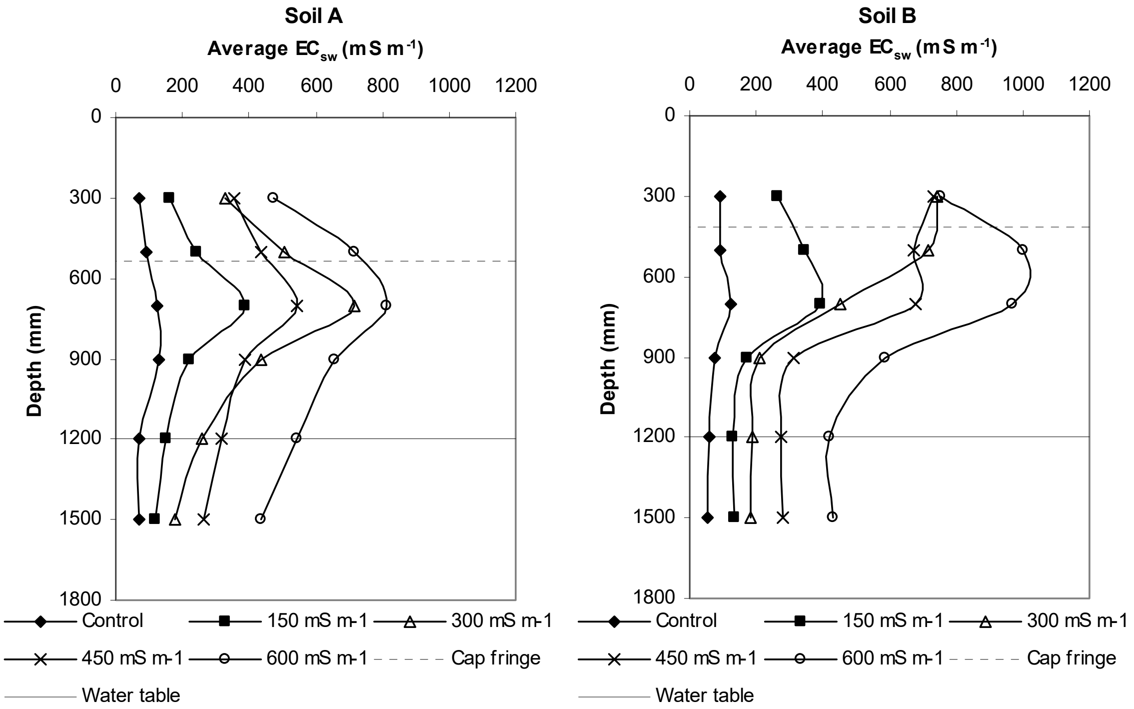


Figure 4.7 Salt distribution profiles (EC_{sw}, mS m^{-1}) at the end of the pea growing season for all the EC_i treatments of Soil A and B.

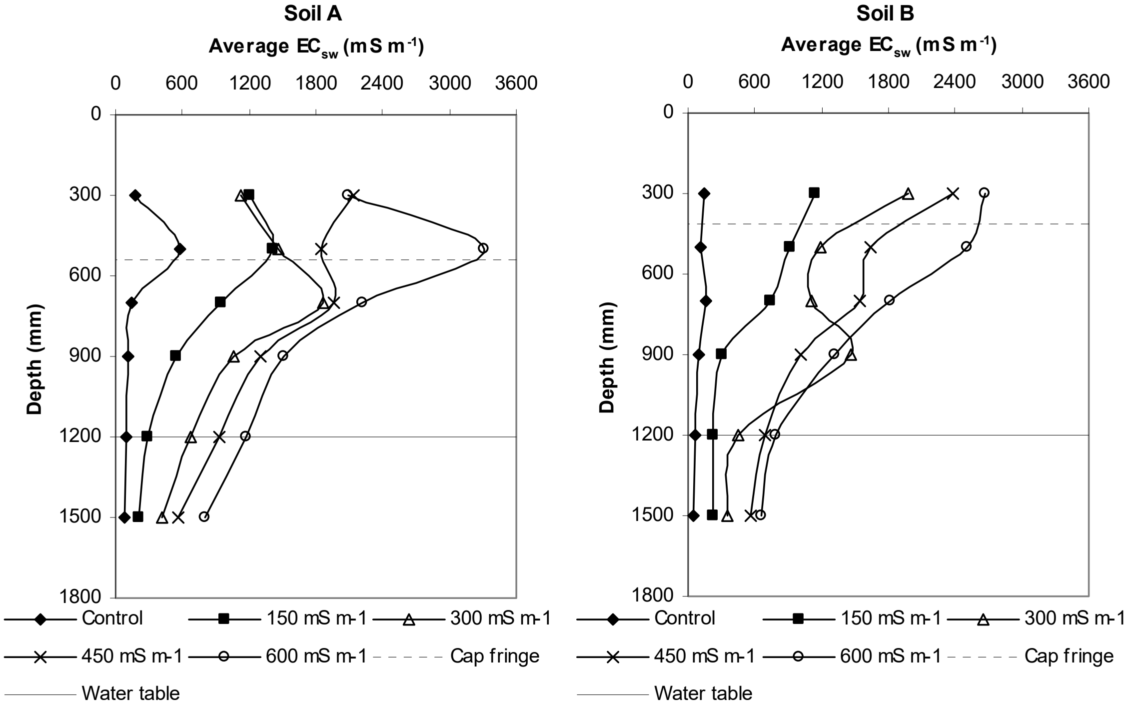


Figure 4.8 Salt distribution profiles (EC_{sw}, mS m^{-1}) at the end of the maize growing season for all the EC_i treatments of Soil A and B.

4.3.3 Verification of the conversion factor for electrical conductivity to total dissolved solids

Total dissolved solids (TDS, mg L^{-1}) were obtained by summation of the measured cations (Ca, Mg, Na and K) and anions (Cl and SO_4) in the soil water extracted with the suction cups for each layer. Since the TDS is directly proportional to the EC of water, the measured EC_{sw} can be converted to TDS_{sw} using a constant of 9.528 as proposed in Section 3.2.3. However, by regressing the EC_{sw} measured at the end of the growing season of each crop and the TDS_{sw} calculated, a constant of 7.568 was obtained (Figure 4.9). The same principle can be applied to convert the electrical conductivity of the irrigation water (EC_i) to total dissolved solids (TDS_i). Using the EC_i and TDS_i values as presented in Table 3.3, a constant of 7.831 was obtained, as shown in Figure 4.10.

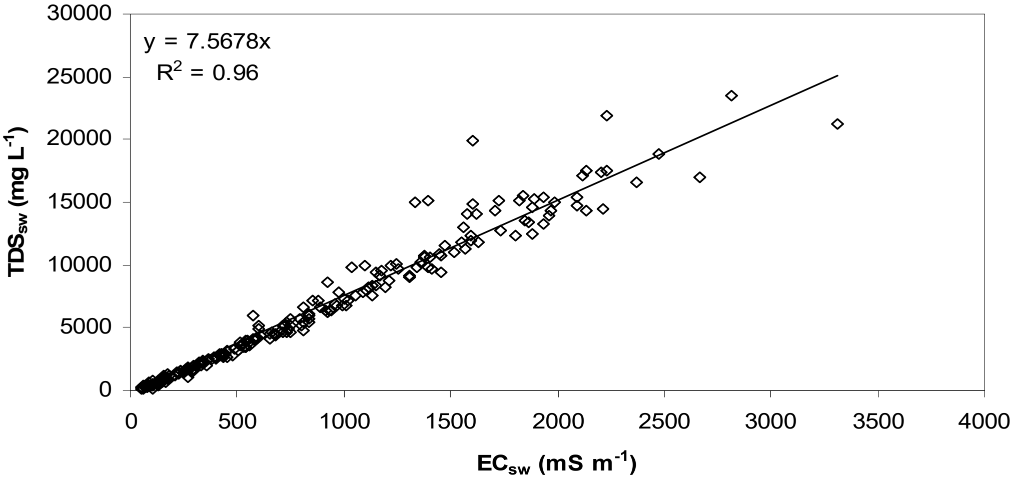


Figure 4.9 The relationship between the EC_{sw} and TDS_{sw} measured at the end of the growing season of all the crops, for both soils.

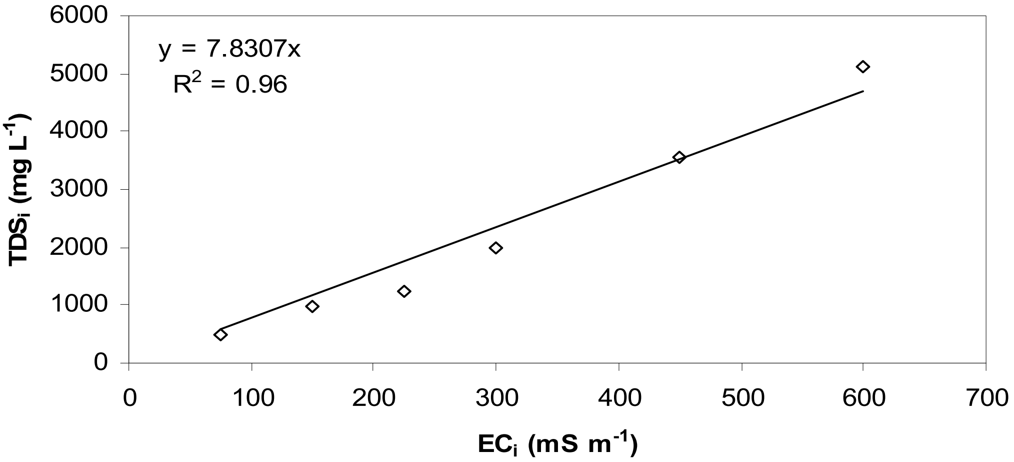


Figure 4.10 The relationship between the electrical conductivity of the irrigation water (EC_i) and the total dissolved solids (TDS_i).

4.3.4 Comparison between salt added through irrigation water and increase in soil salinity

The amount of salt added to the soil profiles, expressed in kg ha^{-1} through irrigation during the growing seasons, was calculated from the volume of irrigation water plus water table uptake (IRR + WT, L), multiplied by the corresponding TDS_i (mg L^{-1}) of the different treatments, for all the crops on both soils (Table 4.1). The increase in soil salinity (ΔEC_{sw}) was calculated as the difference between the mean EC_{sw} of the soil profile, at the beginning and end of the growing season of beans, peas and maize, whereas the EC_{sw} at the beginning of the wheat growing season was taken as identical to the EC_i of the different treatments. Figure 4.11 illustrates the relationship between the increase in the mean EC_{sw} over a depth of 1800 mm (Table 3.10) and the amount of salt added through irrigation. The relationship indicates that for every 1000 kg ha^{-1} of salt added through irrigation water, the mean EC_{sw} will increase with 37 mS m^{-1} over a depth of 1800 mm, for both soil types.

Table 4.1 The amount of salt added (kg ha^{-1}) as irrigation water (IRR) plus water table uptake (WT) and the increase in soil water salinity (EC_{sw}), over a depth of 1800 mm, for all the treatments and crops

Wheat						**Dry beans**					
Soil	**Treatment**	**IRR + WT (litre)**	**TDS (mg L^{-1})**	**Salt added (kg ha^{-1})**	**ΔEC_{sw}**	**Soil**	**Treatment**	**IRR + WT (litre)**	**TDS (mg L^{-1})**	**Salt added (kg ha^{-1})**	**ΔEC_{sw}**
A	Control	1422	198	1106	128	A	Control	1337	198	1040	16
	150	1410	988	5473	335		150	937	988	3637	59
	300	1528	2003	12026	506		300	737	2003	5799	29
	450	1397	3554	19506	708		450	448	3554	6252	333
	600	1478	5107	29667	746		600	441	5107	8849	543
B	Control	1513	198	1177	96	B	Control	1418	198	1104	32
	150	1579	988	6130	305		150	967	988	3752	107
	300	1546	2003	12168	414		300	764	2003	6016	397
	450	1456	3554	20338	795		450	481	3554	6717	275
	600	1375	5107	27582	860		600	474	5107	9516	241
Peas						**Maize**					
Soil	**Treatment**	**IRR + WT (litre)**	**TDS (mg L^{-1})**	**Salt added (kg ha^{-1})**	**ΔEC_{sw}**	**Soil**	**Treatment**	**IRR + WT (litre)**	**TDS (mg L^{-1})**	**Salt added (kg ha^{-1})**	**ΔEC_{sw}**
A	Control	1709	198	1330	38	A	Control	2010	288	2274	123
	75	1746	494	3390	40		150	1849	988	7180	560
	150	1567	988	6083	280		300	1494	2003	11757	732
	225	1411	1229	6814	132		450	1234	3554	17225	931
	300	1292	2003	10167	214		600	988	5107	19816	1159
B	Control	1734	198	1349	29	B	Control	1906	198	1483	31
	75	1750	494	3396	130		150	1924	988	7468	384
	150	1542	988	5985	156		300	1580	2003	12437	733
	225	1448	1229	6991	270		450	1283	3554	17922	783
	300	1162	2003	9143	311		600	1180	5107	23677	837

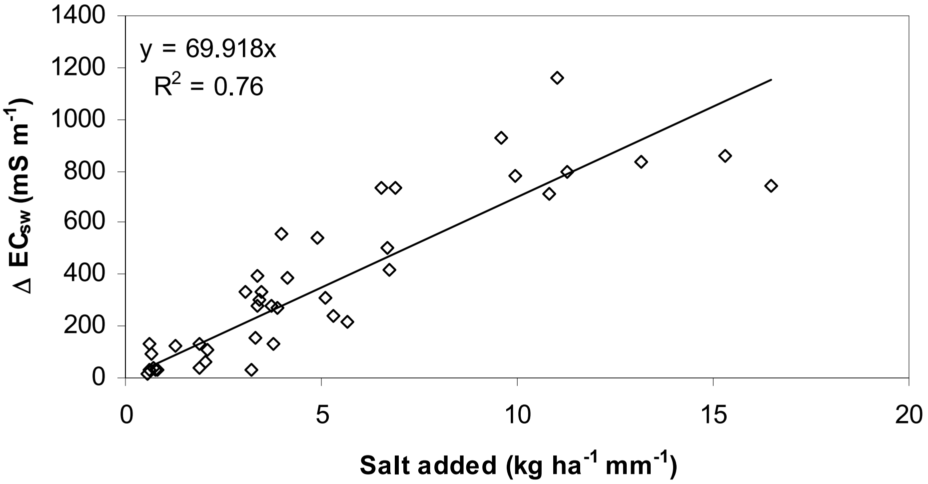


Figure 4.11 The relationship between the increase in soil water salinity and the amount of salts added through irrigation and water table uptake.

4.3.5 Prediction of salt accumulation in soils with restricted drainage

The relationships illustrated in the previous sections can be used to predict the accumulation of salts in the root zone of soils with restricted drainage. This is based on the assumption that all of the salts added through the irrigation water will accumulate in the root zone. Since it is easy and cheap to measure EC_i, the amount of salts dissolved in the water (TDS_i, mg L^{-1}) can be calculated for water of any given quality with approximately the same composition, by multiplying the EC_i with a constant of 7.831. The amount of salts added (kg ha^{-1}) through irrigation is equal to EC_i multiplied by the depth of the cumulative irrigation (mm) over a growing season times 0.0783. This value divided by the depth of root zone or soil to the restricting layer gives the salt accumulation per mm rooting depth, which can be multiplied by 69.918 (Figure 4.11) to obtain the estimated increase in the mean EC_{sw} of the root zone (Equation 4.1). In the previous chapter it was indicated that the relative decrease in yield for any given crop is related to an increase in EC_{sw}. The change in soil water salinity (ΔEC_{sw}, mS m^{-1} over 1800 mm) can be predicted after each irrigation cycle using Equation 4.2. The application of Equation 4.1 will be discussed in Chapter 5. Under saturated soil conditions it can be assumed that ΔEC_{sw} will be comparable to ΔEC_e. As mentioned, the EC_{sw} values in this study were determined in soil water extracted with ceramic cups from the soil. However, significant amounts could only be extracted after the soil in the lysimeters were saturated. It can therefore be assumed that the EC_e values reported by Dikgwatlhe (2006) would be comparable with the EC_{sw} values.

$$\Delta EC_{sw} = [(EC_i \times \text{Cum IR} \times 0.0783)/z] \times 69.918 \qquad (4.2)$$

where ΔEC_{sw} = increase in the mean EC_{sw} of the root zone per mm depth
EC_i = Electrical conductivity of the irrigation water (mS m^{-1})
Cum IR = Cumulative irrigation (mm)

z = Soil depth to restriction (mm)

4.4 Conclusions

Irrigation with saline water on soils with restricted drainage, results in the added salts accumulating in the root zone. The salinity level of the irrigation water determines the long term rate of salt accumulation and distribution in a soil profile. Where a shallow water table is present, in or below the root zone, most of the salt accumulation occurred within the approximately 700 mm thick capillary zone, just above the water table level.

During the growing season of a crop the electrical conductivity of the soil water (EC_{sw}) in the capillary zone can increase to values several fold higher than the EC_i of the irrigation water. The amount of salts that will accumulate in root zones with restricted drainage can be predicted for any known quality and quantity of irrigation water by using Equation 4.1. This allows for the prediction of the decline in yield of different crops (Section 3.3.4.2).

CHAPTER 5

PROCEDURES FOR MANAGING ROOT ZONE SALINITY

5.1 Introduction

Long-term sustainable crop production under irrigation requires periodic information on soil salinity and the distribution of salts within the root zone. The salinity of the root zone should be managed in such a way that it is kept below levels that are harmful to the cultivated crops. It is also important to select crops with higher salt tolerance than the salinity of the root zone. The salinity of root zones generally increases with depth and with drying of the soil at a specific depth.

The change in salt concentration in the root zone depends on the direction of the nett salt flux. Within freely drained root zones, the salinity level will be a function of the irrigation water salinity, and the amount with which irrigation and rainfall exceeds water uptake. The root zone salinity will decline when more salts are removed through drainage below the deepest roots than the amount of salts added through irrigation during a growing season.

Drainage of root zones can be restricted, due to the presence of a water table within or just below the deepest roots, or a soil layer impeding the downward flux of salts. Under these conditions, salinity of the root zone will gradually increase, depending on the amount of salts added through irrigation or sub-surface lateral influx from higher lying soils. When the root zone salinity under these conditions exceeds the salinity threshold value of the cultivated crops, artificial drainage of the soil becomes essential. Temporary alleviation of yield losses can be achieved by using high frequency irrigation, which keeps the upper part of the root zone at or near the upper limit of plant available water.

Complex dynamic models have been developed for simulating the movement and reactions of salts in soils during leaching. Reference to some of these models has been made by Ehlers *et al*. (2007). Without digressing into detail, it can be stated that predictions based on these transport theory models, for purposes of estimating the required amounts of leaching to manage root zone salinity, are not widely used. Estimates are usually based on guidelines established from empirical relationships derived from field experiments and experience (Herald, 1999).

It was the objective of this chapter to formulate procedures, based on the results discussed in Chapters 3 and 4, which can be used to manage the salinity of root zones under different conditions.

5.2 Essential information required for managing root zone salinity

The information required to make the necessary calculations and decisions for the purpose of managing the salinity of root zones, will be discussed in this section.

5.2.1 Potential depth of the rooting zone

The soil or rooting depth is used in calculating the increase in soil salinity during the growing season (Equation 4.1). In Table 5.1 the maximum potential rooting depth of some crops is given. The depth of the soil from the surface to, if present, a layer that will impede root growth or water movement, should be measured. If the soil is deeper than the potential rooting depth, the depth of the soil is set equal to the rooting depth. If the soil is shallower than the rooting depth the rooting depth is set equal to the soil depth.

5.2.2 Internal drainage of the root zone

Different salinity management procedures should be followed for root zones from which excess water can drain freely, or where drainage from the root zone is restricted. When there is no restriction on the drainage of excess water from the root zone, freely drained conditions will prevail. When an impeding layer is present, in or just below the potential rooting depth, resulting in water-logging and the formation of a shallow water table, restricted drainage conditions will prevail.

5.2.3 Initial root zone salinity

The salinity of the soil (EC_{sw}, mS m^{-1}), averaged over the potential rooting depth, is required for comparison with the crop tolerance in order to calculate the expected decline in yield (Equation 3.2) and for calculating the expected soil salinity for the next cropping season (Equation 4.1). Soil salinity can be determined from periodic measurements made: a) on extracts of soil samples; b) on soil water samples collected with porous cup vacuum extractors; c) in soil, using porous salinity sensors which equilibrate with the soil water; d) in soil, using four electrode probes, or e) remotely by electromagnetic induction techniques (Rhoades & Loveday, 1990). Lately wetting front detectors are also being used to collect soil water samples for salinity determinations.

The most convenient measurement of soil salinity relates to the determination of the electrical conductivity of water extracted from saturated soil (EC_e, mS m^{-1}). The salinity of irrigated soils is normally low near the surface and increases with depth. It is essential that representative soil samples should be taken at different depths over the whole rooting depth and mixed thoroughly, before EC_e is determined. A distinction is made in literature between the electrical conductivity of the soil water extracted in the laboratory from a disturbed soil sample (EC_e) and, on water extracted *in situ* from undisturbed soil with porous suction cups (EC_{sw}). For practical purposes it will be assumed, in this discussion, that the conversion of EC_e to EC_{sw} and *vice versa* is available.

5.2.4 Irrigation water salinity

The salinity level and amount of irrigation water applied, determines the quantity of salts added to the root zone. The increase in the salinity of the root zone, over a growing season, can be calculated with Equation 4.1. The electrical conductivity of the irrigation water (EC_i, mS m^{-1}) is also needed to calculate the amount of drainage required (D_w, mm) to leach a specific amount of salts from the root zone.

5.2.5 Crop salt tolerance

An acceptable way to manage root zone salinity is to change to more salt tolerant crops. When the mean root zone salinity exceeds the threshold salinity of a crop, biomass production will decline proportionally to the excess salinity (Equation 3.2). The parameters used in Equation 3.2 for calculating the expected decline in yield, are given in Table 5.1. The ideal situation is to keep the mean electrical conductivity of the root zone (EC_{sw}) below the threshold electrical conductivity of the crop ($EC_{threshold}$).

5.2.6 Crop water demand (CWD, mm)

This is the amount of water that is needed over the growing season of a crop to meet the required transpiration of the crop plus evaporation from the soil surface for a specific target yield. When irrigation plus rainfall equals the CWD, no salts will be leached from the root zone. To make provision for the leaching of salts from the root zone, more water than the CWD should be applied. The amount of water needed to wet the root zone to the upper limit of plant available water should be added to the CWD before any leaching takes place. The most accurate way to calculate the seasonal crop water demand is by using computer programs and models, for example SWB (Annandale *et al.,* 1999), BEWAB (Bennie *et al.,* 1988), SWAMP (Bennie *et al.,* 1998) and SAPWAT (Van Heerden *et al*., 2001). As an alternative, the maximum CWD for different crops is presented in Table 5.1.

Table 5.1 Salt tolerance of different crops (after Rhoades & Loveday, 1990 and this study) and other relevant information

Crop	Botanical name	Threshold-value for Eq 3.2 (EC$_{sw,}$ mS m^{-1})	b-value for Eq 3.2	Maximum rooting depth (mm)	Maximum biomass (kg ha^{-1})	Harvest index	β-value for Eq 3.3	Maximum crop water demand (mm)	Water table contribution with Eq 5.3 & 5.4		
									CF	TWT	SWT
Bean (dry)	*Phaseolus vulgaris*	100	-0.0009	1500	12860	0.35	1.35	620	0.00016	100	0.0015
Cotton	*Gossypium hirsutum*	770	-0.00052	2000	18600	0.35	1.35	1200	0.00031	700	0.0005
Maize	*Zea mays*	350	-0.00073	2200	25300	0.45	1.4	958	0.00043	350	0.0004
Onion	*Allium cepa*	120	-0.0016	800	78000 *	0.9	1.20	800	0	100	0.0015
Pea (dry)	*Pisum sativum*	105	-0.00096	1500	8400	0.40	1.25	618	0.00025	100	0.0010
Peanut	*Arachis hypogaea*	320	-0.0029	2000	14450	0.30	1.37	818	0.00034	300	0.0012
Potato	*Solanum tuberosum*	170	-0.0012	1800	62400 *	0.9	1.52	858	0	170	0.0015
Soybean	*Glycine max*	500	-0.0020	1800	14280	0.35	1.40	845	0.00034	350	0.0015
Sorghum	*Sorghum bicolor*	680	-0.0016	2000	17150	0.35	1.45	636	0.00037	500	0.0005
Sunflower	*Helianthus annuus*	-	-	1800	8500	0.45	1.40	638	0.00037	-	-
Wheat	*Triticum aestivum*	600	-0.0007	2000	14000	0.40	1.26	684	0.00045	400	0.0003

* Fresh mass

5.2.7 Drainage requirement for salt leaching (D_w, mm)

Excess salts, can be leached from freely drained root zones, by wetting the profile above the drained upper limit. According to Barnard (2006), the amount of drainage water needed to reduce the mean EC_{sw} of the root zone to a specified level can be calculated with Equation 5.1:

$$D_w = [(\ln(1 - y)) / b]\, D_s \qquad (5.1)$$

Where y = $1 - (EC_{sw}\text{ actual} - EC_i) / (EC_{sw}\text{ initial} - EC_i)$
EC_{sw} actual = target soil water salinity (mS m^{-1})
b = coefficient dependent on soil type (Equation 5.2)
D_s = depth of the soil (mm)

Barnard (2006) also determined the b-coefficient in Equation 5.1 for both soils. As a first approximation however, the value of the b-coefficient can be estimated from the mean coarse silt-plus-clay percentage (% S+C) of the root zone, using Equation 5.2:

$$b = 0.2673\,(\%\ S+C) - 12.346 \qquad (5.2)$$

5.2.8 Maximum biomass yield and harvest index

The actual ET at a specific target yield can be calculated with a water production function for non-saline conditions (Equation 3.3). The parameters required in Equation 3.3 are presented in Table 5.1. The actual ET for non-saline conditions, multiplied by the relative biomass yield (Y_r) calculated with Equation 3.2, gives the actual ET at a specific mean EC_{sw} for the root zone.

5.2.9 Water table contribution

The capillary rise of water into the root zone from saturated soil to just below or to the lower part of the root zone, can be deducted from the CWD to give a lower irrigation requirement (IR, mm). Less additional salts are added to the root zone in this way. It was reported in Section 3.3.3, that the uptake of the crops from non-saline water tables remained constant with an increase in salinity, until the threshold EC_{sw}-value of the crop is reached. An increase in salinity above the threshold electrical conductivity resulted in a linear decline in the uptake from the water table.

For water tables with an EC_{sw} less than the threshold EC_{sw} of the cultivated crop, the water table uptake can be simulated with SWB or SWAMP. Both of these models were verified by Bennie *et al*. (1998). Bennie et al. (1998) also developed an empirical equation (Equation 5.3) under similar but non-saline conditions.

$$MWT = 0.1 + CF\,(2000 - WTD) + 0.004\,(\%\,S{+}C) \tag{5.3}$$

where MWT = water table uptake under non-saline conditions, expressed as a fraction of the seasonal CWD, taken as 1.

CF = crop type dependent correction factor, see Table 5.1.

WTD = depth to the top of the water table (mm), maximum 2000 mm.

% S+C = percentage soil particles <0.05 mm.

For water tables with an EC_{sw} larger than the threshold EC_{sw} of the cultivated crop, Equation 5.3 can be adapted to predict the water table contribution under non-saline conditions is decreased, using Equation 5.4.

$$WTC = MWT \times [1 - ((EC_{sw} - TWT) \times SWT)] \tag{5.4}$$

where WTC = water table uptake under saline conditions, expressed as a fraction of the seasonal CWD, taken as 1.

EC_{sw} = electrical conductivity of the capillary zone above the water table (mS m^{-1}).

TWT = threshold salinity of the crop (Table 5.1).

SWT = crop type dependent reduction factor for the salinity above the threshold value (Table 5.1).

MWT = fractional water table uptake under non-saline conditions, simulated with SWB or SWAMP, or estimated with Equation 5.3.

5.2.10 Effective rainfall (R_{eff})

Within freely drained root zones, as mentioned previously, the salinity level will be a function of the irrigation water salinity, and the amount with which irrigation plus rainfall exceeds water uptake. If the amount of rainfall during the growing season of a specific crop is not subtracted from the CWD for irrigation scheduling purposes, salts can be leached from the root zone. The amount of salts removed will be a function of the amount of rainfall that exceeds the CWD.

However, during periods of excessive rainfall under conditions with restricted drainage, shallow water tables can rise and cause soils to become waterlogged. Salts from saline water tables will move through capillary upflow into the root zone and cause a severe salinity hazard to crops. It is therefore important to take excessive rainfall into account in irrigation scheduling under these conditions.

R_{eff} is the amount of rainfall that contributes significantly towards the water balance. R_{eff} is obtained by subtracting the amount that evaporates as well as the amount that is captured by the crop canopy from the actual rainfall event. See Section 6.2.2 for a more detail description of the procedure.

5.3 Root zone salinity management options

The proposed stepwise procedures for managing the salinity level of a root zone, are determined by the internal drainage and intrinsic salinity status of the root zone, as well as the availability of excess irrigation water. The diagram in Figure 5.1 can be used to select a relevant root zone salinity management procedure.

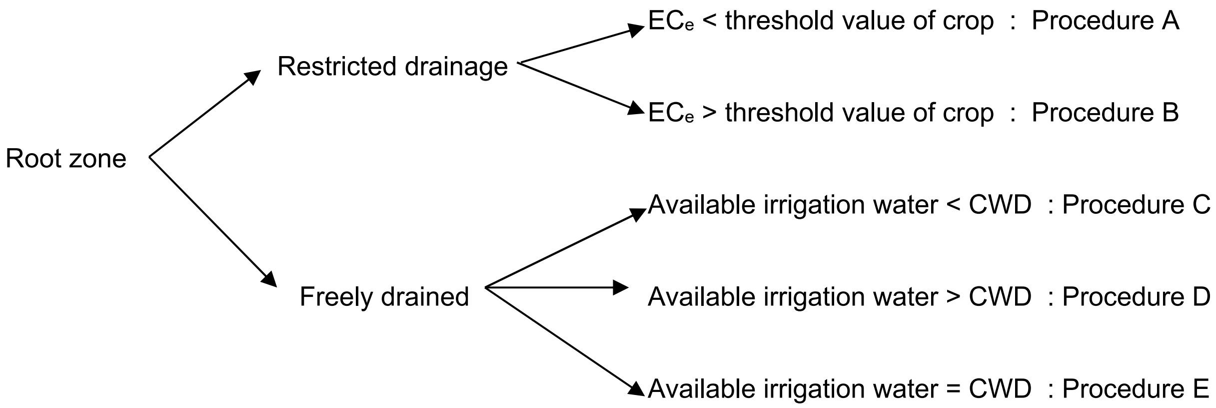


Figure 5.1 Diagram for selecting the appropriate salinity management procedure for a root zone (EC_e = mean EC_{sw} of the root zone).

5.4 Description of the different root zone salinity management procedures

The appropriate procedure can be selected from Figure 5.1.

Procedure A: This procedure represents conditions, where salts that are added to the root zone, accumulate without any possibility for leaching. The mean salinity of the root zone is lower than the threshold value for the irrigated crop. Under these conditions the following steps could be followed:

Step 1 - Determine the seasonal CWD (mm) for a target yield.

Step 2 - If a shallow water table is present, determine or calculate the water table contribution (MWT, mm) with Equation 5.3.

Step 3 - Calculate the irrigation requirement (IR, mm) as IR = CWD – MWT – R_{eff}.

Step 4 - Calculate the increase in root zone salinity (ΔEC_{sw}), over the growing season, with Equation 4.1.

Step 5 - Calculate the initial salinity for the next season: Initial EC_e next season = Initial EC_e this season + ΔEC_{sw} this season.

Step 6 - Calculate the drainage requirement (D_w, mm) with Equations 5.1 and 5.2., when leaching becomes essential for the design of the drainage system.

Step 7 - Compare the initial EC_e for the next season with the EC_e threshold of the crop to be planted. If EC_e next season < EC_e threshold, the procedure can be repeated from Step 1 for the following season. If EC_e next season > EC_e threshold, the soil should be drained or Procedure B should be followed.

Procedure B: This procedure also represents conditions, where salts that are added to the root zone through irrigation, accumulate without any leaching. The mean salinity of the root zone, however, is higher than the threshold value for the cultivated crop. Irrigation should be reduced to compensate for the expected decline in crop growth and yield. The following steps should be followed:

Step 1 - Calculate the expected relative grain yield (Y_r) with Equation 3.2 (Data from Table 5.1)

Step 2 - Determine the CWD at the target yield for non-saline conditions.

Step 3 - Calculate the water table contribution (WTC, mm) with Equation 5.4.

Step 4 - Calculate the irrigation requirement, at the adapted yield which is = target yield x Y_r, for the season IR = (CWD x Y_r) – WTC – $R_{eff.}$

Step 5 - Calculate the increase in root zone salinity (ΔEC_{sw}) over the growing season, using Equation 4.1.

Step 6 - Calculate the drainage requirement (D_w, mm) with Equations 5.1 and 5.2. Determine the required drainage rate (D_{wreq}, mm day^{-1}) for the purpose of drainage design when it becomes necessary.

Step 7 - Calculate the initial salinity for the next season: Initial EC_e next season = Initial EC_e this season + ΔEC_{sw} this season.

Step 8 - Repeat from Step 1 for the following season. Consider selecting more salt tolerant crops or artificial drainage because the yield will decline with every season.

Procedure C: This represents conditions where added salts can be removed from the root zone through natural leaching processes, but with not enough available irrigation water to supply in the CWD. The mean root zone salinity is less than the threshold value of the cultivated crops. The objective for this procedure is to irrigate according to the CWD minus R_{eff} during the growing season, in order to minimize the amount of applied salts. It is assumed that the leaching of salts from the root zone, during periods of high rainfall, will be sufficient to keep the root zone salinity within acceptable limits. The following steps can be followed:

Step 1 - Determine the seasonal CWD for the target yield.

Step 2 - Irrigate according to the target yield where IR = CWD – R_{eff}.

Step 3 - Calculate the increase in root zone salinity (ΔEC_{sw}) over the growing season, using Equation 4.1.

Step 4 - Calculate the drainage requirement (D_w, mm) with Equations 5.1 and 5.2. Determine the required drainage rate (D_{wreq}, mm day^{-1}).

Step 5 - If EC_e < EC_e threshold of the most salt sensitive cultivated crop, continue with Procedure C.

Step 6 - If $EC_e \geq EC_e$ threshold of the most salt sensitive crop cultivated, calculate the irrigation requirement at the adapted yield (target yield x Y_r) and continue with Procedure C. If there is a sufficient amount of additional irrigation water available for leaching, change to Procedure D.

Procedure D: The conditions for this procedure come into play where the accumulation of salts, in a freely drained root zone, exceeds removal by leaching to the extent that crop production is hampered. Under these conditions the natural leaching of salts should be accelerated, by irrigating more than the required CWD because sufficient irrigation water is available. The additional irrigation must be sufficient to leach the excess salts from the root zone. This can be done in two phases, by first reducing the salinity level to the threshold value of salt tolerant cultivated crops, and thereafter to the salinity level of the desired salt sensitive crop. The following steps can be followed:

Step 1 - Determine the CWD for a target yield.
Step 2 - Calculate the drainage requirement (D_w, mm) with Equations 5.1 and 5.2. In Equation 5.1 set EC_e initial equal to EC_e threshold for the most salinity sensitive cultivated crop.
Step 3 - Determine the amount of irrigation required to wet the root zone to the upper limit of plant available water (mm).
Step 4 - Calculate the seasonal irrigation requirement (IR, mm) where: $IR = CWD + D_w - R_{eff}$ + irrigation required to wet the root zone.
Step 5 - Calculate the salt added during the growing season (ΔEC_{sw}) with Equation 4.1.
Step 6 - For the following seasons, repeat the procedure from Step 1, but in Step 2 in Equation 5.1, set EC_e actual = EC_e of crop to be irrigated and EC_e initial = $EC_i + \Delta EC_{sw}$, calculated in Step 5.

Procedure E: This represents conditions where added salts can be removed from the root zone through natural leaching processes, since the available irrigation water is just enough to supply the CWD. The mean root zone salinity is less than the threshold value of the cultivated crops. The objective with this procedure is to irrigate according to the CWD during the growing season, in order to utilize R_{eff} during periods of high rainfall for leaching. It is assumed that R_{eff} will be sufficient to keep the root zone salinity within acceptable limits. The following steps can be followed:

Step 1 - Determine the seasonal CWD for the target yield.
Step 2 - Irrigate according to the target yield where IR = CWD
Step 3 - Calculate the drainage requirement (D_w, mm) with Equations 5.1 and 5.2. Determine the required drainage rate (D_{wreq}, mm day^{-1}).
Step 4 - Calculate the increase in root zone salinity (ΔEC_{sw}) over the growing season, using Equation 4.1. If $R_{eff} > D_w$ it is assumed that all the salts will be leached from the root zone and EC_e next season = EC_e initial. If $R_{eff} < D_w$ then the increase in root zone salinity (ΔEC_{sw}) will be determined by $D_w - R_{eff}$.

Step 5 - Take representative soil samples of the root zone, at least every 5 years, for determination of EC_e to decide on continuation of this procedure or change to another.

Step 6 - If $EC_e < EC_e$ threshold of the most salinity sensitive cultivated crop, continue with Procedure E. If $EC_e \geq EC_e$ threshold of the most salt sensitive crop cultivated, implement a fallow period to leach excess salts from the root zone.

5.5 Conclusions

Effective management of salt accumulation in soils with restricted drainage, can only be done when good quality irrigation water with an $EC_i < 50$ mS m^{-1} is used. With more saline irrigation water the rapid salinization of the root zone is difficult to manage without artificial drainage. The use of irrigation water with an $EC_i > 150$ mS m^{-1} under these conditions, can raise the salinity of the root zone above the threshold value of salt sensitive crops, within one season. The proposed procedures A and B that were discussed, are aimed at alleviating the impact of salinity on crop growth, rather than solving or controlling the problem. A permanent solution to the problem will be to install artificial drainage. When sufficient land is available, the irrigation can be rotated between several fields, to allow for dilution of the root zone salinity by rainfall.

On freely drained soils it is possible to effectively manage the salinity level of the root zone, through controlled over-irrigation, when necessary. When good quality irrigation water with an $EC_i < 50$ mS m^{-1} is used, it will take several years before the increase in root zone salinity will require additional leaching. Irrigating with poorer quality water will necessitate the inclusion of a leaching fraction in the irrigation requirements of crops, after a few seasons. It is absolutely essential to monitor root zone salinity by regular soil sampling. Following procedures C or D, to manage the salinity level of the root zone, should sustain the root zone salinity within acceptable limits.

Simulating the above-mentioned procedures under various scenarios will be the objective of the next chapter.

CHAPTER 6

COMPARISON OF THE PROPOSED SALINITY MANAGEMENT PROCEDURES AS INFLUENCED BY IRRIGATION WATER QUALITY

6.1 Introduction

Many researchers emphasized the need for the application of appropriate practices that prevent the development of excessive salinisation in irrigated land (Rhoades and Loveday, 1990). The best means of managing and controlling soil and water salinity is through efficient irrigation scheduling, combined with adequate but minimum leaching and drainage. According to Le Roux et al. (2007) majority of the soils along the Lower Vaal River in central South Africa can accommodate a small leaching factor without water logging and improved management can therefore control soil salinity. However, the management procedures need not necessarily be aimed at controlling salinity at the lowest possible level, but rather to keep it within limits commensurate with sustained productivity. Crop, soil and irrigation practices can be modified to achieve these limits, but it is important to maintain a check on the efficacy of the control practices with a system of monitoring soil salinity and drainage adequacy.

Procedures for managing root zone salinity as influenced by internal drainage and the intrinsic salinity status of the root zone were discussed in Chapter 5. It is the objective of this chapter to compare the different salinity management procedures, simulated for a range of irrigation water qualities and long-term climatic conditions, on two soil types. The addition of salts through irrigation water is regarded as the single most important contributor to soil salinization (Hoffman, 1990) and therefore salts added to the soil as fertilizer and soil amendments was excluded from the simulations. By simulating the proposed procedures it enables us to compare a number of processes and may indicate how to modify these processes in order to optimise the procedures for sustained management.

6.2 Inputs and assumptions used in the simulations

All the simulations were done in Microsoft Excel. The following inputs were used and assumptions were made in the simulation studies:

6.2.1 Crops and seasonal crop water demand (CWD, mm)

A crop rotation with wheat (*Triticum aestivum*) in the winter and maize (*Zea mays*) in the summer was used in all the simulations. The planting dates were taken as the 15th of June with a growing period of 156 days to physiologically maturity for wheat and the 10th of December with a growing period of 131 days to physiologically maturity for maize. The target yields were taken as 7500 kg ha^{-1} and 12000 kg ha^{-1} for wheat and maize respectively. The CWD for each crop was determined with BEWAB (Bennie *et al*., 1988), using the full irrigation option where the complete crop water demand is irrigated during the growing season. By using this option, it is assumed that the soil profile is at field capacity after harvesting the previous crop and will still be wet upon planting the following crop. Other relevant information regarding both crops is presented in Table 5.1.

6.2.2 Rainfall

A complete weather data set, starting from the 1st of January 1950, for the Glen Agricultural Institution near Bloemfontein was obtained from the ARC-ISCW. The cumulative amount of effective rainfall (R_{eff}, mm) during each growing season was calculated by subtracting the cumulative evaporation following each rainfall event from the measured amount of rainfall, as proposed by Bennie *et al*. (1998). Rainfall events were separated by dry periods without rainfall exceeding 10 days. The sum of the rain showers within rainfall events was used to obtain the amount of rainfall for each event. The effective rainfall, that infiltrated deeper than the zone of active evaporation, was calculated by subtracting an amount of 10 mm from each rainfall event. The amount of 10 mm was the same for both soils since the silt plus clay content in the topsoil of both soils is practically the same. When the measured amount of rainfall during a rainfall event was less than 10 mm, the R_{eff} was taken as zero. In practise the period between harvesting of a crop and planting of the next crop is usually very short and therefore the amount of rainfall between two growing seasons was excluded from the simulations. A summary of the weather data set is presented in Appendix 6.1.

6.2.3 Soil conditions

The potential rooting depths of both soils were taken as 1800 mm, with a mean silt plus clay content of 8% for Soil A and 16% for Soil B (Section 4.3.2). For the restricted drainage options, drainage was taken as zero and the depth to the water table was taken as 1500 mm from the soil surface. The initial root zone salinity measured as electrical conductivity, was taken as 20 mS m^{-1} for both soils.

6.2.4 Irrigation water salinity

Du Preez *et al*. (2000) reported present and future trends in the electrical conductivity of the waters from the Vaal, Riet and Harts Rivers. Based on these trends, irrigation water salinities of 25, 50 and 100 mS m^{-1} were used in the simulations.

6.3 Simulation procedures

The procedures as proposed in Section 5.4 were used as basis to simulate the expected change in soil salinity over a period of 50 years (1950-2000) using the mentioned assumptions and conditions. The simulations were conducted on both soils for restricted and freely drained conditions with three levels of irrigation water salinity.

6.3.1 Root zone with restricted drainage

The simulations, using Procedure A, were started on the 15th of June 1950 (Season 1) with wheat. The mean salinity of the root zone was taken as 20 mS m^{-1} for both soils, which is lower than the threshold value for wheat. Salts are added through irrigation water and allowed to accumulate without leaching. The simulation was repeated for Season 2 using maize and continued on a rotational basis for the following seasons. Procedure A was applied until the mean salinity in the root zone reached the EC_e-threshold value of maize after which Procedure B was used in the simulation. The irrigation requirement (IR, mm) was reduced to correspond with the expected decline in CWD and crop yield. Procedure B was applied until a 50% decline in wheat yield was reached.

6.3.2 Root zone freely drained

Procedure C was used to simulate conditions where there is not enough irrigation water available to supply in the total CWD. The simulations also started at Season 1 with wheat with a mean root zone salinity of 20 mS m^{-1} and continued until the mean salinity in the root zone was higher than the threshold value of the most sensitive crop (maize) after which the irrigation requirements were reduced in accordance with the expected decline in CWD and crop yield. The simulation continued until a 50% decline in the wheat yield was reached.

Simulations with Procedure D assumed conditions where an excess amount of irrigation water is available for artificial leaching of soil profiles. Simulations started at Season 1 using Procedure C until the mean salinity of the root zone exceeded the threshold value of the maize crop, from where on Procedure D was used. The reason for starting with Procedure C is to illustrate the effect of D_w on leaching of excess salts from the root zone. Simulations continued until Season 100 (50 years).

Simulations with Procedure E assumed conditions where the mean soil salinity of the root zone started at 20 mS m^{-1} and enough irrigation water was available to supply in the total CWD. Rainfall during the growing season of the different crops is expected to leach excess salts from the root zone. It was assumed that when the cumulative amount of R_{eff} exceeded D_w all excess salts would be leached out of the root zone. Simulations started at Season 1 and continued until the mean salinity of the root zone exceeded the threshold value of the maize crop after which the irrigation requirement was reduced according to the expected decline in CWD and crop yield. Simulations continued until a 50% decline in the yields of wheat was reached.

6.4 Results and discussion

6.4.1 Root zone with restricted drainage

The simulation results of the proposed procedures under conditions of restricted drainage are presented in Appendices 6.2 to 6.4 for the different irrigation water salinities.

i) 25 mS m^{-1}

Figure 6.1 presents the change in the mean soil salinity over a period of 85 seasons for both soils, using irrigation water with a salinity of 25 mS m^{-1}. From the simulation results it is evident that the EC_e-threshold salinity for maize (350 mS m^{-1}) is reached at the end of Season 15 on Soil A (355 mS m^{-1}) and at the end of Season 17 on Soil B (371 mS m^{-1}). At this point the required drainage rate was in the order of 3 mm day^{-1} in Soil A and 4 mm day^{-1} in Soil B (Appendix 6.2). The EC_e-threshold value for wheat (600 mS m^{-1}) was reached at the end of Season 27 for Soil A and at the end of Season 28 for Soil B. Procedure B was followed from Season 16 onwards for both soils.

A 50% decline in yield of the more salinity sensitive maize crop was reached at the end of Season 51 on Soil A and at the end of Season 53 on Soil B. The average soil salinity at this point was 1029 mS m^{-1} in both soils (Figure 6.1). For wheat, a 50% decline in yield was reached at the end of Season 82 on Soil A and at the end of Season 84 on Soil B. At this point in time the average root zone salinity was 1316 mS m^{-1} (Figure 6.1). The rapid decline in crop yield is a clear indication of the rapid increase in root zone salinity (Appendix 6.2). It is interesting to note that, by reducing irrigation in order to compensate for the expected decline in crop yield, the irrigation requirement decreased rapidly especially during seasons of above average rainfall (Appendix 6.2). During Season 34 for example, the 487 mm of effective rainfall exceeded the CWD of maize on both soils. In this case no salts were added through irrigation water resulting in a zero increase in root zone salinity and therefore complementing the proposed procedures.

ii) 50 mS m^{-1}

Figure 6.2 presents the change in the mean root zone salinity of both soils over a period of 40 seasons. From the results it is alarming that by using irrigation water with a salinity of 50 mS m^{-1} the root zone salinity increased very rapidly over time. The EC_e-threshold salinities were reached at the end of Season 7 and Season 14 for maize and wheat respectively with a required drainage rate of 3 mm day^{-1} on both soils (Appendix 6.3). Procedure B was followed from Season 8 onwards.

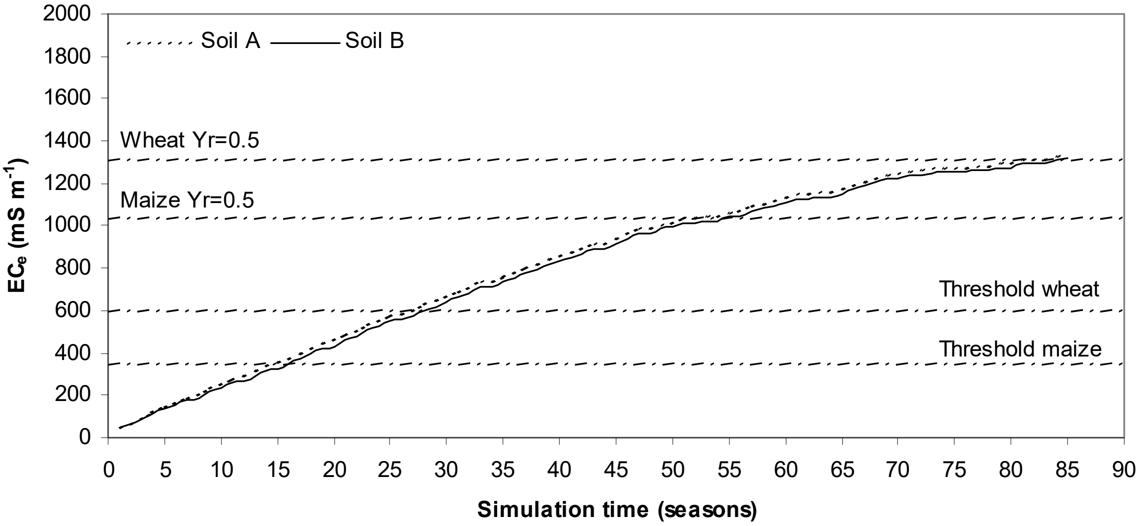


Figure 6.1 The change in average root zone salinity (EC_e, mS m^{-1}) of both soils when managed with Procedure A and B using irrigation water with a salinity of 25 mS m^{-1}.

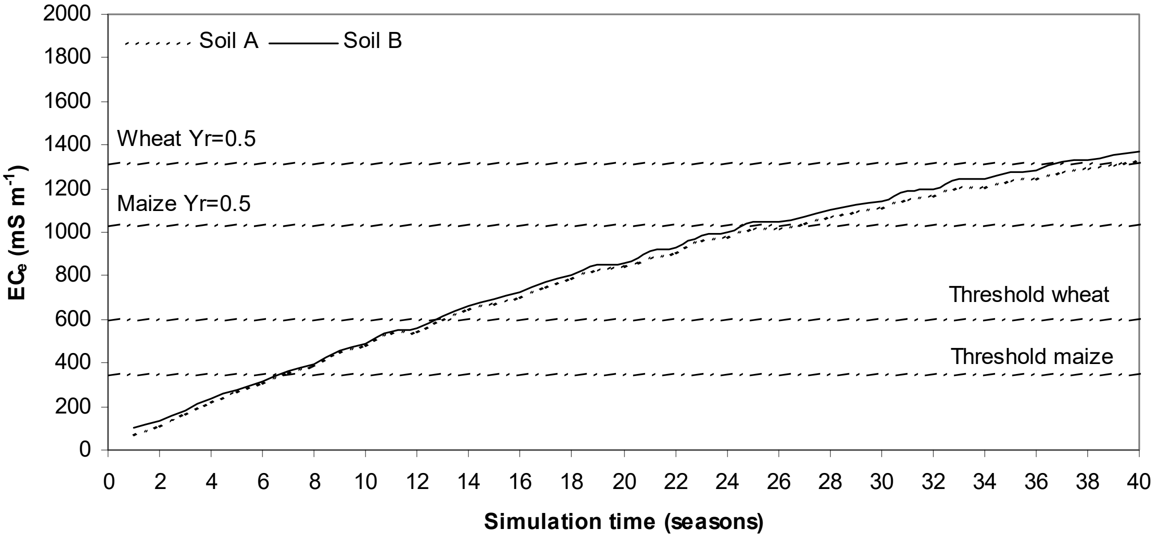


Figure 6.2 The change in average root zone salinity (EC_e, mS m^{-1}) of both soils when managed with Procedure A and B using irrigation water with a salinity of 50 mS m^{-1}.

The 50% decline in expected crop yield was reached at the end of Season 25 and Season 38 for maize and wheat respectively on both soils (Figure 6.2). The average root zone salinities were 1030 mS m^{-1} for maize and 1309 mS m^{-1} for wheat (Appendix 6.3).

iii) 100 mS m^{-1}

Using irrigation water with a salinity of 100 mS m^{-1} results in a very rapid increase in root zone salinity under conditions of restricted drainage. The EC$_e$-threshold salinities were reached at the end of Season 3 and Season 6 for maize and wheat respectively on both soils with a required drainage rate of about 3 mm day^{-1} (Appendix 6.4). Procedure B was followed from Season 6 onwards.

Figure 6.3 shows that the 50% decline in expected maize yield was reached at the end of Season 13 with an average root zone salinity of 1064 mS m^{-1}. For wheat this point, with an average root zone salinity of 1316 mS m^{-1}, was reached at the end of Season 20.

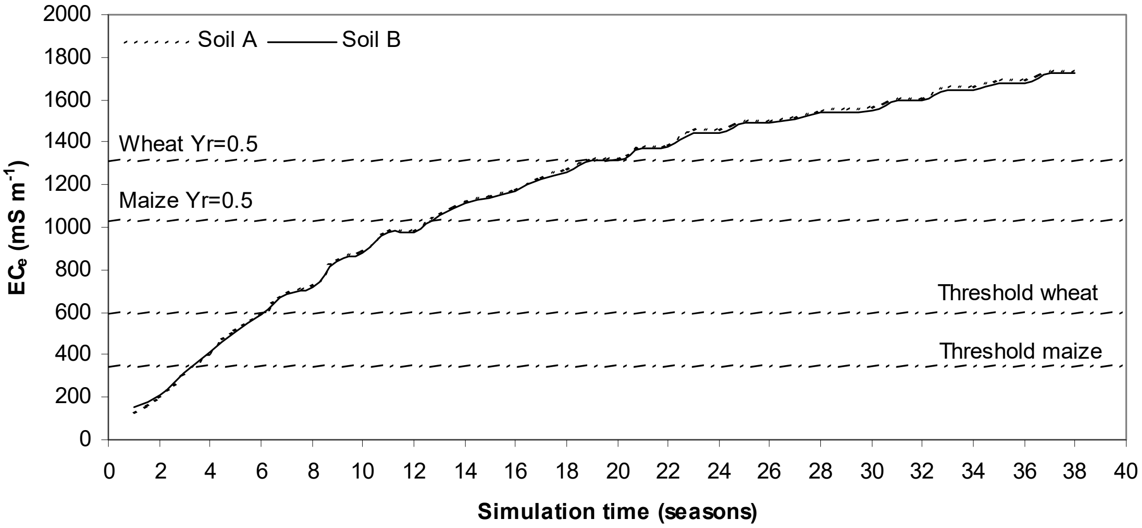


Figure 6.3 The change in average root zone salinity (EC$_e$, mS m^{-1}) of both soils when managed with Procedure A and B using irrigation water with a salinity of 100 mS m^{-1}.

In practice, Le Roux *et al*. (2007) found similar trends of salt accumulation in soils along the Lower Vaal River in South Africa. They indicated that, in soils with restricted drainage, salts accumulated to levels of up to 1 650 mS m^{-1} when irrigated with water qualities ranging from 25 to 100 mS m^{-1} for more than 20 years. They ascribed the main cause of salt accumulation in these soils, to capillary rise from shallow saline water tables.

6.4.2 Root zone freely drained

The simulation results of the proposed procedures for all the different irrigation water salinities under freely drained soil conditions are given in Appendices 6.5 to 6.7 for Procedure C, Appendices 6.8 to 6.10 for Procedure D and Appendices 6.11 to 6.13 for Procedure E.

i) 25 mS m^{-1}

According to Figure 6.4, that presents the increase in the root zone salinity using Procedure C, EC_e was not influenced by soil type and therefore the threshold soil salinity for maize was reached at the end of Season 8 on both soils. However, the drainage requirement of 422 mm in Soil A is drastically lower than the 583 mm required for Soil B (Appendix 6.5) and can be ascribed to the different values of the b-coefficients of the two soils as influenced by the S+C % of the root zone (Section 5.2). The 50% decline in yield was reached at the end of Season 29 for maize and at the end of Season 44 for wheat.

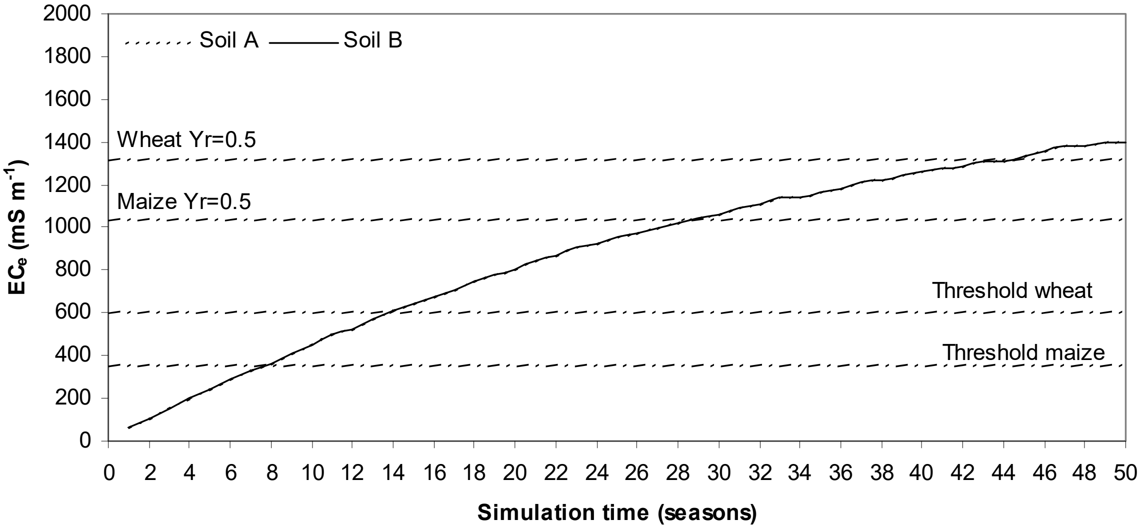


Figure 6.4 The change in average root zone salinity (EC_e, mS m^{-1}) of both soils when managed with Procedure C using irrigation water with a salinity of 25 mS m^{-1}.

Using Procedure D from Season 9 onwards, with which excess salts are leached from the root zone according to the drainage requirement, the average root zone salinity is kept below the threshold salinity of maize (350 mS m^{-1}) for both crops. For this period of 40 seasons, the average drainage requirement was 22 mm $season^{-1}$ and 31 mm $season^{-1}$ for soils A and B respectively (Appendix 6.8).

Figure 6.5 illustrates that with Procedure E, which assumes that R_{eff} is sufficient to keep the root zone salinity within acceptable limits, the threshold salinity of maize is reached at the end of Season 11 for Soil A and at the end of Season 8 for Soil B. This is an indication that R_{eff} is clearly not sufficient to leach excess salts added through irrigation water, from the root zone. The 50% reduction in maize yield was reached at the end of Season 25 on Soil A and Season 17 on Soil B.

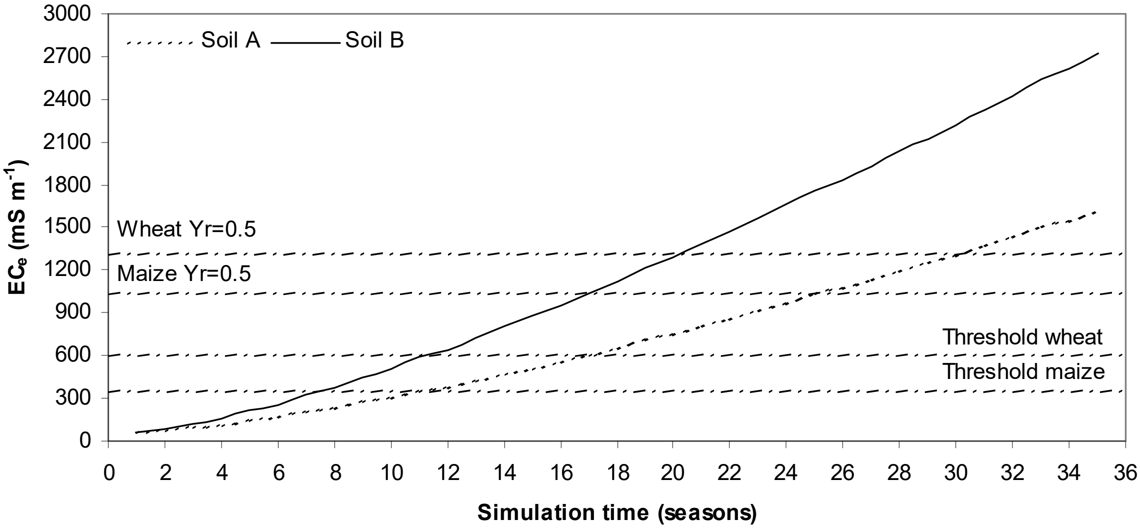


Figure 6.5 The change in average root zone salinity (EC$_e$, mS m^{-1}) of both soils when managed with Procedure E using irrigation water with a salinity of 25 mS m^{-1}.

ii) 50 mS m^{-1}

Managing soil salinity according to Procedure C and using irrigation water with a salinity of 50 mS m^{-1} resulted in salinisation of the root zone above the threshold soil salinity for maize within 4 seasons (Figure 6.6). Even more alarming is that the 50% decrease in maize yield is reached at the end of Season 13 and at the end of Season 22 for wheat.

By increasing the irrigation requirement, from Season 6 onwards, in order to allow for the leaching of excess salts from the root zone, as given in Appendix 6.9 for Procedure D, the average soil salinity is kept below 350 mS m^{-1} resulting in normal crop production and yield. The average drainage requirement over a period of 45 seasons was 46 mm season^{-1} for Soil A and 66 mm season^{-1} for Soil B.

Figure 6.7 indicates a rapid salinisation of the root zone when using Procedure E. In Soil A, an average salinity 336 mS m^{-1} was reached at the end of Season 7, whereas for Soil B, an average soil salinity of 339 mS m^{-1} was reached at the end of Season 4. Once again this is a clear indication that R$_{eff}$ is not sufficient to leach added salts from the root zone and significant (50%) yield reductions will occur within 10 to 18 seasons.

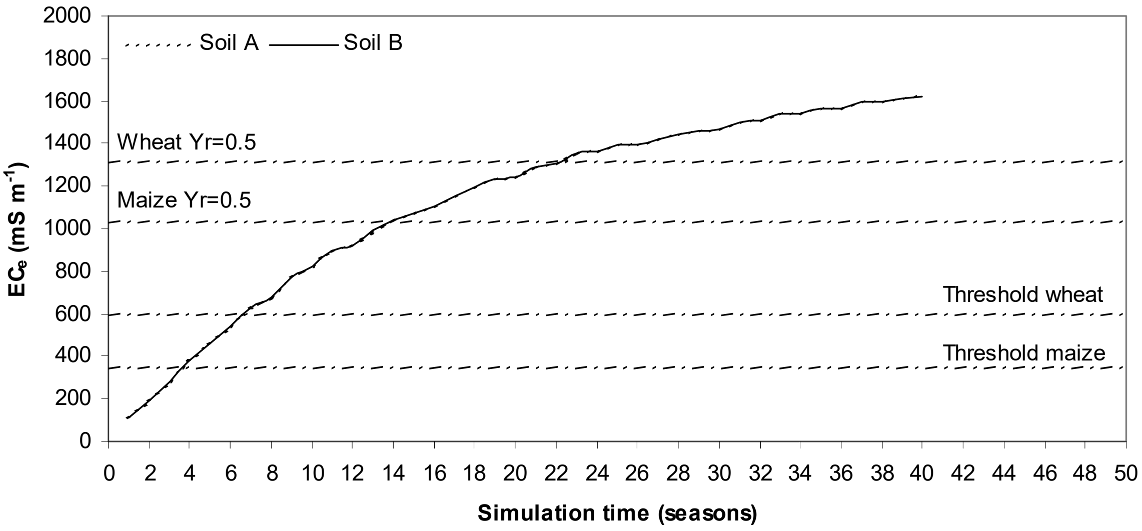


Figure 6.6 The change in average root zone salinity (EC$_e$, mS m^{-1}) of both soils when managed with Procedure C using irrigation water with a salinity of 50 mS m^{-1}.

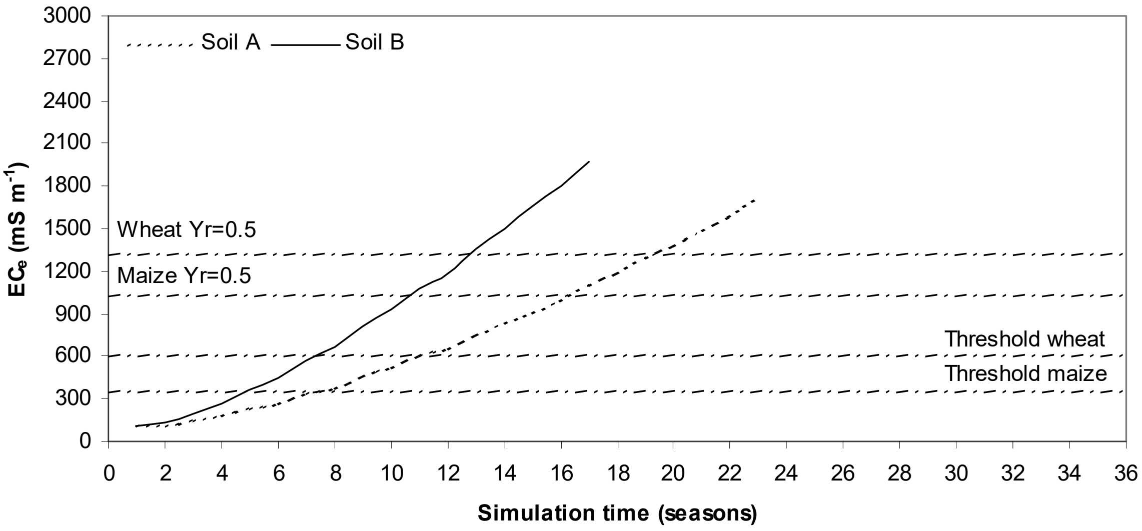


Figure 6.7 The change in average root zone salinity (EC$_e$, mS m^{-1}) of both soils when managed with Procedure E using irrigation water with a salinity of 50 mS m^{-1}.

iii) 100 mS m^{-1}

Irrigating with poor quality water, according to Procedure C (Figure 6.8), resulted in root zone salinisation after only 2 seasons and 50% yield reduction after 7 and 12 seasons for maize and wheat respectively.

However, by increasing the irrigation requirement (Procedure D) with an average of 102 mm season^{-1} on Soil A and 149 mm season^{-1} on Soil B will result in sustainable crop production as illustrated in Appendix 6.10.

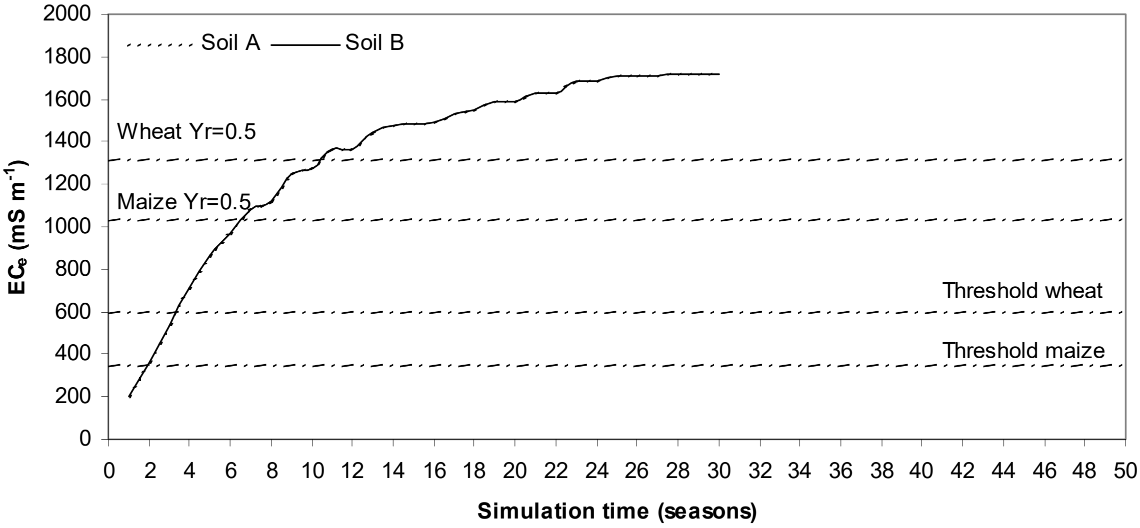


Figure 6.8 The change in average root zone salinity (EC_e, mS m^{-1}) of both soils when managed with Procedure C using irrigation water with a salinity of 100 mS m^{-1}.

Irrigation management according to Procedure E, using poor quality water, resulted in salinisation of the root zone to salinities above 350 mS m^{-1} within 5 seasons on Soil A and 3 seasons on Soil B (Figure 6.9). A 50% reduction in maize yield was reached at the end of Season 11 on Soil A and at the end of Season 7 on Soil B. For wheat this point was reached at the end of Season 12 and Season 8 for Soil A and B respectively.

The results, simulated for the range of irrigation water qualities using Procedure C and E, indicated a rapid increase in soil salinity due to limited provision for leaching. Le Roux *et al*. (2007) found salt accumulation at depths of 400 to 1000 mm in freely drained sandy soils along the Lower Vaal River and concluded that the rainfall in these areas was too low to play a significant role in the leaching of accumulated salts from the root zone. In practice, leaching is limited when scheduled irrigation with mechanical systems like centre pivots merely recharge water depleted by crops. Farmers increasingly prefer this option as it saves on costs, and therefore, effective irrigation scheduling which allows for leaching (Procedure D) must be promoted.

Prediction of salt balances in irrigated soils along the Lower Vaal River (Van Rensburg *et al*., 2007) also showed that salt induced stress could reduce the yield of maize and wheat significantly in the future if appropriate precaution measures are not introduced.

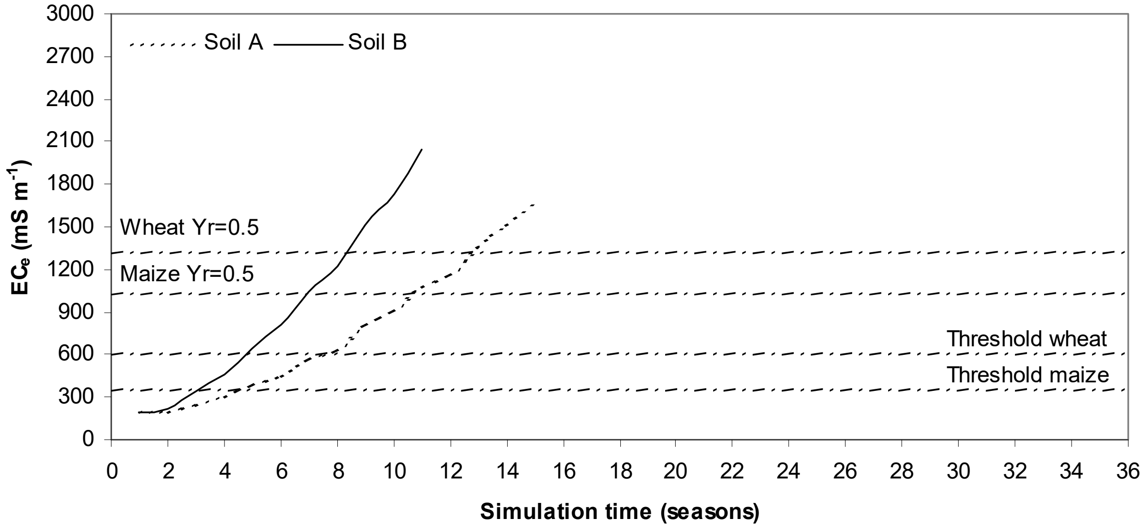


Figure 6.9 The change in average root zone salinity (EC_e, mS m^{-1}) of both soils when managed with Procedure E using irrigation water with a salinity of 100 mS m^{-1}.

6.5 Conclusions

It is evident that under conditions of zero drainage, salinisation of the root zone will occur very rapidly especially when poor quality irrigation water is used. Simulated results of the proposed procedures for zero drainage conditions indicated that sustainable production could be maintained for only 25 to 40 years if good quality irrigation water is used. Using irrigation water with an $EC_i \geq 50$ mS m^{-1} will result in severe soil salinisation and crop losses within 5 to 10 years. It is therefore evident that Procedures A and B will only temporarily alleviate the impact of salinity on crop production, rather than controlling the problem. The only solution for sustainable production under these conditions is to install artificial drainage systems and to make provision for drainage plus crop water use requirements when applying irrigation.

On freely drained soils it is possible to effectively manage the salinity level of the root zone through controlled over-irrigation. Simulated results indicated that with the use of good quality irrigation water, it would take about 5 years before the increase in root zone salinity will require additional leaching. However, under conditions where the amount of irrigation water is not sufficient for leaching (Procedures C and E) crop losses could occur within 11 years. Furthermore, if poor quality irrigation water is used under these conditions, severe salinisation and crop losses could occur within 3 to 6 years. Under these conditions soils should be rotated to allow for natural leaching by rainfall during fallowing or smaller areas should be planted. Sustainable production on freely drained soils is therefore only possible when sufficient amounts of irrigation water are available to leach excess salt from the root zone as proposed in Procedure D.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Introduction

Salinization of irrigated soils is a major problem and an effort must be made to improve the management of irrigation farming. Proper management procedures should address all the different factors affecting salinity and its' effect on crop growth, with the purpose of controlling groundwater, stream flow and farmland salinization. The crop type, the quality of water used for irrigation, the seasonal rainfall amount, climate, and the soil properties are some of the factors that should be taken into account when selecting the most appropriate management option.

Management practices for the safe use of saline water for irrigation primarily consist of:

- selection of crops or crop varieties that will produce satisfactory yields under the existing or predicted conditions of salinity;
- special planting procedures that minimize or compensate for salt accumulation in the vicinity of the seed;
- irrigation to maintain a relatively high soil water content to promote periodic leaching of the soil;
- use of land preparation and irrigation design to increase the uniformity of water application and infiltration to obtain uniform leaching and removal of salts;
- special treatments, such as tillage and additions of chemical amendments, organic matter and growing green manure crops, to sustain soil permeability and tilth.

In this chapter the outcomes of this study are addressed in relation to each of the objectives. This is followed by general conclusions and the practical implications of the research results. Some recommendations for future research are also given.

7.2 Outcomes in relation to the objectives of the study

7.2.1 Objective 1: The quantification of the effect of increasing salt content of irrigation water on the growth and yield of selected crops.

A series of field experiments were conducted in large 5 000 litre lysimeters that were designed to accurately measure both the water and salt balances in the presence of shallow water tables in order to attain the objective.

The lysimeters contained two soil types, viz. Soil A: a Clovelly Setlagole with 5% clay in both the top (0 - 0.3 m) and subsoil (0.3-1.8m) and Soil B: a Bainsvlei Amalia with 8% clay in the topsoil, 14% in the subsoil (0.3 - 1.2 m) and 20% in the deeper subsoil (1.2-1.8m) (Ehlers *et al*., 2003). Irrigation was applied weekly on the surface and daily via a manometer tube connected to the bottom of the lysimeters to maintain a constant water table height. Five irrigation water salinity levels were selected as treatments for the crops. The range of the salinity treatments varied according to the expected salt tolerance of the individual crop species.

The statistical results showed that for the same treatments, the yields of Soil A and B were similar, except for wheat where the more clayey Soil B gave better yields. Very good fittings with polynomial functions, describing the decline in biomass yield with increasing irrigation water salinity (EC_i, mS m^{-1}), were found for all the crops, except wheat where the highest irrigation water salinity treatment of 600 mS m^{-1} was insufficient to reduce growth. The measured decline in biomass production at the highest EC_i treatments, relative to its control, were 10% for wheat at an EC_i of 600 mS m^{-1}, 100% for beans at an EC_i of 600 mS m^{-1}, 37% for peas at EC_i of 300 mS m^{-1} and 40% for maize at 600 mS m $^{-1}$. In retrospect, the yield reduction for wheat showed clearly that the EC_i range used was too small for identifying a critical threshold EC_i value. It was realized that an EC_i treatment of 1200 mS m^{-1} should have been included in the field experiment. Fortunately, this research was done by Dikgwatlhe (2006) in glasshouse pot experiments and reported. The soil water salinity of the lysimeters was measured in suction cup extracts, sampled at different depths. These measurements were taken at the start and end of the growing season for each crop species. The salts that accumulated during a growing season were removed through leaching between seasons. Linear correlations between relative biomass and mean seasonal soil water salinity (EC_{sw}) were obtained, from which the crop threshold values were derived. The EC_{sw} threshold values were 82, 105 and 499 mS m^{-1} for beans, peas and maize, respectively. No threshold value could be calculated for wheat because the salinity levels of the treatments were too low. It was recommended to use the value of 860 mS m^{-1} reported by Rhodes & Loveday (1990). The threshold value of maize was higher than values reported in the literature. It was also possible to obtain the relative yield reduction per mS m^{-1} increase above the threshold value, also known as the b-value of Rhodes & Loveday (1990) as given in Table 3.11. It can be concluded that this part of the study confirmed the findings reported in literature by several researchers.

7.2.2 Objective 2: The determination of the relationship between irrigation water with increasing salinity and water use of selected crops on two soil types.

This objective was achieved mainly from the results of the experiments conducted at the lysimeter unit. Wheat, followed by beans, peas and maize were irrigated with deteriorating water salinities ranging between 15 and 600 mS m^{-1} for maize, wheat and beans and 15 to 300 mS m^{-1} for peas. The daily and total water use, expressed as evapotranspiration (ET), decreased with increasing levels of salt content for both soils. Both the daily and seasonal ET did not differ statistically, amongst the soil types. Consequently the two data sets were combined for most of the regression analyses where salt content was correlated with water use parameters. Despite an adequate water supply through surface irrigation and capillary upflow from the water table at a depth of 1.2 m, evapotranspiration declined linearly with increasing irrigation and soil water salinity. Visual signs of crop water stress were most evident during periods of peak water use, in the high EC_i treatments. For beans the decline in daily ET started much earlier in the growing season. Plants from the 450 and 600 mS m^{-1} EC_i treatments showed severe signs of crop water stress after emergence and the plants started to die at about 45 days after planting. In the absence of drainage, salts accumulate in the profile during the growing season, leading to a decrease in osmotic potential. This decrease in osmotic potential lowers the total soil water potential, and hence lower leaf water potentials are required by the crop to extract sufficient water from the soil solution. It should also be kept in mind that irrigations were applied weekly and that soil drying between irrigations will decrease the total soil water potential further, due to the concentration of the salts. In addition, roots behave as a semi-permeable membrane, thus concentrating the salts around the roots in the rizosphere. The osmotic effect near the soil surface is also increased by evaporation.

The cumulative effect of the soil water salinity on ET was determined for each crop (Figure 3.21). The results indicated that increasing soil water salinity explained between 88 and 92% of the decline in ET. Peas were the most sensitive to osmotic effects, followed by beans, maize and wheat in that their ET decreased relative to the control at rates of 0.0007, 0.0005, 0.0004 and 0.0001 mm per unit increase in soil water salinity measured in mS m^{-1}. Further proof for the osmotic affect was found in the correlation between relative ET and relative yield, based on the formulation of Stewart *et al.* (1977) through Equation 3.3. The relative decrease in growth of all the crops was directly proportional to the relative decrease in ET (Figure 3.26, $R^2 = 0.94$). This relationship proves that irrespective of the differences in salt tolerance among the different crops, the reduction in growth was proportionally related to the increase in plant water stress, induced by lower water uptake in all cases.

7.2.3 Objective 3: Quantification of the root water uptake from shallow water tables with varying salt contents.

This objective was also achieved by analysing the water table uptake data gathered for the different crops in the lysimeter unit. The water table was kept at a constant depth of 1.2 m from the surface by adding water daily through a manometer tube connected to an outlet at the bottom of the lysimeters. The salinity of the irrigation water used to recharge the water table was the same as the treatment value. The daily additions required to fill up the water table to 1.2 m were taken as the daily water uptake from the water table.

The control treatments of the various crops represented good quality water with an EC_i of 15 mS m^{-1}. Under these conditions water table uptake contributed between 23 and 50% of the total evapotranspiration measured in Soil A. For Soil B it varied between 31 and 54%. The water table contribution of the control treatments of both soils compared well with the results obtained by Ehlers *et* *al*. (2003). The slightly higher contribution of Soil B is understandable, because the capillary rise height is, according to Ehlers *et al*. (2003), 124 mm higher than in Soil A. This also explains the observation that the crops grown in Soil B, generally started to take up water from the water table earlier because the roots reach the capillary fringe sooner.

Water uptake from the shallow water tables decreased with an increase in the water table salinity (EC_{sw}, mS m^{-1}) for all the crops and on both soils. This is ascribed to the lower osmotic potential in both the water table and the capillary zone above it. Upflow of the soil water from saline water tables caused rapid salinisation of the capillary zone, which is enhanced with deteriorating irrigation water salinity. The roots in the capillary zone required gradually increasing amounts of energy to absorb water from the layers as the salt content of the zone rose. Consequently, water will be extracted from the zone with the highest water potential and hence the lowest salt content. The EC_{sw} of the topsoil is normally close or slightly higher than the EC_i, while the EC_{sw} of the capillary zone and the water table EC_{sw} below are higher most of the time. Less energy is therefore required to extract water from the topsoil that received weekly irrigations. The salts that accumulated in the topsoil were also pushed downwards into the capillary zone following irrigation, because of ET from this layer. The water uptake from the water tables at a depth of 1200 mm was converted to relative values by dividing it by the control value. The relative water table uptake of all the crops declined linearly with an increase in the capillary zone salinity, above the threshold value. The decline was highest for peas, followed by beans, maize and wheat.

7.2.4 Objective 4: The determination of the salt balance for a range of irrigation water salinity and soil type combinations, over the three-year period.

It was planned that the four crops (wheat, beans, peas and maize) would be successively grown over the four seasons with a range of irrigation water salinities under restricted drainage water table conditions in lysimeters, allowing for an accumulation of salts. However, in the second season it was observed that the beans started to die in the high EC_i treatments. An investigation into the problem revealed that the salts were accumulating much faster in the profile than expected. It was then decided to remove the excess salts at the end of each growing season through leaching. Excess salts were defined as the difference between the mean EC_{sw} of the root zone at the end of the growing season and the planned EC_i treatments set for the next season. The EC_i treatments were chosen according to the salt sensitivity of the specific crop to be planted the next season.

The change in the methodology opened the door for the study of other important aspects of managing soil salinity under water table conditions, viz. the build-up of salts in the root zone, as affected by increasing levels of EC_i (Chapter 4) and the removal thereof (Barnard, 2006). Both these processes are strongly linked to the water and salt balance.

Salt accumulation in the root zone was measured by collecting soil water samples with suction cups, installed at various depths in the profiles of the two soils in the lysimeters (Chapter 4). The samples were analyzed for electrical conductivity of the soil water (EC_{sw}, mS m^{-1}) and total dissolve solids (TDS, mg L^{-1}). Salt distribution profiles were plotted for each crop, showing the change of salt accumulation in the 1800 mm soil profile (Figures 4.1 - 4.4) from the beginning to the end of the growing seasons. These salt profiles showed firstly that the salt content of the water tables increased drastically over a season, due to the lack of leaching. Secondly, there was a steep gradient of salt accumulation from the water table upwards to the fringe of the capillary zone, in both soils. Thirdly, salt accumulation in the capillary zone became more pronounced with increasing levels of EC_i. In order to describe the change in salinity of the profiles, the relationship between EC_{sw} (mS m^{-1}) and TDS_{sw} (mg L^{-1}) (Figure 4.9) as well as EC_i and TDS were determined. The conversion factors were 7.568 and 7.831, respectively. A third relationship was established, viz. salt added (kg ha^{-1}) versus ΔEC_{sw} (mS m^{-1} 1800 mm^{-1}) (Figure 4.11). Lastly, Equation 4.3 was developed to predict the accumulation of salts in soils with limited drainage for any known quality and quantity of irrigation water added. This allows for the prediction of the decline in yield of different crops.

7.2.5 *Objective 5: Formulation of different root zone salinity management procedures.*

A theoretical framework is proposed for managing the salinity of the root zone. The procedures are based on prevailing drainage conditions grouped into restricted or freely drained categories. For conditions with restricted drainage the procedures are divided into two sub-categories, depending if the actual EC_{sw} is smaller or greater than the threshold value of the crop to be planted (Figure 5.1). On freely drained soils it is possible to effectively manage the salinity level of the root zone, through controlled over-irrigation when necessary. However, the amount of available irrigation water for leaching is not always adequate to effectively remove all excess salts from the root zone and therefore the proposed procedures were subdivided into three sub-categories depending on the supply of irrigation water (Figure 5.1).

7.2.6 Objective 6: Calculation of the salt balance of the two soil types over a period of 50 years using the proposed procedures as presented in Chapter 5.

Wheat (*Triticum aestivum*) with a growing period of 156 days and maize (*Zea mays*) with a growing period of 131 days were used in a crop rotation basis as a winter and summer crop respectively in the simulation of the accumulation of salts in the root zone. The target yields were taken as 7500 kg ha^{-1} and 12000 kg ha^{-1} for wheat and maize respectively and the crop water demand (CWD, mm) for each crop was determined using the irrigation scheduling computer program BEWAB (Bennie *et al*., 1988). The total rainfall for each growing season, starting from the 1st of January 1950, of the Glen Agricultural Institution near Bloemfontein was used. The cumulative effective rainfall (R_{eff}, mm) for each growing season was calculated by subtracting the cumulative evaporation following each rainfall event from the amount of rainfall, as proposed by Bennie *et al*. (1998). The potential rooting depth of both soils was taken as 1800 mm, with a mean silt plus clay content of 8% for Soil A and 16% for Soil B (Section 4.3.2). For the restricted drainage options a water table depth of 1500 mm was used. The initial root zone salinity was taken as 20 mS m^{-1} for both soils and the irrigation water salinities were taken as 25, 50 and 100 mS m^{-1}.

The simulation of the accumulation of salts in the root zone, following the proposed procedures to be used under conditions with restricted drainage indicated that sustainable production could be achieved for only 25 to 40 years if good quality irrigation water is used. With Procedure A, using 25 mS m^{-1} irrigation water the threshold salinity for maize was reached after 16 seasons with a required drainage rate of 3 mm day^{-1} on Soil A and 4 mm day^{-1} on Soil B. Using irrigation water with an $EC_i \geq 50$ mS m^{-1} will result in severe soil salinisation and total crop failure within 5 to 10 years. The average required drainage rate was in the order of 3 mm day^{-1} on both soils. It is therefore evident that these procedures will only temporarily alleviate the impact of salinity on crop production, rather than controlling the problem. The only solution for sustainable production under these conditions is to install artificial drainage systems in order to solve the problem of restricted drainage and thus rapid salt accumulation. The artificial system must be able to drain excess ground water at a rate of at least 3 mm day^{-1}.

Simulated results indicated that with the use of good quality irrigation water (25 mS m^{-1}) on freely drained soils, it will take about 5 years before the increase in root zone salinity will require additional leaching. In order to leach the soils to the initial salinity of 20 mS m^{-1}, the drainage requirement will be 422 mm on Soil A and 583 mm on Soil B. However, to keep the soil salinity below the threshold salinity for maize (350 mS m^{-1}), additional irrigation of only 22 mm $season^{-1}$ on Soil A and 31 mm $season^{-1}$ on Soil B is required to leach excess salts from the root zone. Using irrigation water with an $EC_i \geq 50$ mS m^{-1} severe salinisation and crop yield losses could occur within 3 to 6 years. The amount of additional irrigation that is required to keep the soil salinity below the threshold salinity for maize is 46 mm $season^{-1}$ and 66 mm $season^{-1}$ for soils A and B respectively, when using irrigation water with a salinity of 50 mS m^{-1}. With 100 mS m^{-1} irrigation water the leaching requirements increased to 102 mm $season^{-1}$ on Soil A and 149 mm $season^{-1}$ on Soil B. Under conditions where the amount of irrigation water is not sufficient to supply the total crop water demand, the simulated data indicated that the long term average rainfall for the Bloemfontein region is not sufficient for natural leaching during the growing season and soils can therefore be rotated and left fallow to allow for natural leaching. Sustainable production on freely drained soils is therefore only possible when sufficient amounts of irrigation water is available to leach excess salts from the root zone.

7.3 General conclusions and practical implications

The results from this research study are applicable to conditions where the salinity of sandy to sandy loam soils are in equilibrium with the salinity of the irrigation water, and leaching of salts from the root zone is restricted by the presence of a stagnant water table within or just below the potential rooting depth of a crop. Aspects that were studied included the following:

1. The effect of irrigation and soil water salinity on the growth, production and water uptake of maize, wheat, bean and pea crops. It must be kept in mind that the crop reaction results refer only to a first cropping season because in the following season the soil water salinity will be several fold higher due to salt accumulation during the previous season.

2. The amount, rate and depth of salt accumulation, within the potential rooting depth that varies between 1500 and 2000 mm for the crops mentioned, were measured.

3. A procedure was proposed to support irrigation and crop management decision making when taking salinity into account.

4. The proposed procedures were followed to simulate salt accumulation in the root zone over a period of 50 years.

The results from this study on the effect of irrigation and soil water salinity on the above-ground biomass growth of all the crops supported the findings reported in literature. Growth of crops are not affected until a specific salinity threshold value is reached, after which the biomass produced declines linearly with increasing soil water salinity. Of the investigated crops dicotyledonous peas and beans were the most salt sensitive with threshold values around 100 mS m^{-1} followed by maize (500 mS m^{-1}) and wheat (> 600 mS m^{-1}). The rate at which growth and yield declined at increasing salinities, higher than the threshold values, were also peas ≥ beans > maize > wheat. This decline in growth with increasing soil water and irrigation water salinity is directly related to a decline in transpiration or root water uptake because of lower soil water osmotic potentials. The proof for this conclusion can be found in Figures 3.21 and 3.26.

The leaching of salts from the root zone during the growing season of a crop will be impeded by the presence of a shallow water table at a constant depth of 1200 mm. The height of capillary rise from the water table, in the soils investigated, varied between 660 and 790 mm. This implies that over a potential rooting depth of 1800 mm, most of the macro pores in the soil below a depth of 410 to 540 mm will remain near saturation in the capillary zone and saturated with water below the water table. Under non-saline conditions, depending on crop type, between 23 to 50% of the seasonal crop water use can be taken up from the capillary zone and replenished from the water table through a steady upward capillary flux. For a specific crop the uptake from the water table will decline with an increase in the water table salinity, resulting in a slower but more saline upward flux of water.

The amount of salts that will accumulate in the root zone during a cropping season depends on the salt concentration of the irrigation water and the amount applied. Under these experimental conditions the mean electrical conductivity (EC, mS m^{-1}) of the soil water over a depth of 1800 mm increased by 1.8 times the EC of the irrigation water after 612 mm irrigation. In the presence of a shallow water table most salts will accumulate near and just below the capillary fringe. This is a result of the downward leaching of salts, through the unsaturated soil above the capillary fringe, into the capillary zone combined with an upward flux from the saline water table to replace water taken up from the capillary zone. This bulge in the salt distribution profile is always present in the capillary zone of water table soils, as illustrated in Figure 4.5. The salt concentration in this bulge, within the capillary zone, is several folds higher than in the rest of the root zone. This salt barrier that develops in the capillary zone contributes further to less water being taken up from the water table because of an excessive decline in the osmotic soil water potential above the water table.

In practice an increase in root zone salinity in soils with shallow water tables and the corresponding decline in crop water use and yield, necessitate adaptations in the normal approaches to irrigation scheduling and irrigation water management. The root zone can be divided into three management layers, namely, the unsaturated layer between the soil surface and the upper fringe of the capillary zone; the capillary layer between the upper capillary fringe and the surface of the water table and the saturated layer beneath the surface of the water table. In such closed systems the amount of salts added to and accumulating in the root zone are determined by the salinity status and amount of irrigation water applied. Removal of salts from the root zone will only occur through downslope lateral water movement below the surface of the water table, where the upslope water salinity level is lower. In downslope position soils, this lateral water flux below the surface of the water table will be an additional source of salts.

Any change in irrigation strategy under comparable conditions, will always result in a nett upward or downward movement of salts and the water table. When the mean EC of the unsaturated and capillary layers of the root zone exceeds the threshold value for a particular crop, the expected yield, crop water and irrigation requirements will be proportionally less (See Sections 3.3.4.2 to 3.3.4.4).

There are four management options that can be followed by the irrigator when a shallow water table is present in or just below the potential rooting depth, which is about 2000 mm for most crops.

Option 1: To irrigate more than the expected crop water use. The excess salts will then be leached from the unsaturated layer, ensuring a more favourable salinity status. Less water will be taken up from the saturated and capillary layers. The growing season will end with a higher salinity status in the capillary layer, an increase in the height of the water table and a thinner unsaturated layer. This option will initially give better yields but will induce more rapid waterlogging, more downslope salinization of soils and more salts will be added to the root zone compared to the other options. This option will not be sustainable.

Option 2: To irrigate the same amount as the expected crop water use. Less of the excess salts will be leached from the unsaturated layer but fewer salts will also be added to the root zone. The growing season will be ended with a higher salinity status in both the unsaturated and capillary layers with the water table remaining at the same depth. Applying this option will over time result in a gradual increase in total root zone salinity, decreasing yields requiring less irrigation every season, but less and less salts will be added to the root zone.

Option 3: To irrigate less than the expected crop water use. Care should be taken, that the reduction in irrigation amount should not exceed the expected water table uptake of the crop, at the salinity of the saturated layer (See Section 3.3.3). Choosing this option will enhance crop water uptake from the capillary layer, resulting in more capillary movement of water from the saturated layer. This will lower the water table but will increase the rate of salinization in the capillary layer. With this option the least amount of salts will be added to the root zone over time but the risk of rapid salinization of the unsaturated and capillary layers are high. A major advantage of the lowering of the water table is that the thickness of the unsaturated layer will increase, allowing for more effective salt leaching during periods of above normal rainfall.

Option 4: With the first three options a gradual increase in root zone salinity over seasons is a fact with an associated decline in expected yields of the cultivated crops. When the expected yield of a specific crop becomes uneconomical there is always the option to convert to more salt tolerant crops or the installation of artificial drainage.

It should be clear from the discussed options that none will be sustainable over the long term. The installation of artificial subsurface drainage, that will lower the water table, thereby increasing the thickness of the unsaturated layer and allowing for effective salt leaching by controlled over irrigation, is the only long-term solution under these conditions. Different management options to control salt accumulation in soils were all included in a step-by-step procedure in Chapter 5.

Simulation studies were conducted and discussed in Chapter 6 to compare the suitability of the different management options. From the simulated results it was evident that under conditions with zero drainage the only solution for sustainable production is the installation of artificial drainage even with the use of good quality irrigation water. Analysis of the water table management options strongly suggests that drainage management should begin well before the level of the water table reaches depths of approximately 1500 mm. This will delay or may even eliminate the onset of salt accumulation due to poor drainage thereby reducing expected crop losses. A potential solution to reduce the need for artificial drainage is to promote exploitation of the water tables to meet part of the water needs of the crop (Chapter 3). Late maturing, deep-rooted crops with a high salt tolerance can be grown to effectively lower shallow water tables, for example lucerne or green manure crops like clover. Several studies have shown that lucerne is an excellent choice to lower shallow water tables (Zang *et al*., 1999). It can be used in a crop rotation or as a permanent water barrier when it is necessary to control the lateral movement of salt water from one field to another. There may be years when, despite the best water table management practices, excessive rainfall could raise water tables close to the surface. However, the chances of such an event would be greatly reduced if the water table was lower initially. Lowering the water table by means of adapted deficit irrigation practices should be viewed as a long-term management tool, and not a quick or permanent renovation technique.

Analysis of the irrigation management options on freely drained soils indicated that even with the use of good quality irrigation water (25 mS m^{-1}), it will take only about 5 years before the increase in root zone salinity will require additional leaching. Following irrigation, plant roots preferentially absorb water from rooting depths with high water potential. Normally this means that most of the water uptake is initially from the upper, less saline soil depths until sufficient water is removed to increase the total water stress (potential) to a level equal to that in the lower depths. After that water is removed from the deeper, more saline soil depths and the effect of salinity, *per se,* on crop growth is magnified. Once the soil solution has reached the maximum salinity level compatible with the cropping system, at least the amount of salt brought in with additional irrigations should be removed from the root zone through leaching. The minimum amount of water (or rainfall) must, over the long term, be applied in excess of that needed for evapotranspiration (ET) to leach the accumulated salts from the root zone. Under conditions where the amount of available irrigation is not sufficient for additional leaching, the soil profile should be filled to the drained upper limit (DUL) just before the rainy season and left fallow during the rainy season. It will also help to irrigate during the night when evaporation rates are lower.

Regular analysis should be done to determine the salinity status within the crop root zone to quantify the amount of leaching that occurred. This will help to evaluate and improve the effectiveness of the irrigation practices and management strategies that are being used.

As a final conclusion from this study it appears that under freely drained conditions, when the amount irrigated is equal to the crop water demand, thus when good scheduling is practiced, the salt status of the root zone will reach equilibrium. Salts will accumulate gradually in the root zone, as illustrated in Chapter 6, until it reaches a threshold value after which the crop water uptake will decline and the excess applied water will be available for leaching of the salts. This will continue until equilibrium conditions are reached. The equilibrium salt status of the root zone will depend on several factors like soil type, farming practices, climatic conditions, topographic position etc.

7.4 Recommendations for future research

This study provided the opportunity to obtain a theoretical framework on how to manage root zone salinity. It should be stressed that the proposed procedures are based on inputs obtained from experiments under controlled conditions. The following additional information is therefore required:

- The procedures needs to be verified under controlled and on-farm field conditions.
- For managing the soil salinity levels within soil layers, the effect of rhizosphere salinity on water uptake needs to be quantified.
- The effect of soil surface salinity and its effect on seedling emergence in the field need to be quantified for different crop and soil combinations.
- More and different crop combinations should be investigated for various levels of water and soil salinity.
- The evaluation and testing of instrumentation for on-farm monitoring of EC_e are essential.
- Quantification of the balance between the leaching of excessive harmful salts and plant nutrients.

The proposed procedures for managing root zone salinity at field scale should be extended to practices and guidelines for managing the salt load associated with irrigation at farm and scheme level.

REFERENCES

AGASSI, M., SHAINBERG, I. & MORIN, J., 1981. Effect of electrolyte concentration and soil sodicity on infiltration rate and crust formation. *Soil. Sci. Soc. Am. J*. 45, 848-851.

ANNANDALE, J.G., BENADE, N., JOVANOVIC, N.Z., STEYN, J.M. & DU SAUTOY, N., 1999. Facilitating irrigation scheduling by means of the Soil Water Balance model. Water Research Commission Report 753/1/99, Pretoria.

APPLETON, B., 1984. Dam challenge must be answered. *World Water*, November 1984.

ASLAM, M., HUFFAKER, R.C. & RAINS, D.W., 1984. Early effects of salinity on nitrate assimilation in barley seedlings. *Plant Physiol*. 76, 321-325.

AYARS, J.E. & SCHONEMAN, R.A., 1986. Use of saline water from a shallow water table by cotton. *Transactions of the ASAE* 29, 1674-1673.

BACKEBERG, G.R., BEMBRIDGE, T.J., BENNIE A.T.P., GROENEWALD, J.A., HAMMES, P.S., PULLEN, R.A. & THOMSON, H., 1996. Policy proposal for irrigated agriculture in South Africa. Water Research Commission Report KV96/96, Pretoria.

BALL, M.C., CHOW, W.S. & ANDERSON, J.M., 1987. Salinity-induced potassium deficiency causes loss of functional photosystem in leaves of the grey mangrove, *Avicennia marina*, through depletion of the atrazine-binding polypeptide. *Aust.J. Plant Physiol.* 14, 351-361.

BARNARD, J.H., 2006. Leaching of excess salts from the root zone of apedal soils. M.Sc.Agric. dissertation, University of the Free State, Bloemfontein.

BENNIE, A.T.P., COETZEE, M.J., VAN ANTWERPEN, R., VAN RENSBURG, L.D. & BURGER, R. DU T., 1988. ‘n Waterbalansmodel vir besproeiing gebaseer op profielwatervoorsieningstempo en gewaswaterbehoeftes. Water Research Commission Report 144/1/88, Pretoria.

BENNIE, A.T.P., STRYDOM, M.G. & VREY, H.S., 1998. Gebruik van rekenaarmodelle vir landboukundige waterbestuur op ekotoopvlak. Water Research Commission Report TT 102/98, Pretoria.

BERNSTEIN, L. & FRANCOIS, L.E., 1973. Comparisons of drip, furrow and sprinkler irrigation. *Soil Sci*. 115, 73-86.

BLAINE, R.H. & KITE, S.W., 1984. Irrigation scheduling under saline high water tables. *Transactions of the ASAE* 27, 1430-1434.

BRESLER, E., 1987. Application of a conceptual model to irrigation water requirement and salt tolerance of crops. *Soil Sci. Soc. Am. J*. 51, 788-793.

CRAMER, G.R., EPSTEIN, E. & LAUCHLI, A., 1988. Kinetics of root elongation of maize in response to short-term exposure to NaCl and elevated calcium concentration. *J. Expt. Bot.* 39, 1513-1522.

DEPARTMENT OF WATER AFFAIRS AND FORESTRY, 1996. South African water quality guidelines, 2nd edn. Volume 4. Agricultural use. Government Printer, Pretoria.

DIELEMAN, P.J., 1963. Reclaiming of salt affected soils in Iraq Reenman. *Wageningen 175.*

DIKGWATLHE, S.B., 2006. The effect of water quality on the growth and yield of irrigated crops. M.Sc.Agric. dissertation, University of the Free State, Bloemfontein.

DU PLESSIS, H.M., 1998. Water quality and irrigation in South Africa. *S.A. Irrigation*, October/November 1998.

DU PLESSIS, H.M. & VAN VEELEN, M., 1991. Water quality: salinisation and eutrophication time series and trends in South Africa. *S. Afr. J. Sci*. 87, 11-16.

DU PREEZ, C.C., STRYDOM, M.G., LE ROUX, P.A.L., PRETORIUS, J.P., VAN RENSBURG, L.D. & BENNIE, A.T.P., 2000. Effect of water quality on irrigation farming along the lower Vaal River: The influence on soils and crops. Water Research Commission Report 740/1/00, Pretoria

EHLERS, L., BENNIE, A.T.P. & DU PREEZ, C.C., 2003. The contribution of root accessible water tables towards the irrigation requirements of crops. Water Research Commission Report 1089/1/03, Pretoria.

EHLERS, L., BARNARD, J.H., DIKGWATLHE, S.B., VAN RENSBURG, L.D., CERONIO, G.M., DU PREEZ, C.C. & BENNIE, A.T.P., 2007. Effect of deteriorating irrigation water quality on the growth and water use of selected crops. Water Research Commission Report 1359/1/06, Pretoria.

EPSTEIN, E., & RAINS, D.W., 1987. Advances in salt tolerance. *Plant and Soil* 99, 17-29.

FAO, 1990. An International action programme on water and sustainable agricultural development. A strategy for the implementation of the Mar del Plata Action Plan of the 1990s. Rome, Italy.

FLOWERS, T.J., TROKE, P.F. & YEO, A.R., 1977. The mechanism of salt tolerance in halophytes. *Ann. Rev. Plant Physiol*. 28, 89-121.

GHAMARNIA, H., GOWING, J. & ROSE, D., 2004. Wheat water use from shallow saline water tables in lysimeter experiment. The *55th IEC meeting, international workshop on management of poor quality water for irrigation: institutional, health and environmental aspects, 90-101.*

GRATTAN, S.R. & MAAS, E.V., 1988. Effect of salinity on phosphate accumulation and injury in soybean. I. Influence of $CaCl_2$/NaCl ratios. *Plant and Soil* 105, 25-32.

GREENWAY, H. & MUNNS, R., 1980. Mechanisms of salt tolerance in nonhalophytes. *Ann. Rev. Plant Physiol*. 31, 149-190.

GRISMER, R.F. & GATES, T.K., 1988. Estimating saline water table contributions to crop water use. *California Agric. 2, 23-24.*

HALL, G.C. & GöRGENS, A.H.M., 1978. Studies of mineralisation of South African rivers. *S. Nat. Sci. Prog. Rep*. 26.

HERALD, J., 1999. Hydrosalinity studies in the Coerney valley. Volume 1. Final report. Water Research Commission Report 195/1/99, Pretoria.

HEROLD, C.E. & BAILEY, A.K., 1996. Long term salt balance of the Vaalharts Irrigation Scheme. Water Research Commission Report 420/1/96, Pretoria.

HILLEL, D., 1998. Environmental soil physics. Academic Press, New York.

HOFFMAN, G.J., 1990. Leaching fraction and root zone salinity control. In K.K. Tanji (ed.). Agricultural salinity and management. Am. Soc of Civ. Eng., New York.

JOVANOVIC, N.Z, EHLERS, L., BENNIE, A.T.P., DU PREEZ, C.C. & ANNANDALE, J.G., 2004. Modelling the contribution of root accessible water tables towards crop water requirements. Plant and Soil 21 (3), 171-181.

JURINAK, J.J. & SUAREZ, D.L., 1996. The chemistry of salt-affected soils and water. In K.K. Tanji (ed.). Agricultural salinity and management. Am. Soc of Civ. Eng., New York.

JURY, W.A., GARDNER, W.R. & GARDNER, W.H., 1991. Soil physics. John Wiley & Sons, New York.

KANG, S., ZHANG, F., HU, X., JERIE, P. & ZHANG, L., 2001. Effects of shallow water table on capillary contribution, evapotranspiration and crop coefficient of maize and winter wheat in a semi-arid region. *Aust. J. Agric*. Res. 52, 317-327.

KATERJI, N., VAN HOORN, J.W., HANDY, A. & MASTROLLI, M., 2003. Salinity effect of crop development and yield, analysis of salt tolerance according several classification methods. *Agric. Water Manage*. 62, 37-66.

LE ROUX, P.A.L., DU PREEZ, C.C., STRYDOM, M.G., VAN RENSBURG, L.D. & BENNIE, A.T.P., 2007. Effect of irrigation on soil salinity profiles along the Lower Vaal River, South Africa. *Water S.A.* 33 (4), 473-478.

LETEY, J., 1984. Impact of salinity on the development of soil science. In I. Shainberg, & J. Shalhevet (Eds). Soil salinity under irrigation. Springer-Verslag, New York.

MAAS, E.V., 1984. Salt tolerance of plants. In B.R. Christie (ed.). Handbook of plant science in agriculture. CRC Press, Boca Raton, Florida.

MAAS, E.V., 1985. Crop tolerance to saline sprinkling waters. *Plant and Soil* 89, 273-284.

MAAS, E.V., 1986. Salt tolerance of plants. *Appl. Agric. Res.* 1, 12-26.

MAAS, E.V., 1990. Crop salt tolerance. In K.K. Tanji (ed). Agricultural salinity assessment and management. Am. Soc. of Civil Eng., New York.

MAAS, E.V. & GRIEVE, C.M., 1987. Sodium-induced calcium deficiency in salt-stressed corn. *Plant, Cell and Environment* 10, 559-564.

MAAS, E.V. & HOFFMAN, G.J., 1977. Crop salt tolerance – current assessment. *J. Irrig. Drain. Div. Am. Soc. Civ. Eng*. 103, 115-134.

MEYER, W.S., WHITE, B. & SMITH, D., 1994. Water use of lucerne over shallow water tables. Int. Water & Irrigation Review.

MILLER, R.J., NIELSEN, D.R. & BIGGAR, J.W., 1965. Chloride displacement in Panoche clay loam in relation to water movement and distribution. *J. Water Resour. Res*. 1:63-73.

MIYOMOTO, S., GOBRAN, G.R. & PIELA, K., 1985. Salt effects on seedling growth and water uptake of three bean rootstock cultivars. *Agron. J*. 7, 383-388.

MUNNS, R., GREENWAY, H. & KIRST, G.O., 1983. Halotolerant eukaryotes. In O.L. Lange, P.S. Nobel, C.B. Osmond & H. Ziegler (eds.). Encyclopedia of plant physiology new series. Springer-Verlag, Berlin.

NIELSEN, D.R. & BIGGAR, J.W., 1961. Miscible displacement in soils. *Soil Sci. Soc. Am. Proc. 25, 1-5.*

NIELSEN, D.R., BIGGAR, J.W., & LUTHIN, J.N., 1966. Desalination of soils under controlled unsaturated flow conditions. The 6th Congress of International Commission on Irrigation and Drainage Proceedings, New Delhi, India.

NYE, P.H. & TINKER, P.B., 1977. Solute movement in the soil-root system. Studies in ecology, Volume 4. The Alden Press, Oxford.

OSTER, J.D., WILLARDSON, .S. & HOFFMAN, G.J., 1972. Sprinkling and ponding techniques for reclaiming saline soils. *Transactions of the ASAE* 15, 1115-1117.

OSTER, J.D., 1994. Irrigation with poor quality water. *Agric. Water Manage. 25, 271-297.*

RAGAB, R., 2002. A holistic generic integrated approach for irrigation, crop and field management: the SALTMED model. *Environmental Modelling & Software 17, 345-361.*

RHOADES, J.D., 1972. Quality of water for irrigation. *Soil Sci.* 113, 277-284.

RHOADES, J.D., 1974. Drainage for salinity control. In J. Van Schilfgaarde (ed.) Drainage for agriculture. Agronomy 17, 433-461.

RHOADES, J.D., CORWIN, D.L. & HOFFMAN, G.J., 1981. Scheduling and controlling irrigations from measurements of soil electrical conductivity. *Proceedings of ASAE Irrigation Scheduling Conference, Chicago.*

RHOADES, J.D. & LOVEDAY, J., 1990. Salinity in irrigated agriculture. In A.B. Steward & D.R. Nielson (eds). Irrigation of agricultural crops. Agron. Soc. of Am., Madison, Wisconsin.

RHOADES, J.D. & MERRILL, S.D., 1976. Assessing the suitability of water for irrigation: Theoretical and empirical approaches. *FAO Soils Bulletin* 31, 69-109.

SCHWARZ, M. & GALE, J., 1981. Maintenance respiration and carbon balance of plants at low levels of sodium chloride salinity. *J. Exp. Bot*. 32, 933-941.

SEPASKHAH, A.R. & KARIMI-GOGHARI, S.H., 2005, Shallow groundwater contribution to pistachio water use. *Agric. Water Manage. 72, 69-80.*

SHALHEVET, J. & BERNSTEIN, L., 1968. Effects of vertically heterogeneous soil salinity on plant growth and water. *Soil Sci*. 106, 85-93.

SHANNON, M.C., 1982. Genetics of salt tolerance: New challenges. In A. San Pietro (ed.) Biosaline research: A look into the future. Plenum Publ. Corp., New York.

SHANNON, M.C. & FRANCOIS, L.E., 1977. Influence of seed pretreatments on salt tolerance of cotton during germination. *Agron. J.* 69, 619-622.

SOIL CLASSIFICATION WORKING GROUP, 1991. Soil classification: a taxonomic system for South Africa. Memoirs on the Agricultural Natural Resources of South Africa No. 15, Department of Agricultural Development, Pretoria, South Africa.

STEWART, J.L., DANIELSON, R.E., HANKS, R.J., JACKSON, E.B., HAGON, R.M., PRUIT, W.O., FRANKLIN, W.T. & RILEY, J.P., 1977. Optimizing crop production through control of water and salinity levels in the soil. Utah Water Research Laboratory Progress Report 151, Logan, Utah.

STREUTKER, A., VAN VLIET, N. & MOLENAAR, H.W., 1981. Besproeiing, gewasopbrengs en dreinering op die Vaalhartsbesproeiingskema: 3. Die invloed van verbrakking bo ‘n vlak grondwaterstand op die opbrengs van koring en ander gewasse. *Water S.A.* 7, 255-264.

SZABOLCS, I., 1989. Salt-Affected Soils. CRC Press, Boca Raton, Florida.

THE NON AFFILIATED SOIL ANALYSIS WORK COMMITTEE, 1990. Handbook of standard soil testing methods for advisory purposes. Soil Science Society of South Africa, Pretoria.

UNITED STATES SALINITY LABORATORY STAFF, 1969. Diagnosis and improvement of saline and alkaline soils. U.S. Laboratory Handbook 60, USDA, Washington.

VAN HEERDEN, P.S., CROSBY, C.T. & CROSBY, C.P., 2001. Using SAPWAT to estimate water requirements of crops in selected irrigation areas managed by the Orange-Vaal and Orange-Riet Water Users Associations. Water Research Commission Report TT163/01, Pretoria.

VAN RENSBURG, L.D., STRYDOM, L.D., DU PREEZ, C.C., BENNIE, A.T.P., LE ROUX, P.A.L. & PRETORIUS, J.P., 2007. Prediction of salt balances in irrigated soils along the Lower Vaal River, South Africa. *Water S.A.* (Article in press).

VOLSCHENK, T., FEY, M.V. & ZIETSMAN, H.L., 2005. Situation analysis of problems for water quality management in the lower Orange River region with special reference to the contribution of the foothills to salinization. Water Research Commission Report 1358/1/05, Pretoria.

WADLEIGH, C.H. & AYERS, A.D., 1945. Growth and biochemical composition of bean plants as conditioned by soil moisture tension and salt concentration. *Plant Physiol*. 20, 106-132.

WAGENET, R.J., 1984. Salt and water movement in the soil profile. In I. Shainberg & J. Shalhevet (Eds). Soil salinity under irrigation. Springer-Verslag, New York.

WALLENDER, W.W., GRIMES, D.W., HENDERSON, D.W. & STROMBERG, L.K., 1979. Estimating the contribution of a perched water table to the seasonal evapotranspiration of cotton. *Agron. J*. 71, 1056-1060.

WEST, D.W., HOFFMANN, G.J. & FISHER, M.J., 1986. Photosynthesis, leaf conductance and water relations of cowpea under saline conditions. *Irrig. Sci. J.* 7, 183-193.

WYN JONES, R.G., 1981. Salt tolerance. In C.B. Johnson (ed.) Physiological processes limiting plant productivity. Butterworth, London.

WYN JONES, R.G. & GORHAM, J., 1983. Osmoregulation. In O.L. Lange, P.S. Nobel, C.B. Osmond & H. Ziegler (eds.) Encyclopedia of plant physiology new series. Springer-Verlag, Berlin.

ZANG, L., DAWES, W.R., SLAVICH, P.G., MEYER, W.S., THORBURN, P.J., SMITH, D.J. & WALKER, G.R., 1999. Growth and ground water uptake responses of lucerne to changes in groundwater levels and salinity: lysimeter, isotope and modelling studies. *Agric. Water Manage*. 39, 265-282.

APPENDIX 3

Appendix 3.1 The amount of irrigation water applied at specific days after planting (DAP) for all the soils, crops and EC_i treatments

Wheat																				
Soil	**A**										**B**									
EC_i (mS m^{-1})	**15***		**150**		**300**		**450**		**600**		**15***		**150**		**300**		**450**		**600**	
DAP	**mm**	**liter**	**mm**	**liter**	**mm**	**liter**	**mm**	**liter**	**mm**	**liter**	**mm**	**liter**	**mm**	**liter**	**mm**	**liter**	**mm**	**liter**	**mm**	**liter**
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	7	17	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	3	8	0	0	8	21	0	0	0	0	0	0	0	0	0	0
33	7	17	7	17	10	25	0	0	7	17	21	53	12	31	7	19	10	25	11	27
46	0	0	7	17	7	17	17	42	12	30	0	0	0	0	0	0	0	0	0	0
54	43	110	35	88	52	133	41	105	46	118	29	73	33	84	37	95	28	71	23	59
61	0	0	0	0	15	38	3	8	23	59	0	0	0	0	0	0	0	0	0	0
67	0	0	3	8	10	25	7	17	18	47	0	0	0	0	27	70	18	46	13	33
75	38	98	26	66	25	64	29	75	23	59	39	99	48	121	32	81	23	59	25	64
81	27	68	29	73	35	88	33	84	42	107	19	49	20	51	27	68	22	57	15	38
89	0	0	0	0	3	8	0	0	3	8	22	57	32	81	17	42	20	51	25	64
96	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	30	0	0	0	0
103	0	0	3	8	13	34	20	51	30	76	0	0	7	17	23	59	32	81	25	64
110	22	55	30	76	25	64	22	55	20	51	17	42	23	59	24	62	24	62	22	56
117	18	47	17	44	16	42	7	17	25	63	14	36	24	61	12	30	3	8	0	0
124	31	80	30	76	32	82	41	103	19	48	19	49	22	56	10	25	24	62	31	79
131	17	43	28	72	28	72	37	93	38	98	15	39	26	65	17	42	20	51	23	59
134	34	86	38	98	40	101	45	115	43	110	30	76	40	102	40	102	40	102	40	102
145	29	73	30	76	30	76	30	76	30	76	20	51	20	51	20	51	20	51	20	51
Total	**266**	**676**	**283**	**720**	**345**	**879**	**331**	**842**	**395**	**1005**	**246**	**625**	**306**	**780**	**305**	**775**	**285**	**726**	**273**	**695**

Beans																				
Soil	**A**										**B**									
EC_i (mS m^{-1})	**15***		**150**		**300**		**450**		**600**		**15***		**150**		**300**		**450**		**600**	
DAP	**mm**	**liter**	**mm**	**liter**	**mm**	**liter**	**mm**	**liter**	**mm**	**liter**	**mm**	**liter**	**mm**	**liter**	**mm**	**liter**	**mm**	**liter**	**mm**	**liter**
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	24	60	24	60	24	60	24	60	24	60	24	60	24	60	24	60	24	60	24	60
16	16	40	16	40	16	40	16	40	16	40	16	40	16	40	16	40	16	40	16	40
23	39	100	39	100	39	100	39	100	39	100	39	100	39	100	39	100	39	100	39	100
30	16	40	16	40	16	40	16	40	16	40	16	40	16	40	16	40	16	40	16	40
37	24	60	16	40	16	40	16	40	16	40	24	60	16	40	16	40	16	40	16	40
45	39	100	24	60	16	40	8	20	8	20	36	92	31	80	24	60	8	20	16	40
52	39	100	31	80	24	60	8	20	8	20	39	100	31	80	24	60	8	20	8	20
59	39	100	31	80	24	60	8	20	8	20	39	100	31	80	24	60	8	20	8	20
66	39	100	31	80	24	60	8	20	8	20	39	100	31	80	24	60	8	20	8	20
73	31	80	31	80	24	60	8	20	8	20	31	80	31	80	24	60	8	20	8	20
80	31	80	31	80	24	60	8	20	8	20	31	80	31	80	24	60	8	20	8	20
87	24	60	24	60	16	40	8	20	8	20	24	60	8	20	8	20	8	20	8	20
94	24	60	16	40	12	30	8	20	8	20	24	60	8	20	8	20	8	20	8	20
101	16	40	0	0	0	0	0	0	0	0	16	40	0	0	0	0	0	0	0	0
Total	**401**	**1020**	**330**	**840**	**271**	**690**	**173**	**441**	**173**	**441**	**397**	**1012**	**314**	**800**	**267**	**681**	**173**	**441**	**181**	**461**

Appendix 3.1 continued

Peas

Soil	A										B									
EC_i (mS m^{-1})	15*		75		150		225		300		15*		75		150		225		300	
DAP	mm	liter	mm	liter	mm	liter	mm	liter	mm	liter	mm	liter	mm	liter	mm	liter	mm	liter	mm	liter
1	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0
8	8	20	8	20	8	20	8	20	8	20	8	20	8	20	8	20	8	20	8	20
15	8	20	8	20	4	10	8	20	8	20	12	30	12	30	8	20	8	20	8	20
22	16	40	16	40	16	40	16	40	16	40	24	60	16	40	16	40	16	40	16	40
29	16	40	17	43	16	40	16	40	16	40	20	50	16	40	16	40	16	40	16	40
36	54	138	59	150	53	136	51	129	53	134	47	120	45	115	40	102	38	98	37	94
43	5	12	8	20	5	12	5	12	5	12	5	12	5	12	5	12	5	12	5	12
50	38	96	44	111	53	135	43	110	62	159	37	95	45	115	39	99	36	91	35	90
57	20	50	20	50	20	50	20	50	20	50	16	40	16	40	16	40	16	40	16	40
64	24	60	26	65	24	60	24	60	24	60	20	50	20	50	20	50	20	50	20	50
71	24	60	24	60	24	60	24	60	24	60	24	60	24	60	24	60	24	60	24	60
78	28	70	31	80	20	50	20	50	20	50	28	70	28	70	20	50	20	50	20	50
85	47	120	45	113	35	90	35	90	35	90	39	100	35	90	31	80	31	80	32	82
92	43	110	43	110	35	90	35	90	31	80	43	110	39	100	35	90	35	90	31	80
100	31	80	31	80	24	60	24	60	24	60	35	90	31	80	24	60	24	60	24	60
106	16	40	24	60	39	100	20	50	39	100	20	50	31	80	28	70	28	70	28	70
113	28	70	39	100	28	70	28	70	24	60	38	97	31	80	24	60	24	60	24	60
120	47	120	43	110	31	80	31	80	24	60	47	120	43	110	31	80	31	80	24	60
Total	**450**	**1146**	**485**	**1233**	**433**	**1103**	**405**	**1031**	**430**	**1095**	**461**	**1174**	**444**	**1131**	**382**	**973**	**377**	**960**	**365**	**928**

Maize

Soil	A										B									
EC_i (mS m^{-1})	15*		150		300		450		600		15*		150		300		450		600	
DAP	mm	liter	mm	liter	mm	liter	mm	liter	mm	liter	mm	liter	mm	liter	mm	liter	mm	liter	mm	liter
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0
19	16	40	16	40	16	40	16	40	16	40	16	40	16	40	16	40	16	40	16	40
26	24	60	24	60	24	60	24	60	24	60	16	40	16	40	16	40	16	40	16	40
33	24	60	24	60	24	60	24	60	24	60	20	50	20	50	20	50	20	50	20	50
40	28	70	28	70	18	47	24	60	24	60	21	53	35	90	21	53	31	80	31	80
47	35	90	29	73	24	60	22	57	20	50	24	60	30	77	20	50	21	53	24	60
54	35	90	28	70	24	60	22	57	21	53	34	87	33	83	28	70	26	67	25	63
61	29	73	26	67	14	37	12	30	9	23	24	60	21	53	12	30	11	27	11	27
68	35	90	30	77	24	60	21	53	17	43	33	83	33	83	26	67	21	53	21	53
75	21	53	16	40	12	30	9	23	9	23	24	60	20	50	12	30	9	23	9	23
82	21	53	21	53	13	33	11	27	8	20	21	53	20	50	13	33	11	27	9	23
89	22	57	20	50	12	30	12	30	12	30	21	53	18	47	13	33	11	27	12	30
96	18	47	14	37	12	30	12	30	8	20	16	40	17	43	12	30	12	30	12	30
103	18	47	14	37	12	30	12	30	8	20	16	40	13	33	12	30	12	30	12	30
110	16	40	14	37	12	30	8	20	8	20	14	37	13	33	8	20	4	10	12	30
117	14	37	13	33	12	30	8	20	8	20	14	37	13	33	12	30	12	30	8	20
124	14	37	12	30	4	10	8	20	4	10	12	30	4	10	0	0	0	0	4	10
132	8	20	13	33	8	20	8	20	8	20	13	33	12	30	12	30	12	30	8	20
138	12	30	12	30	8	20	8	20	8	20	12	30	4	10	4	10	4	10	12	30
Total	**390**	**993**	**352**	**896**	**270**	**687**	**258**	**657**	**233**	**594**	**348**	**886**	**337**	**857**	**254**	**647**	**246**	**627**	**259**	**660**

* control

Appendix 3.2 Seed and total biomass yield data for all the soils, crops and EC_i treatments

Wheat							
		Yield (kg lysimeter^{-1})			**Biomass (kg lysimeter^{-1})**		
Soil	**EC_i (mS m^{-1})**	**Rep 1**	**Rep 2**	**Rep 3**	**Rep 1**	**Rep 2**	**Rep 3**
A	**15**	1.40	1.38	1.55	2.54	2.61	2.35
	150	1.21	1.48	1.46	2.24	2.23	2.37
	300	0.99	1.61	1.54	2.34	2.35	2.31
	450	1.34	1.41	1.37	2.11	2.00	1.90
	600	1.35	1.18	1.23	2.20	1.95	1.73
B	**15**	1.59	1.50	1.52	2.48	2.47	2.39
	150	1.50	1.55	1.67	2.32	2.51	2.53
	300	1.53	1.62	1.62	2.35	2.37	2.43
	450	1.42	1.59	1.42	2.23	2.31	2.22
	600	1.60	1.60	1.55	2.25	2.10	2.05

Beans							
		Yield (kg lysimeter^{-1})			**Biomass (kg lysimeter^{-1})**		
Soil	**EC_i (mS m^{-1})**	**Rep 1**	**Rep 2**	**Rep 3**	**Rep 1**	**Rep 2**	**Rep 3**
A	**15**	1.25	1.39	1.50	1.68	1.55	1.65
	150	0.95	0.77	0.72	1.22	1.02	1.08
	300	0.30	0.28	0.32	0.51	0.43	0.59
	450	0.00	0.01	0.01	0.01	0.02	0.01
	600	0.00	0.00	0.00	0.00	0.00	0.00
B	**15**	1.37	1.33	1.48	1.59	1.54	1.62
	150	0.51	0.48	0.51	0.98	0.99	1.00
	300	0.27	0.25	0.24	0.70	0.55	0.65
	450	0.10	0.05	0.10	0.22	0.15	0.26
	600	0.02	0.04	0.00	0.07	0.14	0.01

Peas							
		Yield (kg lysimeter^{-1})			**Biomass (kg lysimeter^{-1})**		
Soil	**EC_i (mS m^{-1})**	**Rep 1**	**Rep 2**	**Rep 3**	**Rep 1**	**Rep 2**	**Rep 3**
A	**15**	1.25	1.27	1.25	1.52	1.66	1.72
	75	1.28	1.14	1.09	1.57	1.24	1.61
	150	1.06	1.12	1.09	1.35	1.24	1.32
	225	1.03	0.99	1.01	1.11	1.21	1.29
	300	0.67	0.77	0.53	1.05	0.92	0.92
B	**15**	1.06	1.29	1.14	1.34	1.55	1.33
	75	1.25	1.04	1.25	1.45	1.31	1.50
	150	0.88	1.09	1.07	1.35	1.31	1.28
	225	0.96	0.94	0.95	1.00	1.38	1.16
	300	0.70	0.81	0.53	0.80	0.91	0.79

Maize							
		Yield (kg lysimeter^{-1})			**Biomass (kg lysimeter^{-1})**		
Soil	**EC_i (mS m^{-1})**	**Rep 1**	**Rep 2**	**Rep 3**	**Rep 1**	**Rep 2**	**Rep 3**
A	**15**	3.86	3.64	3.69	4.21	4.34	3.88
	150	3.38	3.31	3.49	4.42	3.81	4.41
	300	3.26	2.63	2.18	3.93	4.20	3.50
	450	1.79	1.94	2.04	2.47	2.89	2.97
	600	1.10	1.10	1.06	1.83	2.48	2.79
B	**15**	2.76	3.38	3.49	3.10	3.60	3.83
	150	3.42	2.56	3.44	4.29	4.25	4.42
	300	2.96	2.66	2.14	3.49	3.98	3.12
	450	1.98	1.98	1.84	2.98	2.73	3.13
	600	1.08	1.28	1.11	2.84	2.67	2.29

Appendix 3.3 Example of a water balance sheet for the control treatment of maize on Soil A during the first 26 days after planting

EXPERIMENTAL SITE : **KENILWORTH - BLOEMFONTEIN**
CROP **Maize**
PLANTING DATE : **17 December 2004**
LYSIMETER NUMBER : **2, 4, 13**
TREATMENT : **SOIL A - CONTROL**

DATE		29-Dec-04										05-Jan-05										12-Jan-05									
DAYS AFTER PLANTING		12										19										26									
		Rep 1			Rep 2			Rep 3				Rep 1			Rep 2			Rep 3				Rep 1			Rep 2			Rep 3			
REPLICATION		Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	**AVE**	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	**AVE**	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	**AVE**
0-300 (mm)		0.069	0.061	0.065	0.065	0.083	0.074	0.049	0.061	0.055	**0.065**	0.054	0.046	0.050	0.053	0.072	0.062	0.039	0.049	0.044	**0.052**	0.048	0.048	0.048	0.049	0.068	0.059	0.036	0.046	0.041	**0.049**
300-600 (mm)		0.151	0.147	0.149	0.155	0.150	0.152	0.153	0.153	0.153	**0.152**	0.142	0.138	0.140	0.144	0.141	0.143	0.141	0.145	0.143	**0.142**	0.139	0.137	0.138	0.142	0.138	0.140	0.144	0.145	0.144	**0.141**
600-900 (mm)		0.172	0.177	0.174	0.175	0.186	0.181	0.180	0.169	0.174	**0.176**	0.161	0.164	0.163	0.167	0.175	0.171	0.164	0.158	0.161	**0.165**	0.170	0.174	0.172	0.173	0.188	0.180	0.177	0.171	0.174	**0.175**
900-1200 (mm)	θv	0.282	0.279	0.281	0.291	0.290	0.290	0.301	0.290	0.295	**0.289**	0.282	0.279	0.281	0.291	0.290	0.290	0.301	0.290	0.295	**0.289**	0.282	0.279	0.281	0.291	0.290	0.290	0.301	0.290	0.295	**0.289**
1200-1500 (mm)		0.303	0.302	0.303	0.309	0.296	0.303	0.308	0.315	0.311	**0.306**	0.303	0.302	0.303	0.309	0.296	0.303	0.308	0.315	0.311	**0.306**	0.303	0.302	0.303	0.309	0.296	0.303	0.308	0.315	0.311	**0.306**
1500-1800 (mm)		0.287	0.286	0.286	0.292	0.289	0.291	0.292	0.278	0.285	**0.287**	0.287	0.286	0.286	0.292	0.289	0.291	0.292	0.278	0.285	**0.287**	0.287	0.286	0.286	0.292	0.289	0.291	0.292	0.278	0.285	**0.287**
MEAN	0-1800mm (mm/mm)			**0.210**			**0.215**			**0.212**	**0.212**			**0.204**			**0.210**			**0.207**	**0.207**			**0.205**			**0.210**			**0.208**	**0.208**
TOTAL W	0-1800mm (mm)			377.43			387.12			382.31	**382.285**			366.59			377.85			371.91	**372.1**			368.22			378.75			375.18	**374.05**
CHANGE W	0-1800mm (mm)			0			0			0	**0**			-10.845			-9.3			-10.395	**-10.2**			1.635			0.9			3.27	**1.935**
PAW upper	0-1800mm (mm)			391			391			391	**391**			391			391			391	**391**			391			391			391	**391**
PAW lower	0-1800mm (mm)			212			212			212	**212**			212			212			212	**212**			212			212			212	**212**
WATER DEFICIT	0-1800mm (mm)			13.57			3.88			8.695	**8.715**			24.415			13.15			19.09	**18.9**			22.78			12.25			15.82	**17.0**
PAW	0-1800mm (mm)			165.43			175.12			170.31	**170.29**			154.59			165.85			159.91	**160.1**			156.22			166.75			163.18	**162.1**
IRRIGATION	**(mm)**			**0**			**0**			**0**	**0**			**15.7**			**15.7**			**15.7**	**15.7**			**23.6**			**23.6**			**23.6**	**23.6**
RAINFALL	(mm)			0			0			0	**0**			0			0			0	**0.0**			0			0			0	**0.0**
IRRIGATION + RAINFALL	(mm)			0			0			0	**0**			15.7			15.7			15.7	**15.7**			23.6			23.6			23.6	**23.6**
WT DEPLETION	(mm)			0			0			0	**0**			0			0			0	**0.0**			0			0			0	**0.0**
	(mm/day)			**0**			**0**			**0**	**0**			**0**			**0**			**0**	**0.0**			**0**			**0**			**0**	**0.0**
PERCOLATION	**1800mm (mm)**			**0**			**0**			**0**	**0**			**0**			**0**			**0**	**0.0**			**0**			**0**			**0**	**0.0**
EVAPOTRANSPIRATION	(mm)			0			0			0	**0**			26.545			24.97			26.095	**25.9**			21.965			22.7			20.33	**21.7**
	(mm/day)			**0**			**0**			**0**	**0**			**3.7921**			**3.5671**			**3.7279**	**3.7**			**3.1379**			**3.2429**			**2.9043**	**3.1**
Eo	(mm/day)			7.16			7.16			7.16	**7.16**			8.54			8.54			8.54	**8.54**			6.6			6.6			6.6	**6.6**
CUM EVAPOTRANSPIRATION	(mm)			0			0			0	**0**			26.55			24.97			26.10	**25.87**			48.51			47.67			46.43	**47.54**
CUM IRRIGATION + RAINFALL	(mm)										**0**			15.70			15.70			15.70	**15.70**			39.30			39.30			39.30	**39.30**
CUM WT DEPLETION	(mm)										**0**			0.00			0.00			0.00	**0.00**			0.00			0.00			0.00	**0.00**
CUM PERCOLATION	1800mm (mm)										**0**			0.00			0.00			0.00	**0.00**			0.00			0.00			0.00	**0.00**

θv = volumetric water content; PAW = plant available water; WT = water table; W = profile water content

APPENDIX 4

Appendix 4.1 The electrical conductivity of the soil water at the beginning (EC_{sw} in, mS m^{-1}) and end (EC_{sw} end, mS m^{-1}) of the growing seasons of all the crops at the various EC_i treatments for both soils

Wheat											
EC_i (mS m^{-1})		**15**		**150**		**300**		**450**		**600**	
Soil	**Depth (mm)**	**EC_{sw} in**	**EC_{sw} end**	**EC_{sw} in**	**EC_{sw} end**	**EC_{sw} in**	**EC_{sw} end**	**EC_{sw} in**	**EC_{sw} end**	**EC_{sw} in**	**EC_{sw} end**
A	**300**	15	162	150	321	300	510	450	720	600	840
	500	15	101	150	553	300	808	450	975	600	918
	700	15	285	150	1136	300	1374	450	1704	600	1988
	900	15	131	150	451	300	854	450	1562	600	1591
	1100	15	90	150	260	300	890	450	1400	600	1570
	1500	15	91	150	190	300	400	450	590	600	1168
B	**300**	15	78	150	271	300	365	450	927	600	880
	500	15	124	150	515	300	609	450	1381	600	1391
	700	15	159	150	1087	300	1333	450	1841	600	2228
	900	15	140	150	397	300	1036	450	1623	600	2133
	1100	15	97	150	250	300	598	450	1098	600	1390
	1500	15	70	150	211	300	343	450	597	600	735

Beans											
EC_i (mS m^{-1})		**15**		**150**		**300**		**450**		**600**	
Soil	**Depth (mm)**	**EC_{sw} in**	**EC_{sw} end**	**EC_{sw} in**	**EC_{sw} end**	**EC_{sw} in**	**EC_{sw} end**	**EC_{sw} in**	**EC_{sw} end**	**EC_{sw} in**	**EC_{sw} end**
A	**300**	162	142	321	528	510	823	720	1785	840	2815
	500	101	144	553	509	808	1002	975	2011	918	2474
	700	285	288	1136	715	1374	936	1704	1640	1988	1736
	900	131	144	451	812	854	842	1562	1110	1591	1255
	1100	90	129	260	473	890	788	1400	1237	1570	1464
	1500	91	103	190	227	400	619	590	1167	1168	1580
B	**300**	78	206	271	580	365	1446	927	1883	880	1891
	500	124	218	515	592	609	2115	1381	1729	1391	1590
	700	159	180	1087	656	1333	1935	1841	1451	2228	1601
	900	140	150	397	837	1036	1345	1623	1591	2133	2230
	1100	97	140	250	453	598	963	1098	1355	1390	1727
	1500	70	64	211	696	343	428	597	839	735	1151

Peas											
EC_i (mS m^{-1})		**15**		**75**		**150**		**225**		**300**	
Soil	**Depth (mm)**	**EC_{sw} in**	**EC_{sw} end**	**EC_{sw} in**	**EC_{sw} end**	**EC_{sw} in**	**EC_{sw} end**	**EC_{sw} in**	**EC_{sw} end**	**EC_{sw} in**	**EC_{sw} end**
A	**300**		68	120	163	119	328	255	354	367	475
	500	45	93	118	240	132	507	248	436	410	716
	700	48	123	110	390	131	715	260	544	415	812
	900	49	128	116	222	131	436	251	387	420	654
	1100	52	70	117	149	114	259	253	315	385	542
	1500	75	72	122	117	115	178	240	262	384	436
B	**300**	52	91	102	266	175	743	209	731	386	752
	500	45	92	95	343	179	713	213	675	344	1003
	700	45	126	97	393	129	453	214	676	352	967
	900	44	76	88	171	114	207	204	313	378	585
	1100	61	57	114	130	120	188	217	273	373	419
	1500	74	52	157	133	216	184	272	279	457	430

Maize											
EC_i (mS m^{-1})		**15**		**150**		**300**		**450**		**600**	
Soil	**Depth (mm)**	**EC_{sw} in**	**EC_{sw} end**	**EC_{sw} in**	**EC_{sw} end**	**EC_{sw} in**	**EC_{sw} end**	**EC_{sw} in**	**EC_{sw} end**	**EC_{sw} in**	**EC_{sw} end**
A	**300**	70	174	213	1209	382	1131	592	2138	708	2088
	500	65	578	196	1415	354	1456	521	1844	870	3314
	700	67	150	204	943	384	1864	557	1964	624	2216
	900	80	121	184	540	324	1054	483	1303	578	1512
	1100	94	101	192	293	268	683	461	931	543	1172
	1500	89	78	265	212	497	414	536	559	830	808
B	**300**	61	139	228	1149	358	1970	610	2374	663	2670
	500	52	108	169	923	329	1190	505	1633	686	2510
	700	75	163	200	738	334	1110	495	1548	701	1817
	900	92	89	200	298	353	1458	524	1012	742	1311
	1100	88	70	234	223	415	443	503	696	781	794
	1500	69	50	221	223	340	356	486	558	715	664

APPENDIX 6

Appendix 6.1 Summary of 50 year meteorological data for the Glen Agricultural Institution near Bloemfontein

Season No	Year	Crop	Days to FR	Cum ETo (mm)	Ave ETo (mm day^{-1})	Cum Rain (mm)	No of Rainfall Events	R_{eff} (mm)
1	1950	Wheat	156	595	3.8	129	6	80
2	1950/1951	Maize	131	699	5.3	320	1	310
3	1951	Wheat	156	589	3.8	102	5	85
4	1951/1952	Maize	131	749	5.7	206	3	181
5	1952	Wheat	156	588	3.8	152	5	108
6	1952/1953	Maize	132	717	5.4	301	4	261
7	1953	Wheat	156	601	3.9	142	4	113
8	1953/1954	Maize	131	676	5.2	393	4	360
9	1954	Wheat	156	666	4.3	41	5	24
10	1954/1955	Maize	131	683	5.2	339	4	309
11	1955	Wheat	156	614	3.9	104	4	74
12	1955/1956	Maize	131	693	5.3	443	2	423
13	1956	Wheat	156	654	4.2	99	3	79
14	1956/57	Maize	132	726	5.5	247	4	207
15	1957	Wheat	156	591	3.8	275	3	245
16	1957/1958	Maize	131	731	5.6	280	1	270
17	1958	Wheat	156	653	4.2	144	3	124
18	1958/1959	Maize	131	729	5.6	243	3	213
19	1959	Wheat	156	623	4.0	147	4	126
20	1959/1960	Maize	131	717	5.5	364	1	354
21	1960	Wheat	156	631	4.0	128	6	83
22	1960/1961	Maize	132	712	5.4	286	1	276
23	1961	Wheat	156	631	4.0	54	6	27
24	1961/1962	Maize	131	723	5.5	312	2	292
25	1962	Wheat	156	660	4.2	108	5	93
26	1962/1963	Maize	131	660	5.0	436	2	416
27	1963	Wheat	156	617	4.0	198	4	170
28	1963/1964	Maize	131	790	6.0	178	3	158
29	1964	Wheat	156	606	3.9	235	4	207
30	1964/1965	Maize	132	730	5.5	248	3	228
31	1965	Wheat	156	603	3.9	97	5	64
32	1965/1966	Maize	131	710	5.4	292	4	267
33	1966	Wheat	156	618	4.0	47	3	28
34	1966/1967	Maize	131	664	5.1	497	1	487
35	1967	Wheat	156	642	4.1	90	5	68
36	1967/1968	Maize	131	735	5.6	305	2	285
37	1968	Wheat	156	632	4.0	58	5	34
38	1968/1969	Maize	132	748	5.7	271	2	251
39	1969	Wheat	156	617	4.0	150	5	120
40	1969/1970	Maize	131	778	5.9	210	3	180
41	1970	Wheat	156	603	3.9	191	5	147
42	1970/1971	Maize	131	692	5.3	286	3	256
43	1971	Wheat	156	609	3.9	95	4	81
44	1971/1972	Maize	131	643	4.9	508	3	478
45	1972	Wheat	156	651	4.2	28	3	8
47	1972/1973	Maize	132	614	4.7	95	4	65
47	1973	Wheat	156	749	4.8	230	4	65
48	1973/1974	Maize	131	605	4.6	595	1	585
49	1974	Wheat	156	616	4.0	121	5	95
50	1974/1975	Maize	131	682	5.2	317	2	297

Appendix 6.1 continued

Season No	Year	Crop	Days to FR	Cum ETo (mm)	Ave ETo (mm day^{-1})	Cum Rain (mm)	No of Rainfall Events	R_{eff} (mm)
51	1975	Wheat	156	639	4.1	145	6	109
52	1975/1976	Maize	131	589	4.5	544	2	524
53	1976	Wheat	156	605	3.9	196	4	169
54	1976/1977	Maize	132	694	5.3	448	2	428
55	1977	Wheat	156	656	4.2	128	5	99
56	1977/1978	Maize	131	760	5.8	359	2	339
57	1978	Wheat	156	711	4.6	61	5	29
58	1978/1979	Maize	131	832	6.4	211	2	199
59	1979	Wheat	156	666	4.3	193	6	135
60	1979/1980	Maize	131	827	6.3	214	1	204
61	1980	Wheat	156	720	4.6	138	5	105
62	1980/1981	Maize	132	773	5.9	476	3	455
63	1981	Wheat	156	678	4.3	188	5	158
64	1981/1982	Maize	131	801	6.1	442	3	421
65	1982	Wheat	156	685	4.4	165	6	125
66	1982/1983	Maize	131	905	6.9	140	5	100
67	1983	Wheat	156	686	4.4	109	4	80
68	1983/1984	Maize	131	841	6.4	156	4	116
69	1984	Wheat	156	676	4.3	98	5	75
70	1984/1985	Maize	132	791	6.0	310	2	290
71	1985	Wheat	156	720	4.6	152	2	132
72	1985/1986	Maize	131	829	6.3	310	2	290
73	1986	Wheat	156	672	4.3	215	5	176
74	1986/1987	Maize	131	854	6.5	291	3	261
75	1987	Wheat	156	636	4.1	337	3	315
76	1987/1988	Maize	131	762	5.8	686	4	646
77	1988	Wheat	156	655	4.2	222	4	192
78	1988/1989	Maize	132	704	5.3	410	2	393
79	1989	Wheat	156	733	4.7	158	6	115
80	1989/1990	Maize	131	813	6.2	323	1	313
81	1990	Wheat	156	756	4.8	55	3	28
82	1990/1991	Maize	131	778	5.9	440	3	410
83	1991	Wheat	156	683	4.4	330	4	293
84	1991/1992	Maize	131	920	7.0	114	2	94
85	1992	Wheat	156	713	4.6	206	5	174
86	1992/1993	Maize	132	809	6.1	225	2	207
87	1993	Wheat	156	743	4.8	222	4	198
88	1993/1994	Maize	131	795	6.1	385	2	365
89	1994	Wheat	156	731	4.7	38	3	27
90	1994/1995	Maize	131	826	6.3	246	2	231
91	1995	Wheat	156	717	4.6	84	4	58
92	1995/1996	Maize	131	709	5.4	448	3	418
93	1996	Wheat	156	654	4.2	274	5	241
94	1996/1997	Maize	132	731	5.5	340	3	318
95	1997	Wheat	156	714	4.6	114	6	73
96	1997/1998	Maize	131	755	5.8	435	2	425
97	1998	Wheat	156	701	4.5	140	5	114
98	1998/1999	Maize	131	836	6.4	200	3	179
99	1999	Wheat	156	776	5.0	104	5	82
100	1999/2000	Maize	131	834	6.4	346	2	326

Appendix 6.2 Simulation results for Procedure A and B using irrigation water with a salinity of 25 mS m^{-1} on both soils

Procedure	Soil A											Soil B									
	Season	Crop	Yr	Target yield (kg/ha)	R_{eff} (mm)	IR (mm)	ΔEC_{sw} (mS m^{-1})	EC_e next (mS m^{-1})	D_w (mm)	D_{wreq} mm/day	D_w+IR (mm)	Season	Crop	Yr	Target yield (kg/ha)	R_{eff} (mm)	IR (mm)	ΔEC_{sw} (mS m^{-1})	EC_e next (mS m^{-1})	D_w (mm)	D_{wreq} mm/day
A	1	Wheat	1.00	7500	80	349	27	47	259	1.66	608	1	Wheat	1.00	7500	80	328	25	45	339	2.17
	2	Maize	1.00	12000	310	237	18	65	108	0.82	345	2	Maize	1.00	12000	310	210	16	61	144	1.10
	3	Wheat	1.00	7500	85	345	26	91	198	1.27	542	3	Wheat	1.00	7500	85	323	25	85	272	1.74
	4	Maize	1.00	12000	181	367	28	119	260	1.99	627	4	Maize	1.00	12000	181	340	26	111	359	2.74
	5	Wheat	1.00	7500	108	322	24	143	302	1.93	623	5	Wheat	1.00	7500	108	300	23	134	417	2.67
	6	Maize	1.00	12000	261	286	22	165	332	2.53	618	6	Maize	1.00	12000	261	259	20	154	457	3.49
	7	Wheat	1.00	7500	113	316	24	189	360	2.31	676	7	Wheat	1.00	7500	113	295	22	176	497	3.18
	8	Maize	1.00	12000	360	188	14	203	374	2.86	562	8	Maize	1.00	12000	360	161	12	189	516	3.94
	9	Wheat	1.00	7500	24	405	31	234	403	2.58	808	9	Wheat	1.00	7500	24	384	29	218	556	3.56
	10	Maize	1.00	12000	309	239	18	252	418	3.19	656	10	Maize	1.00	12000	309	212	16	234	576	4.39
	11	Wheat	1.00	7500	74	355	27	279	437	2.80	792	11	Wheat	1.00	7500	74	333	25	259	604	3.87
	12	Maize	1.00	12000	423	124	9	289	444	3.39	568	12	Maize	1.00	12000	423	98	7	267	611	4.67
	13	Wheat	1.00	7500	79	351	27	315	461	2.95	812	13	Wheat	1.00	7500	79	329	25	292	635	4.07
	14	Maize	1.00	12000	207	340	26	341	476	3.63	816	14	Maize	1.00	12000	207	313	24	315	656	5.01
	15	Wheat	1.00	7500	245	184	14	355	484	3.10	668	15	Wheat	1.00	7500	245	163	12	328	667	4.27
B	16	Maize	1.00	11955	270	276	21	376	13	0.10	289	16	Maize	1.00	12000	270	274	21	349	0	0.00
	17	Wheat	1.00	7500	124	300	23	399	24	0.16	324	17	Wheat	1.00	7500	124	298	23	371	15	0.10
	18	Maize	0.96	11572	213	319	24	423	35	0.27	354	18	Maize	0.98	11814	213	324	25	396	32	0.24
	19	Wheat	1.00	7500	126	301	23	446	45	0.29	346	19	Wheat	1.00	7500	126	299	23	419	46	0.30
	20	Maize	0.93	11159	354	169	13	459	51	0.39	219	20	Maize	0.95	11399	354	174	13	432	54	0.41
	21	Wheat	1.00	7500	83	347	26	485	61	0.39	408	21	Wheat	1.00	7500	83	344	26	458	69	0.44
	22	Maize	0.90	10816	276	238	18	503	68	0.52	305	22	Maize	0.92	11054	276	242	18	476	79	0.61
	23	Wheat	1.00	7500	27	406	31	534	79	0.50	484	23	Wheat	1.00	7500	27	403	31	507	95	0.61
	24	Maize	0.87	10387	292	212	16	550	84	0.64	296	24	Maize	0.89	10624	292	216	16	524	104	0.79
	25	Wheat	1.00	7500	93	343	26	576	93	0.59	436	25	Wheat	1.00	7500	93	340	26	549	116	0.74
	26	Maize	0.83	10017	416	79	6	582	94	0.72	173	26	Maize	0.85	10253	416	83	6	556	119	0.91
	27	Wheat	1.00	7500	170	270	20	603	101	0.65	370	27	Wheat	1.00	7500	170	266	20	576	128	0.82
	28	Maize	0.82	9785	158	332	25	628	108	0.83	440	28	Maize	0.84	10020	158	336	26	602	139	1.06
	29	Wheat	0.98	7353	207	227	17	645	113	0.73	340	29	Wheat	1.00	7492	207	231	18	619	146	0.94
	30	Maize	0.78	9413	228	253	19	665	119	0.91	372	30	Maize	0.80	9643	228	257	20	639	154	1.18
	31	Wheat	0.95	7161	64	362	28	692	126	0.81	488	31	Wheat	0.97	7297	64	366	28	666	165	1.06
	32	Maize	0.75	9004	267	203	15	707	130	0.99	333	32	Maize	0.77	9228	267	206	16	682	171	1.30
	33	Wheat	0.92	6936	28	389	30	737	138	0.88	527	33	Wheat	0.94	7069	28	393	30	712	181	1.16
	34	Maize	0.72	8609	487	0	0	737	138	1.05	138	34	Maize	0.74	8829	487	0	0	712	181	1.38
	35	Wheat	0.90	6780	68	343	26	763	144	0.92	487	35	Wheat	0.92	6912	68	347	26	738	191	1.22
	36	Maize	0.70	8381	285	168	13	776	147	1.12	315	36	Maize	0.72	8598	285	171	13	751	195	1.49
	37	Wheat	0.88	6576	34	368	28	804	153	0.98	521	37	Wheat	0.89	6705	34	371	28	780	204	1.31
	38	Maize	0.67	8024	251	192	15	819	157	1.20	349	38	Maize	0.69	8237	251	195	15	794	209	1.60
	39	Wheat	0.85	6353	120	272	21	839	161	1.03	433	39	Wheat	0.86	6479	120	275	21	815	215	1.38
	40	Maize	0.64	7715	180	255	19	859	165	1.26	420	40	Maize	0.66	7924	180	257	20	835	221	1.69
	41	Wheat	0.82	6142	147	236	18	877	169	1.08	405	41	Wheat	0.84	6267	147	239	18	853	227	1.45
	42	Maize	0.62	7388	256	171	13	890	172	1.31	343	42	Maize	0.63	7594	256	173	13	866	231	1.76
	43	Wheat	0.80	5980	81	294	22	912	176	1.13	471	43	Wheat	0.81	6103	81	297	23	889	237	1.52
	44	Maize	0.59	7078	478	0	0	912	176	1.35	176	44	Maize	0.61	7280	478	0	0	889	237	1.81

Appendix 6.2 continued

Procedure	Soil A											Soil B									
	Season	Crop	Yr	Target yield (kg/ha)	R_{eff} (mm)	IR (mm)	ΔEC_{sw} (mS m^{-1})	EC_e next (mS m^{-1})	D_w (mm)	D_{wreq} mm/day	D_w+IR (mm)	Season	Crop	Yr	Target yield (kg/ha)	R_{eff} (mm)	IR (mm)	ΔEC_{sw} (mS m^{-1})	EC_e next (mS m^{-1})	D_w (mm)	D_{wreq} mm/day
B	45	Wheat	0.78	5863	8	363	28	940	182	1.16	545	45	Wheat	0.80	5984	8	366	28	917	245	1.57
	47	Maize	0.57	6836	65	346	26	966	187	1.42	533	47	Maize	0.59	7037	65	348	26	943	252	1.92
	47	Wheat	0.74	5579	65	292	22	988	191	1.22	483	47	Wheat	0.76	5699	65	294	22	965	258	1.65
	48	Maize	0.53	6411	585	0	0	988	191	1.46	191	48	Maize	0.55	6609	585	0	0	965	258	1.97
	49	Wheat	0.73	5463	95	257	20	1008	194	1.25	452	49	Wheat	0.74	5581	95	260	20	985	263	1.69
	50	Maize	0.52	6239	297	96	7	1015	196	1.49	292	50	Maize	0.54	6436	297	98	7	993	265	2.02
	51	Wheat	0.71	5322	109	236	18	1033	199	1.27	435	51	Wheat	0.73	5439	109	239	18	1011	269	1.73
	52	Maize	0.50	6018	524	0	0	1033	199	1.52	199	52	Maize	0.52	6211	524	0	0	1011	269	2.06
	53	Wheat	0.70	5227	169	173	13	1046	201	1.29	374	53	Wheat	0.71	5343	169	175	13	1024	273	1.75
	54	Maize	0.49	5903	428	0	0	1046	201	1.53	201	54	Maize	0.51	6095	428	0	0	1024	273	2.08
	55	Wheat	0.69	5158	99	240	18	1064	204	1.31	444	55	Wheat	0.70	5273	99	242	18	1043	277	1.78
	56	Maize	0.48	5743	339	41	3	1067	205	1.56	245	56	Maize	0.49	5933	339	42	3	1046	278	2.12
	57	Wheat	0.67	5046	29	304	23	1091	209	1.34	513	57	Wheat	0.69	5160	29	306	23	1069	283	1.82
	58	Maize	0.46	5513	199	174	13	1104	211	1.61	385	58	Maize	0.48	5701	199	175	13	1082	286	2.19
	59	Wheat	0.65	4855	135	189	14	1118	213	1.37	402	59	Wheat	0.66	4968	135	191	14	1097	290	1.86
	60	Maize	0.44	5271	204	162	12	1130	215	1.64	377	60	Maize	0.45	5458	204	163	12	1109	293	2.23
	61	Wheat	0.63	4715	105	213	16	1147	218	1.40	431	61	Wheat	0.64	4827	105	215	16	1126	296	1.90
	62	Maize	0.42	5022	455	0	0	1147	218	1.66	218	62	Maize	0.43	5206	455	0	0	1126	296	2.26
	63	Wheat	0.62	4630	158	157	12	1159	220	1.41	376	63	Wheat	0.63	4741	158	159	12	1138	299	1.92
	64	Maize	0.41	4917	421	0	0	1159	220	1.68	220	64	Maize	0.43	5100	421	0	0	1138	299	2.28
	65	Wheat	0.61	4568	125	187	14	1173	222	1.42	409	65	Wheat	0.62	4677	125	189	14	1152	302	1.94
	66	Maize	0.40	4793	100	253	19	1192	225	1.71	478	66	Maize	0.41	4975	100	254	19	1171	306	2.34
	67	Wheat	0.59	4392	80	222	17	1209	227	1.46	449	67	Wheat	0.60	4501	80	223	17	1188	310	1.99
	68	Maize	0.37	4477	116	227	17	1226	230	1.75	456	68	Maize	0.39	4657	116	227	17	1206	313	2.39
	69	Wheat	0.56	4213	75	218	17	1243	232	1.49	450	69	Wheat	0.58	4321	75	220	17	1222	317	2.03
	70	Maize	0.35	4180	290	43	3	1246	233	1.78	276	70	Maize	0.36	4359	290	44	3	1226	317	2.42
	71	Wheat	0.55	4109	132	157	12	1258	234	1.50	392	71	Wheat	0.56	4216	132	159	12	1238	320	2.05
	72	Maize	0.34	4047	290	40	3	1261	235	1.79	274	72	Maize	0.35	4224	290	40	3	1241	320	2.45
	73	Wheat	0.54	4030	176	110	8	1269	236	1.51	346	73	Wheat	0.55	4136	176	111	8	1249	322	2.07
	74	Maize	0.33	3947	261	67	5	1274	237	1.81	303	74	Maize	0.34	4123	261	67	5	1254	323	2.47
	75	Wheat	0.53	3960	315	0	0	1274	237	1.52	237	75	Wheat	0.54	4065	315	0	0	1254	323	2.07
	76	Maize	0.33	3903	646	0	0	1274	237	1.81	237	76	Maize	0.34	4078	646	0	0	1254	323	2.47
	77	Wheat	0.53	3960	192	92	7	1281	238	1.52	330	77	Wheat	0.54	4065	192	93	7	1261	325	2.08
	78	Maize	0.32	3842	393	0	0	1281	238	1.81	238	78	Maize	0.33	4016	393	0	0	1261	325	2.48
	79	Wheat	0.52	3923	115	167	13	1294	239	1.53	407	79	Wheat	0.54	4027	115	169	13	1274	327	2.10
	80	Maize	0.31	3730	313	8	1	1295	240	1.83	248	80	Maize	0.33	3903	313	9	1	1275	327	2.50
	81	Wheat	0.51	3853	28	251	19	1314	242	1.55	493	81	Wheat	0.53	3957	28	252	19	1294	331	2.12
	82	Maize	0.30	3558	410	0	0	1314	242	1.85	242	82	Maize	0.31	3730	410	0	0	1294	331	2.53
	83	Wheat	0.50	3753	293	0	0	1314	242	1.55	242	83	Wheat	0.51	3856	293	0	0	1294	331	2.12
	84	Maize	0.30	3558	94	224	17	1331	244	1.87	469	84	Maize	0.31	3730	94	224	17	1311	334	2.55
	85	Wheat	0.49	3664	174	95	7	1338	245	1.57	340	85	Wheat	0.50	3767	174	96	7	1318	336	2.15

Appendix 6.3 Simulation results for Procedure A and B using irrigation water with a salinity of 50 mS m^{-1} on both soils

Procedure	Soil A											Soil B									
	Season	Crop	Yr	Target yield (kg/ha)	R_{eff} (mm)	IR (mm)	ΔEC_{sw} (mS m^{-1})	EC_e next (mS m^{-1})	D_w (mm)	D_{wreq} mm/day	D_w+HR (mm)	Season	Crop	Yr	Target yield (kg/ha)	R_{eff} (mm)	IR (mm)	ΔEC_{sw} (mS m^{-1})	EC_e next (mS m^{-1})	D_w (mm)	D_{wreq} mm/day
A	1	Wheat	1.00	7500	80	349	53	73	148	0.95	497	1	Wheat	1.00	7500	80	328	50	100	394	2.52
	2	Maize	1.00	12000	310	237	36	109	167	1.27	404	2	Maize	1.00	12000	310	210	32	132	121	0.93
	3	Wheat	1.00	7500	85	345	52	162	279	1.79	624	3	Wheat	1.00	7500	85	323	49	181	237	1.52
	4	Maize	1.00	12000	181	367	56	217	351	2.68	718	4	Maize	1.00	12000	181	340	52	233	318	2.43
	5	Wheat	1.00	7500	108	322	49	266	396	2.54	718	5	Wheat	1.00	7500	108	300	46	278	373	2.39
	6	Maize	1.00	12000	261	286	44	310	429	3.27	715	6	Maize	1.00	12000	261	259	39	318	412	3.14
	7	Wheat	1.00	7500	113	316	48	358	459	2.94	775	7	Wheat	1.00	7500	113	295	45	363	450	2.88
B	8	Maize	0.99	11932	360	183	28	386	18	0.14	201	8	Maize	0.99	11890	360	185	28	391	31	0.24
	9	Wheat	1.00	7500	24	402	61	447	46	0.29	447	9	Wheat	1.00	7500	24	428	65	456	74	0.47
	10	Maize	0.93	11153	309	216	33	480	59	0.45	275	10	Maize	0.92	11074	309	217	33	489	93	0.71
	11	Wheat	1.00	7500	74	358	54	534	79	0.50	436	11	Wheat	1.00	7500	74	384	58	547	124	0.79
	12	Maize	0.87	10388	423	83	13	547	83	0.63	166	12	Maize	0.86	10274	423	80	12	559	130	0.99
	13	Wheat	1.00	7500	79	358	55	601	100	0.64	459	13	Wheat	1.00	7500	79	385	59	618	156	1.00
	14	Maize	0.82	9800	207	284	43	644	113	0.86	397	14	Maize	0.80	9655	207	282	43	661	174	1.33
	15	Wheat	0.97	7268	245	186	28	672	121	0.77	307	15	Wheat	0.96	7182	245	206	31	692	186	1.19
	16	Maize	0.76	9175	270	205	31	704	129	0.99	334	16	Maize	0.75	9005	270	201	31	722	198	1.51
	17	Wheat	0.93	6956	124	294	45	748	140	0.90	434	17	Wheat	0.91	6857	124	314	48	770	215	1.38
	18	Maize	0.71	8511	213	243	37	785	149	1.14	392	18	Maize	0.69	8319	213	240	36	807	227	1.73
	19	Wheat	0.87	6528	126	272	41	827	158	1.02	431	19	Wheat	0.86	6415	126	288	44	850	240	1.54
	20	Maize	0.65	7825	354	82	13	839	161	1.23	244	20	Maize	0.63	7616	354	77	12	862	244	1.86
	21	Wheat	0.83	6244	83	302	46	885	171	1.10	473	21	Wheat	0.82	6124	83	318	48	911	258	1.65
	22	Maize	0.61	7313	276	144	22	907	175	1.34	320	22	Maize	0.59	7090	276	141	21	932	264	2.02
	23	Wheat	0.79	5888	27	341	52	959	185	1.19	526	23	Wheat	0.77	5758	27	357	54	986	279	1.79
	24	Maize	0.56	6666	292	109	17	975	188	1.44	297	24	Maize	0.54	6428	292	106	16	1002	283	2.16
	25	Wheat	0.74	5529	93	257	39	1015	196	1.25	453	25	Wheat	0.72	5389	93	272	41	1044	293	1.88
	26	Maize	0.51	6179	416	0	0	1015	196	1.49	196	26	Maize	0.49	5925	416	0	0	1044	293	2.24
	27	Wheat	0.71	5324	170	170	26	1040	200	1.28	370	27	Wheat	0.69	5171	170	184	28	1072	300	1.92
	28	Maize	0.50	5952	158	220	33	1074	206	1.57	425	28	Maize	0.47	5679	158	219	33	1105	308	2.35
	29	Wheat	0.67	5013	207	118	18	1092	209	1.34	326	29	Wheat	0.65	4849	207	132	20	1125	313	2.00
	30	Maize	0.46	5503	228	135	21	1112	212	1.62	347	30	Maize	0.43	5212	228	135	21	1145	317	2.42
	31	Wheat	0.64	4811	64	250	38	1150	218	1.40	468	31	Wheat	0.62	4637	64	264	40	1186	326	2.09
	32	Maize	0.42	4991	267	79	12	1162	220	1.68	299	32	Maize	0.39	4681	267	79	12	1198	329	2.51
	33	Wheat	0.61	4549	28	273	41	1204	226	1.45	499	33	Wheat	0.58	4363	28	287	44	1241	338	2.17
	34	Maize	0.38	4522	487	0	0	1204	226	1.73	226	34	Maize	0.35	4194	487	0	0	1241	338	2.58
	35	Wheat	0.58	4331	68	221	34	1237	231	1.48	452	35	Wheat	0.55	4134	68	235	36	1277	345	2.21
	36	Maize	0.35	4228	285	34	5	1242	232	1.77	266	36	Maize	0.32	3881	285	34	5	1282	346	2.64
	37	Wheat	0.55	4128	34	244	37	1279	237	1.52	481	37	Wheat	0.52	3920	34	257	39	1321	354	2.27
	38	Maize	0.32	3858	251	54	8	1288	239	1.82	293	38	Maize	0.29	3493	251	56	9	1330	355	2.71
	39	Wheat	0.52	3890	120	145	22	1310	242	1.55	386	39	Wheat	0.49	3670	120	158	24	1354	360	2.31
	40	Maize	0.30	3593	180	115	17	1327	244	1.86	359	40	Maize	0.27	3208	180	118	18	1372	363	2.77

Appendix 6.4 Simulation results for Procedure A and B using irrigation water with a salinity of 100 mS m^{-1} on both soils

Procedure	Soil A											Soil B									
	Season	Crop	Yr	Target yield (kg/ha)	R_{eff} (mm)	IR (mm)	ΔEC_{sw} (mS m^{-1})	EC_e next (mS m^{-1})	D_w (mm)	D_{wreq} mm/day	D_w+IR (mm)	Season	Crop	Yr	Target yield (kg/ha)	R_{eff} (mm)	IR (mm)	ΔEC_{sw} (mS m^{-1})	EC_e next (mS m^{-1})	D_w (mm)	D_{wreq} mm/day
A	1	Wheat	1.00	7500	80	349	106	126	48	0.31	397	1	Wheat	1.00	7500	80	328	100	150	223	1.43
	2	Maize	1.00	12000	310	237	72	198	234	1.79	472	2	Maize	1.00	12000	310	210	64	214	203	1.55
	3	Wheat	1.00	7500	85	345	105	303	363	2.33	708	3	Wheat	1.00	7500	85	323	98	312	355	2.28
	4	Maize	1.00	12000	181	367	112	415	441	3.36	807	4	Maize	1.00	12000	181	340	103	415	453	3.46
	5	Wheat	1.00	7500	108	322	98	512	489	3.13	810	5	Wheat	1.00	7500	108	300	91	507	515	3.30
B	6	Maize	0.88	10577	261	259	79	591	97	0.74	356	6	Maize	0.89	10628	261	259	79	585	142	1.08
	7	Wheat	1.00	7500	113	335	102	693	126	0.81	461	7	Wheat	1.00	7500	113	333	101	687	184	1.18
	8	Maize	0.75	8996	360	116	35	728	135	1.03	251	8	Maize	0.75	9050	360	115	35	722	197	1.51
	9	Wheat	0.91	6828	24	398	121	849	163	1.05	561	9	Wheat	0.91	6861	24	397	121	843	238	1.53
	10	Maize	0.64	7629	309	130	40	889	172	1.31	302	10	Maize	0.64	7685	309	129	39	882	250	1.91
	11	Wheat	0.80	5985	74	308	94	982	190	1.22	498	11	Wheat	0.80	6021	74	307	93	975	276	1.77
	12	Maize	0.54	6462	423	0	0	982	190	1.45	190	12	Maize	0.54	6524	423	0	0	975	276	2.11
	13	Wheat	0.73	5493	79	282	86	1068	205	1.31	487	13	Wheat	0.74	5531	79	281	85	1060	297	1.91
	14	Maize	0.48	5711	207	179	54	1122	214	1.63	393	14	Maize	0.48	5776	207	176	54	1114	310	2.37
	15	Wheat	0.63	4758	245	77	24	1146	218	1.39	295	15	Wheat	0.64	4801	245	76	23	1137	315	2.02
	16	Maize	0.42	5029	270	96	29	1175	222	1.70	318	16	Maize	0.43	5103	270	94	28	1166	322	2.46
	17	Wheat	0.60	4481	124	189	58	1233	231	1.48	420	17	Wheat	0.60	4530	124	188	57	1223	334	2.14
	18	Maize	0.36	4269	213	131	40	1272	236	1.80	367	18	Maize	0.36	4352	213	128	39	1262	342	2.61
	19	Wheat	0.53	3971	126	162	49	1321	243	1.56	405	19	Wheat	0.54	4024	126	161	49	1311	352	2.25
	20	Maize	0.29	3490	354	0	0	1321	243	1.86	243	20	Maize	0.30	3581	354	0	0	1311	352	2.69
	21	Wheat	0.49	3712	83	193	59	1380	251	1.61	444	21	Wheat	0.50	3767	83	192	58	1370	363	2.33
	22	Maize	0.25	2975	276	25	7	1388	252	1.92	277	22	Maize	0.26	3069	276	23	7	1376	364	2.78
	23	Wheat	0.45	3364	27	233	71	1458	261	1.67	494	23	Wheat	0.46	3424	27	232	71	1447	377	2.42
	24	Maize	0.19	2290	292	0	0	1458	261	1.99	261	24	Maize	0.20	2390	292	0	0	1447	377	2.88
	25	Wheat	0.40	2993	93	146	44	1503	266	1.71	412	25	Wheat	0.41	3053	93	145	44	1491	384	2.46
	26	Maize	0.16	1902	416	0	0	1503	266	2.03	266	26	Maize	0.17	2003	416	0	0	1491	384	2.93
	27	Wheat	0.37	2761	170	55	17	1520	268	1.72	324	27	Wheat	0.38	2821	170	55	17	1508	387	2.48
	28	Maize	0.15	1754	158	105	32	1552	272	2.08	377	28	Maize	0.15	1857	158	103	31	1539	393	3.00
	29	Wheat	0.33	2505	207	5	2	1553	272	1.75	278	29	Wheat	0.34	2569	207	5	2	1541	393	2.52
	30	Maize	0.12	1461	228	26	8	1561	273	2.09	299	30	Maize	0.13	1568	228	25	8	1548	394	3.01
	31	Wheat	0.33	2454	64	149	45	1606	278	1.78	428	31	Wheat	0.34	2521	64	149	45	1594	401	2.57
	32	Maize	0.08	994	267	0	0	1606	278	2.12	278	32	Maize	0.09	1104	267	0	0	1594	401	3.06
	33	Wheat	0.30	2216	28	173	53	1659	284	1.82	457	33	Wheat	0.30	2283	28	173	53	1646	410	2.63
	34	Maize	0.04	533	487	0	0	1659	284	2.17	284	34	Maize	0.05	644	487	0	0	1646	410	3.13
	35	Wheat	0.26	1940	68	113	34	1693	288	1.84	401	35	Wheat	0.27	2007	68	114	35	1681	415	2.66
	36	Maize	0.02	231	285	0	0	1693	288	2.20	288	36	Maize	0.03	341	285	0	0	1681	415	3.17
	37	Wheat	0.23	1759	34	137	42	1735	292	1.87	429	37	Wheat	0.24	1825	34	138	42	1723	421	2.70
	38	Maize	0.00	0	251	0	0	1735	292	2.23	292	38	Maize	0.00	0	251	0	0	1723	421	3.21

Appendix 6.5 Simulation results for Procedure C using irrigation water with a salinity of 25 mS m^{-1} on both soils

Soil A											Soil B										
Season	Crop	Yr	Target yield (kg/ha)	R_{eff} (mm)	IR (mm)	ΔEC_{sw} (mS m^{-1})	EC_e next (mS m^{-1})	D_w (mm)	D_{wreq} mm/day	D_w+IR (mm)	Season	Crop	Yr	Target yield (kg/ha)	R_{eff} (mm)	IR (mm)	ΔEC_{sw} (mS m^{-1})	EC_e next (mS m^{-1})	D_w (mm)	D_{wreq} mm/day	D_w+IR (mm)
1	Wheat	1.00	7500	80	587	45	65	367	2.35	955	1	Wheat	1.00	7500	80	587	45	65	238	1.53	826
2	Maize	1.00	12000	310	528	40	105	145	1.11	673	2	Maize	1.00	12000	310	528	40	105	201	1.53	729
3	Wheat	1.00	7500	85	583	44	149	204	1.31	787	3	Wheat	1.00	7500	85	583	44	149	282	1.80	864
4	Maize	1.00	12000	181	658	50	199	240	1.83	898	4	Maize	1.00	12000	181	658	50	199	331	2.53	989
5	Wheat	1.00	7500	108	560	43	242	311	1.99	870	5	Wheat	1.00	7500	108	560	43	242	429	2.75	989
6	Maize	1.00	12000	261	577	44	286	337	2.57	914	6	Maize	1.00	12000	261	577	44	286	466	3.56	1043
7	Wheat	1.00	7500	113	554	42	328	372	2.38	926	7	Wheat	1.00	7500	113	554	42	328	514	3.29	1068
8	Maize	1.00	12000	360	479	36	364	422	3.22	901	8	Maize	1.00	12000	360	479	36	364	583	4.45	1062
9	Wheat	1.00	7500	24	644	49	413	386	2.48	1030	9	Wheat	1.00	7500	24	644	49	413	533	3.42	1177
10	Maize	0.95	11448	309	499	38	451	355	2.71	854	10	Maize	0.95	11448	309	499	38	451	490	3.74	990
11	Wheat	1.00	7500	74	593	45	496	48	0.31	641	11	Wheat	1.00	7500	74	593	45	496	544	3.49	1137
12	Maize	0.89	10720	423	345	26	522	66	0.50	411	12	Maize	0.89	10720	423	345	26	522	513	3.91	858
13	Wheat	1.00	7500	79	589	45	567	75	0.48	664	13	Wheat	1.00	7500	79	589	45	567	613	3.93	1202
14	Maize	0.84	10098	207	527	40	607	91	0.69	617	14	Maize	0.84	10098	207	527	40	607	515	3.93	1041
15	Wheat	0.99	7462	245	419	32	639	103	0.66	522	15	Wheat	0.99	7462	245	419	32	639	496	3.18	915
16	Maize	0.79	9468	270	430	33	672	113	0.86	542	16	Maize	0.79	9468	270	430	33	672	609	4.65	1038
17	Wheat	0.95	7124	124	512	39	711	122	0.78	634	17	Wheat	0.95	7124	124	512	39	711	524	3.36	1036
18	Maize	0.74	8841	213	452	34	745	132	1.01	584	18	Maize	0.74	8841	213	452	34	745	537	4.10	989
19	Wheat	0.90	6739	126	477	36	781	141	0.90	618	19	Wheat	0.90	6739	126	477	36	781	498	3.19	975
20	Maize	0.69	8222	354	277	21	802	150	1.14	427	20	Maize	0.69	8222	354	277	21	802	538	4.10	815
21	Wheat	0.86	6438	83	494	38	840	155	0.99	649	21	Wheat	0.86	6438	83	494	38	840	569	3.65	1063
22	Maize	0.64	7709	276	326	25	865	163	1.24	489	22	Maize	0.64	7709	276	326	25	865	517	3.94	843
23	Wheat	0.81	6110	27	522	40	904	168	1.08	690	23	Wheat	0.81	6110	27	522	40	904	527	3.38	1050
24	Maize	0.60	7143	292	280	21	926	176	1.35	457	24	Maize	0.60	7143	292	280	21	926	492	3.75	772
25	Wheat	0.77	5790	93	428	33	958	181	1.16	609	25	Wheat	0.77	5790	93	428	33	958	535	3.43	964
26	Maize	0.56	6671	416	130	10	968	187	1.43	317	26	Maize	0.56	6671	416	130	10	968	522	3.98	652
27	Wheat	0.74	5567	170	333	25	993	189	1.21	521	27	Wheat	0.74	5567	170	333	25	993	608	3.90	941
28	Maize	0.53	6363	158	371	28	1022	194	1.48	564	28	Maize	0.53	6363	158	371	28	1022	562	4.29	933
29	Wheat	0.70	5286	207	272	21	1042	199	1.27	471	29	Wheat	0.70	5286	207	272	21	1042	475	3.05	747
30	Maize	0.49	5935	228	278	21	1063	202	1.54	480	30	Maize	0.49	5935	228	278	21	1063	583	4.45	861
31	Wheat	0.68	5067	64	396	30	1094	206	1.32	602	31	Wheat	0.68	5067	64	396	30	1094	504	3.23	900
32	Maize	0.46	5486	267	214	16	1110	211	1.61	425	32	Maize	0.46	5486	267	214	16	1110	508	3.88	722
33	Wheat	0.64	4823	28	412	31	1141	214	1.37	626	33	Wheat	0.64	4823	28	412	31	1141	523	3.35	935
34	Maize	0.42	5069	487	0	0	1141	219	1.67	219	34	Maize	0.42	5069	487	0	0	1141	492	3.75	492
35	Wheat	0.62	4659	68	357	27	1168	219	1.40	576	35	Wheat	0.62	4659	68	357	27	1168	663	4.25	1020
36	Maize	0.40	4831	285	160	12	1181	223	1.70	383	36	Maize	0.40	4831	285	160	12	1181	510	3.89	670
37	Wheat	0.59	4452	34	374	28	1209	225	1.44	599	37	Wheat	0.59	4452	34	374	28	1209	532	3.41	906
38	Maize	0.37	4475	251	174	13	1222	229	1.75	404	38	Maize	0.37	4475	251	174	13	1222	494	3.77	669
39	Wheat	0.56	4233	120	269	20	1243	231	1.48	500	39	Wheat	0.56	4233	120	269	20	1243	515	3.30	784
40	Maize	0.35	4180	180	229	17	1260	234	1.79	463	40	Maize	0.35	4180	180	229	17	1260	535	4.08	764

Appendix 6.5 continued

Soil A											Soil B										
Season	Crop	Yr	Target yield (kg/ha)	R_{eff} (mm)	IR (mm)	ΔEC_{sw} (mS m^{-1})	EC_e next (mS m^{-1})	D_w (mm)	D_{wreq} mm/day	D_w+IR (mm)	Season	Crop	Yr	Target yield (kg/ha)	R_{eff} (mm)	IR (mm)	ΔEC_{sw} (mS m^{-1})	EC_e next (mS m^{-1})	D_w (mm)	D_{wreq} mm/day	D_w+IR (mm)
41	Wheat	0.54	4034	147	226	17	1277	237	1.52	462	41	Wheat	0.54	4034	147	226	17	1277	484	3.10	710
42	Maize	0.32	3877	256	137	10	1288	239	1.83	376	42	Maize	0.32	3877	256	137	10	1288	549	4.19	685
43	Wheat	0.52	3890	81	279	21	1309	241	1.54	520	43	Wheat	0.52	3890	81	279	21	1309	518	3.32	797
44	Maize	0.30	3600	478	0	0	1309	244	1.86	244	44	Maize	0.30	3600	478	0	0	1309	516	3.94	516
45	Wheat	0.50	3778	8	343	26	1335	244	1.56	586	45	Wheat	0.50	3778	8	343	26	1335	656	4.20	998
47	Maize	0.28	3372	65	300	23	1358	247	1.89	547	47	Maize	0.28	3372	65	300	23	1358	483	3.69	784
47	Wheat	0.47	3522	65	264	20	1378	250	1.60	514	47	Wheat	0.47	3522	65	264	20	1378	440	2.82	705
48	Maize	0.25	2996	585	0	0	1378	253	1.93	253	48	Maize	0.25	2996	585	0	0	1378	508	3.88	508
49	Wheat	0.46	3416	95	224	17	1395	253	1.62	477	49	Wheat	0.46	3416	95	224	17	1395	765	4.91	990
50	Maize	0.24	2846	297	39	3	1398	255	1.95	294	50	Maize	0.24	2846	297	39	3	1398	523	3.99	562

Appendix 6.6 Simulation results for Procedure C using irrigation water with a salinity of 50 mS m^{-1} on both soils

Soil A											Soil B										
Season	Crop	Yr	Target yield (kg/ha)	R_{eff} (mm)	IR (mm)	ΔEC_{sw} (mS m^{-1})	EC_e next (mS m^{-1})	D_w (mm)	D_{wreq} mm/day	D_w+IR (mm)	Season	Crop	Yr	Target yield (kg/ha)	R_{eff} (mm)	IR (mm)	ΔEC_{sw} (mS m^{-1})	EC_e next (mS m^{-1})	D_w (mm)	D_{wreq} mm/day	D_w+IR (mm)
1	Wheat	1.00	7500	80	587	89	109	316	2.02	903	1	Wheat	1.00	7500	80	587	89	109	167	1.07	754
2	Maize	1.00	12000	310	528	80	190	181	1.38	709	2	Maize	1.00	12000	310	528	80	190	250	1.91	778
3	Wheat	1.00	7500	85	583	89	278	241	1.54	824	3	Wheat	1.00	7500	85	583	89	278	333	2.13	916
4	Maize	1.00	12000	181	658	100	378	274	2.09	932	4	Maize	1.00	12000	181	658	100	378	378	2.89	1036
5	Wheat	1.00	7500	108	560	85	463	357	2.29	917	5	Wheat	1.00	7500	108	560	85	463	493	3.16	1053
6	Maize	0.92	11007	261	523	79	543	57	0.43	579	6	Maize	0.90	10744	261	508	77	543	529	4.04	1106
7	Wheat	1.00	7500	113	554	84	627	88	0.56	642	7	Wheat	1.00	7500	113	554	84	627	582	3.73	1137
8	Maize	0.80	9572	360	346	53	680	116	0.89	461	8	Maize	0.78	9329	360	332	51	680	669	5.11	1148
9	Wheat	0.94	7082	24	608	92	772	131	0.84	739	9	Wheat	0.93	6946	24	596	91	772	590	3.78	1234
10	Maize	0.69	8302	309	327	50	822	156	1.19	482	10	Maize	0.67	8092	309	315	48	822	687	5.25	1217
11	Wheat	0.84	6335	74	494	75	897	168	1.07	661	11	Wheat	0.83	6219	74	484	74	897	670	4.29	1263
12	Maize	0.60	7209	423	152	23	920	184	1.40	336	12	Maize	0.59	7027	423	142	22	920	832	6.35	1247
13	Wheat	0.78	5820	79	446	68	988	189	1.21	634	13	Wheat	0.76	5719	79	437	66	988	710	4.55	1298
14	Maize	0.53	6412	207	324	49	1037	202	1.54	526	14	Maize	0.52	6255	207	316	48	1037	705	5.38	1336
15	Wheat	0.69	5205	245	227	35	1072	211	1.35	438	15	Wheat	0.68	5118	245	219	33	1072	879	5.64	1301
16	Maize	0.47	5678	270	222	34	1105	217	1.66	439	16	Maize	0.46	5542	270	214	33	1105	773	5.90	1342
17	Wheat	0.65	4847	124	318	48	1154	223	1.43	541	17	Wheat	0.64	4771	124	311	47	1154	805	5.16	1349
18	Maize	0.41	4960	213	239	36	1190	231	1.76	470	18	Maize	0.40	4842	213	232	35	1190	769	5.87	1394
19	Wheat	0.59	4402	126	278	42	1232	237	1.52	515	19	Wheat	0.58	4337	126	273	41	1232	835	5.35	1377
20	Maize	0.36	4271	354	60	9	1242	243	1.86	303	20	Maize	0.35	4170	354	55	8	1242	891	6.80	1375
21	Wheat	0.55	4132	83	298	45	1287	244	1.57	542	21	Wheat	0.54	4076	83	293	45	1287	831	5.32	1415
22	Maize	0.32	3794	276	112	17	1304	251	1.92	363	22	Maize	0.31	3706	276	107	16	1304	857	6.54	1419
23	Wheat	0.51	3805	27	326	50	1353	254	1.63	579	23	Wheat	0.50	3757	27	322	49	1353	822	5.27	1462
24	Maize	0.27	3211	292	64	10	1363	260	1.99	325	24	Maize	0.26	3136	292	60	9	1363	890	6.80	1437
25	Wheat	0.47	3494	93	233	35	1398	262	1.68	495	25	Wheat	0.46	3452	93	229	35	1398	882	5.66	1456
26	Maize	0.23	2815	416	0	0	1398	266	2.03	266	26	Maize	0.23	2750	416	0	0	1398	1016	7.75	1438
27	Wheat	0.44	3308	170	140	21	1420	266	1.71	407	27	Wheat	0.44	3269	170	137	21	1420	954	6.12	1451
28	Maize	0.22	2629	158	166	25	1445	269	2.05	435	28	Maize	0.21	2568	158	162	25	1445	848	6.48	1528
29	Wheat	0.41	3064	207	83	13	1458	272	1.75	355	29	Wheat	0.40	3030	207	80	12	1458	1004	6.44	1465
30	Maize	0.19	2297	228	78	12	1469	274	2.09	352	30	Maize	0.19	2245	228	75	11	1469	903	6.89	1514
31	Wheat	0.39	2935	64	214	33	1502	276	1.77	490	31	Wheat	0.39	2906	64	212	32	1502	916	5.87	1519
32	Maize	0.16	1908	267	18	3	1505	280	2.13	297	32	Maize	0.16	1862	267	15	2	1505	944	7.20	1516
33	Wheat	0.37	2750	28	235	36	1541	280	1.79	515	33	Wheat	0.36	2725	28	233	35	1541	912	5.84	1552
34	Maize	0.13	1570	487	0	0	1541	284	2.17	284	34	Maize	0.13	1531	487	0	0	1541	1174	8.97	1526
35	Wheat	0.34	2562	68	179	27	1568	284	1.82	463	35	Wheat	0.34	2538	68	177	27	1568	948	6.07	1547
36	Maize	0.11	1332	285	0	0	1568	287	2.19	287	36	Maize	0.11	1295	285	0	0	1568	984	7.51	1538
37	Wheat	0.32	2419	34	201	31	1598	287	1.84	488	37	Wheat	0.32	2397	34	199	30	1598	942	6.04	1576
38	Maize	0.09	1064	251	0	0	1598	291	2.22	291	38	Maize	0.09	1030	251	0	0	1598	976	7.45	1564
39	Wheat	0.30	2258	120	101	15	1614	291	1.86	392	39	Wheat	0.30	2238	120	99	15	1614	1009	6.47	1557
40	Maize	0.08	929	180	50	8	1621	293	2.23	343	40	Maize	0.07	898	180	49	7	1621	949	7.25	1607

Appendix 6.7 Simulation results for Procedure C using irrigation water with a salinity of 100 mS m^{-1} on both soils

Soil A											Soil B										
Season	**Crop**	**Yr**	**Target yield (kg/ha)**	**R_{eff} (mm)**	**IR (mm)**	**ΔEC_{sw} (mS m^{-1})**	**EC_e next (mS m^{-1})**	**D_w (mm)**	**D_{wreq} mm/day**	**D_w+IR (mm)**	**Season**	**Crop**	**Yr**	**Target yield (kg/ha)**	**R_{eff} (mm)**	**IR (mm)**	**ΔEC_{sw} (mS m^{-1})**	**EC_e next (mS m^{-1})**	**D_w (mm)**	**D_{wreq} mm/day**	**D_w+IR (mm)**
1	Wheat	1.00	7500	80	587	179	199	283	1.81	870	1	Wheat	1.00	7500	80	587	179	199	292	1.87	879
2	Maize	1.00	12000	310	528	161	359	207	1.58	735	2	Maize	1.00	12000	310	528	161	359	286	2.18	814
3	Wheat	1.00	7500	85	583	177	536	266	1.71	849	3	Wheat	1.00	7500	85	583	177	536	368	2.36	950
4	Maize	0.86	10366	181	568	173	709	99	0.75	667	4	Maize	0.86	10366	181	568	173	709	137	1.04	705
5	Wheat	0.92	6926	108	511	155	865	158	1.01	669	5	Wheat	0.92	6926	108	511	155	865	218	1.40	729
6	Maize	0.62	7492	261	330	100	965	198	1.51	528	6	Maize	0.62	7492	261	330	100	965	274	2.09	604
7	Wheat	0.74	5584	113	391	119	1084	220	1.41	611	7	Wheat	0.74	5584	113	391	119	1084	304	1.95	695
8	Maize	0.46	5571	360	126	38	1122	243	1.85	369	8	Maize	0.46	5571	360	126	38	1122	336	2.56	461
9	Wheat	0.63	4759	24	410	125	1247	250	1.60	660	9	Wheat	0.63	4759	24	410	125	1247	345	2.21	755
10	Maize	0.35	4143	309	98	30	1277	270	2.06	368	10	Maize	0.35	4143	309	98	30	1277	373	2.85	472
11	Wheat	0.53	3947	74	291	88	1365	275	1.76	565	11	Wheat	0.53	3947	74	291	88	1365	379	2.43	670
12	Maize	0.26	3107	423	0	0	1365	287	2.19	287	12	Maize	0.26	3107	423	0	0	1365	397	3.03	397
13	Wheat	0.46	3483	79	247	75	1440	287	1.84	534	13	Wheat	0.46	3483	79	247	75	1440	397	2.55	644
14	Maize	0.20	2450	207	107	32	1473	298	2.27	404	14	Maize	0.20	2450	207	107	32	1473	411	3.14	518
15	Wheat	0.39	2918	245	32	10	1482	302	1.94	334	15	Wheat	0.39	2918	245	32	10	1482	417	2.67	449
16	Maize	0.17	2080	270	24	7	1490	303	2.31	327	16	Maize	0.17	2080	270	24	7	1490	419	3.20	443
17	Wheat	0.38	2829	124	146	44	1534	304	1.95	450	17	Wheat	0.38	2829	124	146	44	1534	420	2.69	566
18	Maize	0.14	1627	213	56	17	1551	310	2.36	366	18	Maize	0.14	1627	213	56	17	1551	428	3.27	484
19	Wheat	0.33	2506	126	117	35	1587	312	2.00	428	19	Wheat	0.33	2506	126	117	35	1587	431	2.76	548
20	Maize	0.10	1167	354	0	0	1587	316	2.41	316	20	Maize	0.10	1167	354	0	0	1587	437	3.33	437
21	Wheat	0.31	2320	83	143	44	1630	316	2.03	459	21	Wheat	0.31	2320	83	143	44	1630	437	2.80	580
22	Maize	0.07	785	276	0	0	1630	321	2.45	321	22	Maize	0.07	785	276	0	0	1630	444	3.39	444
23	Wheat	0.28	2091	27	180	55	1685	321	2.06	501	23	Wheat	0.28	2091	27	180	55	1685	444	2.85	624
24	Maize	0.03	306	292	0	0	1685	327	2.50	327	24	Maize	0.03	306	292	0	0	1685	452	3.45	452
25	Wheat	0.24	1804	93	89	27	1712	327	2.10	416	25	Wheat	0.24	1804	93	89	27	1712	452	2.90	541
26	Maize	0.01	68	416	0	0	1712	330	2.52	330	26	Maize	0.01	68	416	0	0	1712	457	3.49	457
27	Wheat	0.22	1662	170	0	0	1712	330	2.12	330	27	Wheat	0.22	1662	170	0	0	1712	457	2.93	457
28	Maize	0.01	68	158	25	8	1720	330	2.52	356	28	Maize	0.01	68	158	25	8	1720	457	3.49	482
29	Wheat	0.22	1622	207	0	0	1720	331	2.12	331	29	Wheat	0.22	1622	207	0	0	1720	458	2.93	458
30	Maize	0.00	1	228	0	0	1720	331	2.53	331	30	Maize	0.00	1	228	0	0	1720	458	3.49	458

Appendix 6.8 Simulation results for Procedure D using irrigation water with a salinity of 25 mS m^{-1} on both soils

Soil A										Soil B									
Season	**Crop**	**Yr**	**Target yield (kg/ha)**	**R_{eff} (mm)**	**IR (mm)**	**ΔEC_{sw} (mS m^{-1})**	**EC_e next (mS m^{-1})**	**D_w (mm)**	**D_{wreq} mm/day**	**Season**	**Crop**	**Yr**	**Target yield (kg/ha)**	**R_{eff} (mm)**	**IR (mm)**	**ΔEC_{sw} (mS m^{-1})**	**EC_e next (mS m^{-1})**	**D_w (mm)**	**D_{wreq} mm/day**
1	Wheat	1.00	7500	80	587	45	65	367	2.35	1	Wheat	1.00	7500	80	587	45	65	238	1.53
2	Maize	1.00	12000	310	528	40	105	145	1.11	2	Maize	1.00	12000	310	528	40	105	201	1.53
3	Wheat	1.00	7500	85	583	44	149	204	1.31	3	Wheat	1.00	7500	85	583	44	149	282	1.80
4	Maize	1.00	12000	181	658	50	199	240	1.83	4	Maize	1.00	12000	181	658	50	199	331	2.53
5	Wheat	1.00	7500	108	560	43	242	311	1.99	5	Wheat	1.00	7500	108	560	43	242	429	2.75
6	Maize	1.00	12000	261	577	44	286	337	2.57	6	Maize	1.00	12000	261	577	44	286	466	3.56
7	Wheat	1.00	7500	113	554	42	328	372	2.38	7	Wheat	1.00	7500	113	554	42	328	514	3.29
8	Maize	1.00	12000	360	479	36	364	422	3.22	8	Maize	1.00	12000	360	479	36	364	583	4.45
9	Wheat	1.00	7500	24	644	49	413	386	2.48	9	Wheat	1.00	7500	24	644	49	413	533	3.42
10	Maize	1.00	12000	309	561	43	350	31	0.24	10	Maize	1.00	12000	309	573	44	350	43	0.33
11	Wheat	1.00	7500	74	615	47	350	22	0.14	11	Wheat	1.00	7500	74	624	47	350	31	0.20
12	Maize	1.00	12000	423	439	33	350	24	0.18	12	Maize	1.00	12000	423	449	34	350	33	0.25
13	Wheat	1.00	7500	79	606	46	350	17	0.11	13	Wheat	1.00	7500	79	613	47	350	24	0.16
14	Maize	1.00	12000	207	654	50	350	24	0.18	14	Maize	1.00	12000	207	664	50	350	33	0.25
15	Wheat	1.00	7500	245	448	34	350	25	0.16	15	Wheat	1.00	7500	245	458	35	350	35	0.23
16	Maize	1.00	12000	270	586	45	350	18	0.13	16	Maize	1.00	12000	270	594	45	350	25	0.19
17	Wheat	1.00	7500	124	567	43	350	23	0.15	17	Wheat	1.00	7500	124	576	44	350	32	0.20
18	Maize	1.00	12000	213	647	49	350	22	0.17	18	Maize	1.00	12000	213	656	50	350	31	0.24
19	Wheat	1.00	7500	126	567	43	350	25	0.16	19	Wheat	1.00	7500	126	577	44	350	35	0.22
20	Maize	1.00	12000	354	507	39	350	22	0.17	20	Maize	1.00	12000	354	516	39	350	31	0.24
21	Wheat	1.00	7500	83	604	46	350	20	0.13	21	Wheat	1.00	7500	83	612	47	350	28	0.18
22	Maize	1.00	12000	276	586	45	350	23	0.18	22	Maize	1.00	12000	276	595	45	350	33	0.25
23	Wheat	1.00	7500	27	663	50	350	23	0.15	23	Wheat	1.00	7500	27	672	51	350	32	0.20
24	Maize	1.00	12000	292	572	44	350	26	0.20	24	Maize	1.00	12000	292	582	44	350	36	0.27
25	Wheat	1.00	7500	93	596	45	350	22	0.14	25	Wheat	1.00	7500	93	605	46	350	31	0.20
26	Maize	1.00	12000	416	446	34	350	23	0.18	26	Maize	1.00	12000	416	455	35	350	32	0.25
27	Wheat	1.00	7500	170	515	39	350	18	0.11	27	Wheat	1.00	7500	170	522	40	350	25	0.16
28	Maize	1.00	12000	158	700	53	350	20	0.15	28	Maize	1.00	12000	158	708	54	350	28	0.22
29	Wheat	1.00	7500	207	488	37	350	27	0.17	29	Wheat	1.00	7500	207	498	38	350	38	0.24
30	Maize	1.00	12000	228	630	48	350	19	0.15	30	Maize	1.00	12000	228	638	49	350	27	0.21
31	Wheat	1.00	7500	64	627	48	350	24	0.16	31	Wheat	1.00	7500	64	637	48	350	34	0.22
32	Maize	1.00	12000	267	596	45	350	24	0.19	32	Maize	1.00	12000	267	606	46	350	34	0.26
33	Wheat	1.00	7500	28	663	50	350	23	0.15	33	Wheat	1.00	7500	28	672	51	350	32	0.21
34	Maize	1.00	12000	487	377	29	350	26	0.20	34	Maize	1.00	12000	487	387	29	350	36	0.27
35	Wheat	1.00	7500	68	614	47	350	15	0.10	35	Wheat	1.00	7500	68	621	47	350	21	0.14
36	Maize	1.00	12000	285	577	44	350	24	0.18	36	Maize	1.00	12000	285	587	45	350	33	0.25
37	Wheat	1.00	7500	34	656	50	350	22	0.14	37	Wheat	1.00	7500	34	665	51	350	32	0.20

Appendix 6.8 continued

Soil A										Soil B									
Season	Crop	Yr	Target yield (kg/ha)	R_{eff} (mm)	IR (mm)	ΔEC_{sw} (mS m^{-1})	EC_e next (mS m^{-1})	D_w (mm)	D_{wreq} mm/day	Season	Crop	Yr	Target yield (kg/ha)	R_{eff} (mm)	IR (mm)	ΔEC_{sw} (mS m^{-1})	EC_e next (mS m^{-1})	D_w (mm)	D_{wreq} mm/day
38	Maize	1.00	12000	251	613	47	350	25	0.19	38	Maize	1.00	12000	251	623	47	350	35	0.27
39	Wheat	1.00	7500	120	571	43	350	24	0.15	39	Wheat	1.00	7500	120	581	44	350	33	0.21
40	Maize	1.00	12000	180	680	52	350	22	0.17	40	Maize	1.00	12000	180	689	52	350	31	0.24
41	Wheat	1.00	7500	147	547	42	350	26	0.17	41	Wheat	1.00	7500	147	558	42	350	37	0.23
42	Maize	1.00	12000	256	604	46	350	21	0.16	42	Maize	1.00	12000	256	613	47	350	30	0.23
43	Wheat	1.00	7500	81	610	46	350	23	0.15	43	Wheat	1.00	7500	81	619	47	350	33	0.21
44	Maize	1.00	12000	478	384	29	350	24	0.18	44	Maize	1.00	12000	478	393	30	350	33	0.25
45	Wheat	1.00	7500	8	675	51	350	15	0.10	45	Wheat	1.00	7500	8	681	52	350	22	0.14
47	Maize	1.00	12000	65	800	61	350	26	0.20	47	Maize	1.00	12000	65	810	62	350	36	0.28
47	Wheat	1.00	7500	65	633	48	350	30	0.19	47	Wheat	1.00	7500	65	645	49	350	43	0.27
48	Maize	1.00	12000	585	278	21	350	24	0.19	48	Maize	1.00	12000	585	288	22	350	34	0.26
49	Wheat	1.00	7500	95	583	44	350	11	0.07	49	Wheat	1.00	7500	95	588	45	350	16	0.10
50	Maize	1.00	12000	297	564	43	350	23	0.17	50	Maize	1.00	12000	297	573	44	350	32	0.24
51	Wheat	1.00	7500	109	580	44	350	22	0.14	51	Wheat	1.00	7500	109	589	45	350	31	0.20
52	Maize	1.00	12000	524	337	26	350	23	0.17	52	Maize	1.00	12000	524	346	26	350	32	0.24
53	Wheat	1.00	7500	169	512	39	350	13	0.09	53	Wheat	1.00	7500	169	517	39	350	19	0.12
54	Maize	1.00	12000	428	430	33	350	20	0.15	54	Maize	1.00	12000	428	438	33	350	28	0.21
55	Wheat	1.00	7500	99	586	45	350	17	0.11	55	Wheat	1.00	7500	99	593	45	350	24	0.15
56	Maize	1.00	12000	339	522	40	350	23	0.17	56	Maize	1.00	12000	339	531	40	350	32	0.24
57	Wheat	1.00	7500	29	658	50	350	20	0.13	57	Wheat	1.00	7500	29	667	51	350	29	0.18
58	Maize	1.00	12000	199	665	51	350	25	0.19	58	Maize	1.00	12000	199	675	51	350	36	0.27
59	Wheat	1.00	7500	135	558	42	350	26	0.16	59	Wheat	1.00	7500	135	568	43	350	36	0.23
60	Maize	1.00	12000	204	656	50	350	22	0.17	60	Maize	1.00	12000	204	665	51	350	31	0.23
61	Wheat	1.00	7500	105	588	45	350	25	0.16	61	Wheat	1.00	7500	105	598	45	350	35	0.23
62	Maize	1.00	12000	455	406	31	350	23	0.17	62	Maize	1.00	12000	455	415	32	350	32	0.24
63	Wheat	1.00	7500	158	526	40	350	16	0.10	63	Wheat	1.00	7500	158	532	40	350	23	0.15
64	Maize	1.00	12000	421	438	33	350	21	0.16	64	Maize	1.00	12000	421	446	34	350	29	0.22
65	Wheat	1.00	7500	125	560	43	350	17	0.11	65	Wheat	1.00	7500	125	567	43	350	24	0.16
66	Maize	1.00	12000	100	761	58	350	22	0.17	66	Maize	1.00	12000	100	769	58	350	31	0.23
67	Wheat	1.00	7500	80	616	47	350	29	0.19	67	Wheat	1.00	7500	80	628	48	350	41	0.26
68	Maize	1.00	12000	116	747	57	350	24	0.18	68	Maize	1.00	12000	116	756	58	350	34	0.26
69	Wheat	1.00	7500	75	621	47	350	29	0.18	69	Wheat	1.00	7500	75	632	48	350	40	0.26
70	Maize	1.00	12000	290	573	44	350	24	0.18	70	Maize	1.00	12000	290	583	44	350	34	0.26
71	Wheat	1.00	7500	132	558	42	350	22	0.14	71	Wheat	1.00	7500	132	567	43	350	31	0.20
72	Maize	1.00	12000	290	571	43	350	22	0.17	72	Maize	1.00	12000	290	579	44	350	31	0.23
73	Wheat	1.00	7500	176	514	39	350	22	0.14	73	Wheat	1.00	7500	176	523	40	350	31	0.20
74	Maize	1.00	12000	261	598	45	350	20	0.15	74	Maize	1.00	12000	261	606	46	350	28	0.22
75	Wheat	1.00	7500	315	376	29	350	23	0.15	75	Wheat	1.00	7500	315	385	29	350	32	0.21
76	Maize	1.00	12000	646	207	16	350	15	0.11	76	Maize	1.00	12000	646	213	16	350	21	0.16

Appendix 6.8 continued

Soil A										Soil B									
Season	**Crop**	**Yr**	**Target yield (kg/ha)**	**R_{eff} (mm)**	**IR (mm)**	**ΔEC_{sw} (mS m^{-1})**	**EC_e next (mS m^{-1})**	**D_w (mm)**	**D_{wreq} mm/day**	**Season**	**Crop**	**Yr**	**Target yield (kg/ha)**	**R_{eff} (mm)**	**IR (mm)**	**ΔEC_{sw} (mS m^{-1})**	**EC_e next (mS m^{-1})**	**D_w (mm)**	**D_{wreq} mm/day**
77	Wheat	1.00	7500	192	484	37	350	8	0.05	77	Wheat	1.00	7500	192	488	37	350	12	0.08
78	Maize	1.00	12000	393	465	35	350	19	0.15	78	Maize	1.00	12000	393	472	36	350	26	0.20
79	Wheat	1.00	7500	115	571	43	350	18	0.12	79	Wheat	1.00	7500	115	578	44	350	26	0.16
80	Maize	1.00	12000	313	547	42	350	22	0.17	80	Maize	1.00	12000	313	556	42	350	31	0.24
81	Wheat	1.00	7500	28	661	50	350	21	0.14	81	Wheat	1.00	7500	28	669	51	350	30	0.19
82	Maize	1.00	12000	410	454	35	350	25	0.19	82	Maize	1.00	12000	410	464	35	350	36	0.27
83	Wheat	1.00	7500	293	393	30	350	18	0.11	83	Wheat	1.00	7500	293	400	30	350	25	0.16
84	Maize	1.00	12000	94	760	58	350	16	0.12	84	Maize	1.00	12000	94	766	58	350	22	0.17
85	Wheat	1.00	7500	174	522	40	350	29	0.19	85	Wheat	1.00	7500	174	534	41	350	40	0.26
86	Maize	1.00	12000	207	652	50	350	20	0.16	86	Maize	1.00	12000	207	660	50	350	29	0.22
87	Wheat	1.00	7500	198	494	38	350	25	0.16	87	Wheat	1.00	7500	198	504	38	350	35	0.23
88	Maize	1.00	12000	365	493	37	350	19	0.15	88	Maize	1.00	12000	365	501	38	350	27	0.21
89	Wheat	1.00	7500	27	660	50	350	19	0.12	89	Wheat	1.00	7500	27	668	51	350	27	0.17
90	Maize	1.00	12000	231	632	48	350	25	0.19	90	Maize	1.00	12000	231	643	49	350	36	0.27
91	Wheat	1.00	7500	58	634	48	350	24	0.16	91	Wheat	1.00	7500	58	644	49	350	34	0.22
92	Maize	1.00	12000	418	445	34	350	25	0.19	92	Maize	1.00	12000	418	454	35	350	34	0.26
93	Wheat	1.00	7500	241	444	34	350	18	0.11	93	Wheat	1.00	7500	241	451	34	350	25	0.16
94	Maize	1.00	12000	318	538	41	350	18	0.13	94	Maize	1.00	12000	318	545	41	350	25	0.19
95	Wheat	1.00	7500	73	615	47	350	21	0.13	95	Wheat	1.00	7500	73	623	47	350	29	0.19
96	Maize	1.00	12000	425	437	33	350	24	0.18	96	Maize	1.00	12000	425	447	34	350	33	0.25
97	Wheat	1.00	7500	114	571	43	350	17	0.11	97	Wheat	1.00	7500	114	578	44	350	24	0.16
98	Maize	1.00	12000	179	682	52	350	22	0.17	98	Maize	1.00	12000	179	691	53	350	31	0.24
99	Wheat	1.00	7500	82	612	47	350	26	0.17	99	Wheat	1.00	7500	82	622	47	350	37	0.24
100	Maize	1.00	12000	326	536	41	350	24	0.18	100	Maize	1.00	12000	326	545	41	350	33	0.25

Appendix 6.9 Simulation results for Procedure D using irrigation water with a salinity of 50 mS m^{-1} on both soils

Soil A										Soil B									
Season	Crop	Yr	Target yield (kg/ha)	R_{eff} (mm)	IR (mm)	ΔEC_{sw} (mS m^{-1})	EC_e next (mS m^{-1})	D_w (mm)	D_{wreq} mm/day	Season	Crop	Yr	Target yield (kg/ha)	R_{eff} (mm)	IR (mm)	ΔEC_{sw} (mS m^{-1})	EC_e next (mS m^{-1})	D_w (mm)	D_{wreq} mm/day
1	Wheat	1.00	7500	80	587	89	109	316	2.02	1	Wheat	1.00	7500	80	587	89	109	167	1.07
2	Maize	1.00	12000	310	528	80	190	181	1.38	2	Maize	1.00	12000	310	528	80	190	250	1.91
3	Wheat	1.00	7500	85	583	89	278	241	1.54	3	Wheat	1.00	7500	85	583	89	278	333	2.13
4	Maize	1.00	12000	181	658	100	378	274	2.09	4	Maize	1.00	12000	181	658	100	378	378	2.89
5	Wheat	1.00	7500	108	560	85	463	357	2.29	5	Wheat	1.00	7500	108	560	85	463	493	3.16
6	Maize	1.00	12000	261	634	96	350	57	0.43	6	Maize	1.00	12000	261	673	102	350	79	0.60
7	Wheat	1.00	7500	113	604	92	350	49	0.32	7	Wheat	1.00	7500	113	626	95	350	70	0.45
8	Maize	1.00	12000	360	526	80	350	47	0.36	8	Maize	1.00	12000	360	546	83	350	67	0.51
9	Wheat	1.00	7500	24	686	104	350	42	0.27	9	Wheat	1.00	7500	24	703	107	350	60	0.38
10	Maize	1.00	12000	309	583	89	350	53	0.40	10	Maize	1.00	12000	309	604	92	350	75	0.57
11	Wheat	1.00	7500	74	639	97	350	46	0.29	11	Wheat	1.00	7500	74	659	100	350	65	0.42
12	Maize	1.00	12000	423	465	71	350	50	0.38	12	Maize	1.00	12000	423	486	74	350	71	0.54
13	Wheat	1.00	7500	79	626	95	350	38	0.24	13	Wheat	1.00	7500	79	643	98	350	54	0.35
14	Maize	1.00	12000	207	680	103	350	49	0.37	14	Maize	1.00	12000	207	700	106	350	69	0.53
15	Wheat	1.00	7500	245	475	72	350	52	0.34	15	Wheat	1.00	7500	245	497	76	350	74	0.48
16	Maize	1.00	12000	270	607	92	350	38	0.29	16	Maize	1.00	12000	270	624	95	350	55	0.42
17	Wheat	1.00	7500	124	591	90	350	48	0.30	17	Wheat	1.00	7500	124	611	93	350	67	0.43
18	Maize	1.00	12000	213	672	102	350	46	0.35	18	Maize	1.00	12000	213	691	105	350	66	0.50
19	Wheat	1.00	7500	126	594	90	350	52	0.33	19	Wheat	1.00	7500	126	616	94	350	74	0.47
20	Maize	1.00	12000	354	531	81	350	47	0.36	20	Maize	1.00	12000	354	551	84	350	67	0.51
21	Wheat	1.00	7500	83	627	95	350	42	0.27	21	Wheat	1.00	7500	83	645	98	350	60	0.39
22	Maize	1.00	12000	276	611	93	350	49	0.37	22	Maize	1.00	12000	276	631	96	350	69	0.53
23	Wheat	1.00	7500	27	688	105	350	48	0.31	23	Wheat	1.00	7500	27	708	108	350	68	0.44
24	Maize	1.00	12000	292	600	91	350	53	0.40	24	Maize	1.00	12000	292	622	95	350	75	0.57
25	Wheat	1.00	7500	93	621	94	350	47	0.30	25	Wheat	1.00	7500	93	641	97	350	67	0.43
26	Maize	1.00	12000	416	471	72	350	49	0.37	26	Maize	1.00	12000	416	491	75	350	69	0.53
27	Wheat	1.00	7500	170	535	81	350	38	0.24	27	Wheat	1.00	7500	170	552	84	350	54	0.35
28	Maize	1.00	12000	158	723	110	350	43	0.32	28	Maize	1.00	12000	158	741	113	350	60	0.46
29	Wheat	1.00	7500	207	516	78	350	55	0.35	29	Wheat	1.00	7500	207	539	82	350	78	0.50
30	Maize	1.00	12000	228	652	99	350	41	0.31	30	Maize	1.00	12000	228	670	102	350	59	0.45
31	Wheat	1.00	7500	64	654	99	350	51	0.32	31	Wheat	1.00	7500	64	675	103	350	72	0.46
32	Maize	1.00	12000	267	623	95	350	51	0.39	32	Maize	1.00	12000	267	644	98	350	72	0.55
33	Wheat	1.00	7500	28	689	105	350	49	0.31	33	Wheat	1.00	7500	28	709	108	350	69	0.44
34	Maize	1.00	12000	487	405	62	350	53	0.41	34	Maize	1.00	12000	487	427	65	350	75	0.57
35	Wheat	1.00	7500	68	632	96	350	33	0.21	35	Wheat	1.00	7500	68	647	98	350	48	0.31
36	Maize	1.00	12000	285	603	92	350	49	0.38	36	Maize	1.00	12000	285	623	95	350	70	0.53
37	Wheat	1.00	7500	34	681	104	350	47	0.30	37	Wheat	1.00	7500	34	701	107	350	67	0.43
38	Maize	1.00	12000	251	640	97	350	53	0.40	38	Maize	1.00	12000	251	662	101	350	74	0.57

Appendix 6.9 continued

Soil A										Soil B									
Season	**Crop**	**Yr**	**Target yield (kg/ha)**	**R_{eff} (mm)**	**IR (mm)**	**ΔEC_{sw} (mS m^{-1})**	**EC_e next (mS m^{-1})**	**D_w (mm)**	**D_{wreq} mm/day**	**Season**	**Crop**	**Yr**	**Target yield (kg/ha)**	**R_{eff} (mm)**	**IR (mm)**	**ΔEC_{sw} (mS m^{-1})**	**EC_e next (mS m^{-1})**	**D_w (mm)**	**D_{wreq} mm/day**
39	Wheat	1.00	7500	120	597	91	350	50	0.32	39	Wheat	1.00	7500	120	618	94	350	71	0.45
40	Maize	1.00	12000	180	705	107	350	47	0.36	40	Maize	1.00	12000	180	725	110	350	67	0.51
41	Wheat	1.00	7500	147	575	87	350	54	0.35	41	Wheat	1.00	7500	147	598	91	350	77	0.49
42	Maize	1.00	12000	256	628	95	350	45	0.35	42	Maize	1.00	12000	256	647	98	350	65	0.49
43	Wheat	1.00	7500	81	635	97	350	49	0.31	43	Wheat	1.00	7500	81	656	100	350	70	0.45
44	Maize	1.00	12000	478	409	62	350	49	0.38	44	Maize	1.00	12000	478	430	65	350	70	0.54
45	Wheat	1.00	7500	8	693	105	350	33	0.21	45	Wheat	1.00	7500	8	708	108	350	48	0.31
47	Maize	1.00	12000	65	827	126	350	53	0.41	47	Maize	1.00	12000	65	849	129	350	75	0.57
47	Wheat	1.00	7500	65	665	101	350	62	0.40	47	Wheat	1.00	7500	65	691	105	350	88	0.56
48	Maize	1.00	12000	585	305	46	350	51	0.39	48	Maize	1.00	12000	585	327	50	350	74	0.56
49	Wheat	1.00	7500	95	598	91	350	26	0.16	49	Wheat	1.00	7500	95	610	93	350	38	0.24
50	Maize	1.00	12000	297	588	89	350	47	0.36	50	Maize	1.00	12000	297	607	92	350	66	0.50
51	Wheat	1.00	7500	109	604	92	350	46	0.30	51	Wheat	1.00	7500	109	624	95	350	66	0.42
52	Maize	1.00	12000	524	361	55	350	47	0.36	52	Maize	1.00	12000	524	381	58	350	67	0.51
53	Wheat	1.00	7500	169	528	80	350	30	0.19	53	Wheat	1.00	7500	169	541	82	350	43	0.28
54	Maize	1.00	12000	428	452	69	350	42	0.32	54	Maize	1.00	12000	428	470	71	350	59	0.45
55	Wheat	1.00	7500	99	605	92	350	37	0.23	55	Wheat	1.00	7500	99	621	94	350	52	0.34
56	Maize	1.00	12000	339	547	83	350	47	0.36	56	Maize	1.00	12000	339	566	86	350	67	0.51
57	Wheat	1.00	7500	29	681	104	350	43	0.28	57	Wheat	1.00	7500	29	700	106	350	62	0.40
58	Maize	1.00	12000	199	692	105	350	53	0.40	58	Maize	1.00	12000	199	714	109	350	74	0.57
59	Wheat	1.00	7500	135	585	89	350	53	0.34	59	Wheat	1.00	7500	135	608	92	350	76	0.49
60	Maize	1.00	12000	204	680	103	350	46	0.35	60	Maize	1.00	12000	204	700	106	350	66	0.50
61	Wheat	1.00	7500	105	615	94	350	53	0.34	61	Wheat	1.00	7500	105	637	97	350	74	0.48
62	Maize	1.00	12000	455	431	66	350	48	0.37	62	Maize	1.00	12000	455	452	69	350	69	0.52
63	Wheat	1.00	7500	158	545	83	350	35	0.22	63	Wheat	1.00	7500	158	560	85	350	50	0.32
64	Maize	1.00	12000	421	461	70	350	43	0.33	64	Maize	1.00	12000	421	479	73	350	61	0.47
65	Wheat	1.00	7500	125	580	88	350	37	0.24	65	Wheat	1.00	7500	125	596	91	350	53	0.34
66	Maize	1.00	12000	100	784	119	350	46	0.35	66	Maize	1.00	12000	100	803	122	350	65	0.49
67	Wheat	1.00	7500	80	646	98	350	59	0.38	67	Wheat	1.00	7500	80	671	102	350	84	0.54
68	Maize	1.00	12000	116	773	118	350	50	0.38	68	Maize	1.00	12000	116	795	121	350	72	0.55
69	Wheat	1.00	7500	75	651	99	350	59	0.38	69	Wheat	1.00	7500	75	675	103	350	83	0.53
70	Maize	1.00	12000	290	599	91	350	51	0.39	70	Maize	1.00	12000	290	621	94	350	72	0.55
71	Wheat	1.00	7500	132	583	89	350	47	0.30	71	Wheat	1.00	7500	132	603	92	350	67	0.43
72	Maize	1.00	12000	290	595	90	350	46	0.35	72	Maize	1.00	12000	290	614	93	350	65	0.50
73	Wheat	1.00	7500	176	538	82	350	47	0.30	73	Wheat	1.00	7500	176	558	85	350	66	0.43
74	Maize	1.00	12000	261	621	94	350	43	0.33	74	Maize	1.00	12000	261	639	97	350	61	0.47
75	Wheat	1.00	7500	315	401	61	350	48	0.31	75	Wheat	1.00	7500	315	421	64	350	69	0.44
76	Maize	1.00	12000	646	225	34	350	33	0.25	76	Maize	1.00	12000	646	239	36	350	47	0.36

Appendix 6.9 continued

Soil A										Soil B									
Season	**Crop**	**Yr**	**Target yield (kg/ha)**	**R_{eff} (mm)**	**IR (mm)**	**ΔEC_{sw} (mS m^{-1})**	**EC_e next (mS m^{-1})**	**D_w (mm)**	**D_{wreq} mm/day**	**Season**	**Crop**	**Yr**	**Target yield (kg/ha)**	**R_{eff} (mm)**	**IR (mm)**	**ΔEC_{sw} (mS m^{-1})**	**EC_e next (mS m^{-1})**	**D_w (mm)**	**D_{wreq} mm/day**
77	Wheat	1.00	7500	192	495	75	350	19	0.12	77	Wheat	1.00	7500	192	504	77	350	28	0.18
78	Maize	1.00	12000	393	485	74	350	40	0.30	78	Maize	1.00	12000	393	501	76	350	56	0.43
79	Wheat	1.00	7500	115	592	90	350	39	0.25	79	Wheat	1.00	7500	115	608	92	350	55	0.36
80	Maize	1.00	12000	313	572	87	350	47	0.35	80	Maize	1.00	12000	313	591	90	350	66	0.50
81	Wheat	1.00	7500	28	684	104	350	45	0.29	81	Wheat	1.00	7500	28	704	107	350	64	0.41
82	Maize	1.00	12000	410	481	73	350	53	0.40	82	Maize	1.00	12000	410	503	77	350	75	0.57
83	Wheat	1.00	7500	293	413	63	350	39	0.25	83	Wheat	1.00	7500	293	430	65	350	56	0.36
84	Maize	1.00	12000	94	778	118	350	34	0.26	84	Maize	1.00	12000	94	793	121	350	48	0.37
85	Wheat	1.00	7500	174	552	84	350	59	0.38	85	Wheat	1.00	7500	174	576	88	350	83	0.53
86	Maize	1.00	12000	207	675	103	350	44	0.33	86	Maize	1.00	12000	207	694	106	350	63	0.48
87	Wheat	1.00	7500	198	521	79	350	52	0.33	87	Wheat	1.00	7500	198	543	83	350	74	0.47
88	Maize	1.00	12000	365	515	78	350	42	0.32	88	Maize	1.00	12000	365	533	81	350	60	0.45
89	Wheat	1.00	7500	27	682	104	350	41	0.26	89	Wheat	1.00	7500	27	699	106	350	59	0.38
90	Maize	1.00	12000	231	660	100	350	53	0.40	90	Maize	1.00	12000	231	681	104	350	74	0.57
91	Wheat	1.00	7500	58	661	100	350	51	0.33	91	Wheat	1.00	7500	58	682	104	350	73	0.47
92	Maize	1.00	12000	418	471	72	350	51	0.39	92	Maize	1.00	12000	418	493	75	350	73	0.56
93	Wheat	1.00	7500	241	464	71	350	38	0.24	93	Wheat	1.00	7500	241	481	73	350	55	0.35
94	Maize	1.00	12000	318	558	85	350	37	0.29	94	Maize	1.00	12000	318	574	87	350	53	0.41
95	Wheat	1.00	7500	73	638	97	350	44	0.28	95	Wheat	1.00	7500	73	657	100	350	63	0.40
96	Maize	1.00	12000	425	463	70	350	50	0.38	96	Maize	1.00	12000	425	484	74	350	70	0.54
97	Wheat	1.00	7500	114	591	90	351	37	0.24	97	Wheat	1.00	7500	114	607	92	351	54	0.34
98	Maize	1.00	12000	179	707	107	352	47	0.36	98	Maize	1.00	12000	179	726	110	352	66	0.51
99	Wheat	1.00	7500	82	641	97	353	55	0.35	99	Wheat	1.00	7500	82	663	101	353	78	0.50
100	Maize	1.00	12000	326	563	86	354	51	0.39	100	Maize	1.00	12000	326	585	89	354	73	0.56

Appendix 6.10 Simulation results for Procedure D using irrigation water with a salinity of 100 mS m^{-1} on both soils

Soil A										Soil B									
Season	**Crop**	**Yr**	**Target yield (kg/ha)**	**R_{eff} (mm)**	**IR (mm)**	**ΔEC_{sw} (mS m^{-1})**	**EC_e next (mS m^{-1})**	**D_w (mm)**	**D_{wreq} mm/day**	**Season**	**Crop**	**Yr**	**Target yield (kg/ha)**	**R_{eff} (mm)**	**IR (mm)**	**ΔEC_{sw} (mS m^{-1})**	**EC_e next (mS m^{-1})**	**D_w (mm)**	**D_{wreq} mm/day**
1	Wheat	1.00	7500	80	587	179	199	283	1.81	1	Wheat	1.00	7500	80	587	179	199	292	1.87
2	Maize	1.00	12000	310	528	161	359	207	1.58	2	Maize	1.00	12000	310	528	161	359	286	2.18
3	Wheat	1.00	7500	85	583	177	536	266	1.71	3	Wheat	1.00	7500	85	583	177	536	368	2.36
4	Maize	1.00	12000	181	756	230	350	99	0.75	4	Maize	1.00	12000	181	811	247	350	137	1.04
5	Wheat	1.00	7500	108	675	205	350	116	0.74	5	Wheat	1.00	7500	108	728	221	350	166	1.06
6	Maize	1.00	12000	261	684	208	350	106	0.81	6	Maize	1.00	12000	261	733	223	350	155	1.18
7	Wheat	1.00	7500	113	661	201	350	107	0.69	7	Wheat	1.00	7500	113	710	216	350	156	1.00
8	Maize	1.00	12000	360	583	177	350	105	0.80	8	Maize	1.00	12000	360	631	192	350	153	1.16
9	Wheat	1.00	7500	24	739	225	350	95	0.61	9	Wheat	1.00	7500	24	783	238	350	140	0.89
10	Maize	1.00	12000	309	643	196	350	114	0.87	10	Maize	1.00	12000	309	694	211	350	164	1.25
11	Wheat	1.00	7500	74	696	212	350	102	0.66	11	Wheat	1.00	7500	74	743	226	350	150	0.96
12	Maize	1.00	12000	423	524	159	350	109	0.83	12	Maize	1.00	12000	423	573	174	350	158	1.20
13	Wheat	1.00	7500	79	676	206	350	87	0.56	13	Wheat	1.00	7500	79	718	218	350	130	0.83
14	Maize	1.00	12000	207	737	224	350	106	0.81	14	Maize	1.00	12000	207	785	239	350	154	1.17
15	Wheat	1.00	7500	245	536	163	350	114	0.73	15	Wheat	1.00	7500	245	587	178	350	164	1.05
16	Maize	1.00	12000	270	658	200	350	89	0.68	16	Maize	1.00	12000	270	701	213	350	132	1.01
17	Wheat	1.00	7500	124	648	197	350	104	0.67	17	Wheat	1.00	7500	124	695	211	350	151	0.97
18	Maize	1.00	12000	213	728	222	350	103	0.79	18	Maize	1.00	12000	213	775	236	350	150	1.15
19	Wheat	1.00	7500	126	654	199	350	112	0.72	19	Wheat	1.00	7500	126	705	214	350	163	1.04
20	Maize	1.00	12000	354	589	179	350	104	0.79	20	Maize	1.00	12000	354	636	194	350	152	1.16
21	Wheat	1.00	7500	83	680	207	350	96	0.61	21	Wheat	1.00	7500	83	725	220	350	140	0.90
22	Maize	1.00	12000	276	669	203	350	107	0.82	22	Maize	1.00	12000	276	717	218	350	155	1.18
23	Wheat	1.00	7500	27	746	227	350	106	0.68	23	Wheat	1.00	7500	27	794	241	350	154	0.98
24	Maize	1.00	12000	292	661	201	350	114	0.87	24	Maize	1.00	12000	292	712	217	350	166	1.26
25	Wheat	1.00	7500	93	679	206	350	105	0.67	25	Wheat	1.00	7500	93	727	221	350	153	0.98
26	Maize	1.00	12000	416	529	161	350	107	0.81	26	Maize	1.00	12000	416	578	176	350	155	1.18
27	Wheat	1.00	7500	170	585	178	350	88	0.56	27	Wheat	1.00	7500	170	627	191	350	130	0.84
28	Maize	1.00	12000	158	775	236	350	95	0.73	28	Maize	1.00	12000	158	819	249	350	139	1.06
29	Wheat	1.00	7500	207	578	176	350	118	0.76	29	Wheat	1.00	7500	207	630	192	350	169	1.09
30	Maize	1.00	12000	228	705	215	350	94	0.72	30	Maize	1.00	12000	228	750	228	350	139	1.06
31	Wheat	1.00	7500	64	713	217	350	110	0.70	31	Wheat	1.00	7500	64	762	232	350	159	1.02
32	Maize	1.00	12000	267	683	208	350	111	0.84	32	Maize	1.00	12000	267	733	223	350	161	1.23
33	Wheat	1.00	7500	28	747	227	350	107	0.69	33	Wheat	1.00	7500	28	796	242	350	156	1.00
34	Maize	1.00	12000	487	466	142	350	115	0.87	34	Maize	1.00	12000	487	517	157	350	166	1.27
35	Wheat	1.00	7500	68	679	207	350	80	0.51	35	Wheat	1.00	7500	68	719	219	350	120	0.77
36	Maize	1.00	12000	285	660	201	350	107	0.81	36	Maize	1.00	12000	285	708	215	350	154	1.18
37	Wheat	1.00	7500	34	738	225	350	105	0.67	37	Wheat	1.00	7500	34	786	239	350	152	0.98
38	Maize	1.00	12000	251	701	213	350	114	0.87	38	Maize	1.00	12000	251	752	229	350	164	1.25

Appendix 6.10 continued

Soil A										Soil B									
Season	Crop	Yr	Target yield (kg/ha)	R_{eff} (mm)	IR (mm)	ΔEC_{sw} (mS m^{-1})	EC_e next (mS m^{-1})	D_w (mm)	D_{wreq} mm/day	Season	Crop	Yr	Target yield (kg/ha)	R_{eff} (mm)	IR (mm)	ΔEC_{sw} (mS m^{-1})	EC_e next (mS m^{-1})	D_w (mm)	D_{wreq} mm/day
39	Wheat	1.00	7500	120	657	200	350	109	0.70	39	Wheat	1.00	7500	120	707	215	350	159	1.02
40	Maize	1.00	12000	180	762	232	350	104	0.79	40	Maize	1.00	12000	180	810	246	350	152	1.16
41	Wheat	1.00	7500	147	637	194	350	116	0.75	41	Wheat	1.00	7500	147	689	210	350	168	1.08
42	Maize	1.00	12000	256	684	208	350	102	0.78	42	Maize	1.00	12000	256	732	223	350	149	1.14
43	Wheat	1.00	7500	81	694	211	350	107	0.69	43	Wheat	1.00	7500	81	742	226	350	156	1.00
44	Maize	1.00	12000	478	468	142	350	108	0.83	44	Maize	1.00	12000	478	518	157	350	158	1.20
45	Wheat	1.00	7500	8	740	225	350	80	0.51	45	Wheat	1.00	7500	8	779	237	350	120	0.77
47	Maize	1.00	12000	65	888	270	350	114	0.87	47	Maize	1.00	12000	65	937	285	350	163	1.25
47	Wheat	1.00	7500	65	733	223	350	130	0.83	47	Wheat	1.00	7500	65	789	240	350	186	1.19
48	Maize	1.00	12000	585	367	112	350	113	0.86	48	Maize	1.00	12000	585	419	127	350	165	1.26
49	Wheat	1.00	7500	95	637	194	350	65	0.42	49	Wheat	1.00	7500	95	673	205	350	101	0.65
50	Maize	1.00	12000	297	643	196	350	102	0.78	50	Maize	1.00	12000	297	688	209	350	147	1.12
51	Wheat	1.00	7500	109	661	201	350	102	0.66	51	Wheat	1.00	7500	109	707	215	350	149	0.96
52	Maize	1.00	12000	524	419	127	350	105	0.80	52	Maize	1.00	12000	524	466	142	350	152	1.16
53	Wheat	1.00	7500	169	571	174	350	73	0.47	53	Wheat	1.00	7500	169	608	185	350	110	0.71
54	Maize	1.00	12000	428	504	153	350	94	0.71	54	Maize	1.00	12000	428	546	166	350	136	1.04
55	Wheat	1.00	7500	99	654	199	350	85	0.54	55	Wheat	1.00	7500	99	694	211	350	125	0.80
56	Maize	1.00	12000	339	603	183	350	104	0.79	56	Maize	1.00	12000	339	649	197	350	150	1.14
57	Wheat	1.00	7500	29	736	224	350	98	0.63	57	Wheat	1.00	7500	29	781	237	350	143	0.91
58	Maize	1.00	12000	199	753	229	350	113	0.86	58	Maize	1.00	12000	199	803	244	350	164	1.25
59	Wheat	1.00	7500	135	647	197	350	115	0.74	59	Wheat	1.00	7500	135	699	213	350	167	1.07
60	Maize	1.00	12000	204	737	224	350	103	0.79	60	Maize	1.00	12000	204	785	239	350	151	1.15
61	Wheat	1.00	7500	105	676	206	350	113	0.73	61	Wheat	1.00	7500	105	727	221	350	164	1.05
62	Maize	1.00	12000	455	489	149	350	106	0.81	62	Maize	1.00	12000	455	538	164	350	155	1.19
63	Wheat	1.00	7500	158	592	180	350	83	0.53	63	Wheat	1.00	7500	158	633	193	350	123	0.79
64	Maize	1.00	12000	421	514	156	350	96	0.73	64	Maize	1.00	12000	421	558	170	350	140	1.07
65	Wheat	1.00	7500	125	629	191	350	86	0.55	65	Wheat	1.00	7500	125	670	204	350	127	0.81
66	Maize	1.00	12000	100	839	255	350	101	0.77	66	Maize	1.00	12000	100	885	269	350	146	1.11
67	Wheat	1.00	7500	80	712	216	350	125	0.80	67	Wheat	1.00	7500	80	766	233	350	179	1.15
68	Maize	1.00	12000	116	833	253	350	111	0.84	68	Maize	1.00	12000	116	884	269	350	161	1.23
69	Wheat	1.00	7500	75	716	218	350	124	0.80	69	Wheat	1.00	7500	75	771	235	350	179	1.15
70	Maize	1.00	12000	290	660	201	350	111	0.85	70	Maize	1.00	12000	290	711	216	350	162	1.24
71	Wheat	1.00	7500	132	640	195	350	104	0.67	71	Wheat	1.00	7500	132	688	209	350	153	0.98
72	Maize	1.00	12000	290	651	198	350	102	0.78	72	Maize	1.00	12000	290	698	212	350	149	1.14
73	Wheat	1.00	7500	176	595	181	350	103	0.66	73	Wheat	1.00	7500	176	642	195	350	151	0.97
74	Maize	1.00	12000	261	674	205	350	97	0.74	74	Maize	1.00	12000	261	719	219	350	141	1.08
75	Wheat	1.00	7500	315	459	140	350	106	0.68	75	Wheat	1.00	7500	315	507	154	350	154	0.99
76	Maize	1.00	12000	646	271	82	350	79	0.60	76	Maize	1.00	12000	646	310	94	350	118	0.90

Appendix 6.10 continued

Soil A										Soil B									
Season	**Crop**	**Yr**	**Target yield (kg/ha)**	**R_{eff} (mm)**	**IR (mm)**	**ΔEC_{sw} (mS m^{-1})**	**EC_e next (mS m^{-1})**	**D_w (mm)**	**D_{wreq} mm/day**	**Season**	**Crop**	**Yr**	**Target yield (kg/ha)**	**R_{eff} (mm)**	**IR (mm)**	**ΔEC_{sw} (mS m^{-1})**	**EC_e next (mS m^{-1})**	**D_w (mm)**	**D_{wreq} mm/day**
77	Wheat	1.00	7500	192	526	160	350	50	0.32	77	Wheat	1.00	7500	192	554	168	350	78	0.50
78	Maize	1.00	12000	393	533	162	350	88	0.67	78	Maize	1.00	12000	393	572	174	350	126	0.96
79	Wheat	1.00	7500	115	641	195	350	89	0.57	79	Wheat	1.00	7500	115	682	207	350	129	0.83
80	Maize	1.00	12000	313	627	191	350	102	0.78	80	Maize	1.00	12000	313	673	205	350	148	1.13
81	Wheat	1.00	7500	28	740	225	350	101	0.64	81	Wheat	1.00	7500	28	786	239	350	147	0.94
82	Maize	1.00	12000	410	542	165	350	114	0.87	82	Maize	1.00	12000	410	593	180	350	164	1.25
83	Wheat	1.00	7500	293	465	141	350	90	0.58	83	Wheat	1.00	7500	293	508	154	350	133	0.85
84	Maize	1.00	12000	94	824	251	350	79	0.61	84	Maize	1.00	12000	94	862	262	350	118	0.90
85	Wheat	1.00	7500	174	616	187	350	123	0.79	85	Wheat	1.00	7500	174	669	204	350	176	1.13
86	Maize	1.00	12000	207	730	222	350	99	0.76	86	Maize	1.00	12000	207	777	236	350	146	1.11
87	Wheat	1.00	7500	198	582	177	350	113	0.72	87	Wheat	1.00	7500	198	632	192	350	163	1.04
88	Maize	1.00	12000	365	568	173	350	95	0.72	88	Maize	1.00	12000	365	613	186	350	140	1.07
89	Wheat	1.00	7500	27	734	223	350	93	0.60	89	Wheat	1.00	7500	27	777	236	350	136	0.87
90	Maize	1.00	12000	231	720	219	350	113	0.86	90	Maize	1.00	12000	231	770	234	350	163	1.24
91	Wheat	1.00	7500	58	721	219	350	112	0.71	91	Wheat	1.00	7500	58	772	235	350	162	1.04
92	Maize	1.00	12000	418	532	162	350	112	0.85	92	Maize	1.00	12000	418	582	177	350	162	1.24
93	Wheat	1.00	7500	241	514	156	350	88	0.57	93	Wheat	1.00	7500	241	557	169	350	131	0.84
94	Maize	1.00	12000	318	607	184	350	86	0.66	94	Maize	1.00	12000	318	647	197	350	127	0.97
95	Wheat	1.00	7500	73	692	210	351	98	0.63	95	Wheat	1.00	7500	73	736	224	351	142	0.91
96	Maize	1.00	12000	425	522	159	352	109	0.83	96	Maize	1.00	12000	425	571	174	352	157	1.20
97	Wheat	1.00	7500	114	641	195	353	88	0.56	97	Wheat	1.00	7500	114	684	208	353	130	0.84
98	Maize	1.00	12000	179	763	232	354	103	0.79	98	Maize	1.00	12000	179	810	246	354	150	1.14
99	Wheat	1.00	7500	82	703	214	355	118	0.76	99	Wheat	1.00	7500	82	755	230	355	170	1.09
100	Maize	1.00	12000	326	623	190	356	111	0.85	100	Maize	1.00	12000	326	674	205	356	162	1.24

Appendix 6.11 Simulation results for Procedure E using irrigation water with a salinity of 25 mS m^{-1} on both soils

Soil A										Soil B									
Season	Crop	Yr	Target yield (kg/ha)	R_{eff} (mm)	IR (mm)	ΔEC_{sw} (mS m^{-1})	EC_e next (mS m^{-1})	D_w (mm)	D_{wreq} mm/day	Season	Crop	Yr	Target yield (kg/ha)	R_{eff} (mm)	IR (mm)	ΔEC_{sw} (mS m^{-1})	EC_e next (mS m^{-1})	D_w (mm)	D_{wreq} mm/day
1	Wheat	1.00	7500	80	667	45	65	367	2.35	1	Wheat	1.00	7500	80	667	45	65	507	3.25
2	Maize	1.00	12000	310	838	4	69	385	2.94	2	Maize	1.00	12000	310	838	15	80	586	4.47
3	Wheat	1.00	7500	85	667	23	92	460	2.95	3	Wheat	1.00	7500	85	667	38	118	715	4.58
4	Maize	1.00	12000	181	838	21	113	508	3.88	4	Maize	1.00	12000	181	838	41	158	804	6.14
5	Wheat	1.00	7500	108	667	30	144	561	3.60	5	Wheat	1.00	7500	108	667	53	211	886	5.68
6	Maize	1.00	12000	261	838	23	166	592	4.52	6	Maize	1.00	12000	261	838	48	259	942	7.19
7	Wheat	1.00	7500	113	667	36	203	633	4.06	7	Wheat	1.00	7500	113	667	63	322	1000	6.41
8	Maize	1.00	12000	360	838	21	224	653	4.98	8	Maize	1.00	12000	360	838	49	371	1037	7.92
9	Wheat	1.00	7500	24	667	48	271	691	4.43	9	Wheat	1.00	7500	24	667	77	448	1087	6.97
10	Maize	1.00	12000	309	838	29	300	711	5.42	10	Maize	0.93	11145	309	791	59	507	1119	8.54
11	Wheat	1.00	7500	74	667	48	349	739	4.74	11	Wheat	1.00	7500	74	667	79	586	1156	7.41
12	Maize	1.00	12000	423	838	24	373	752	5.74	12	Maize	0.83	9931	423	725	56	642	1179	9.00
13	Wheat	1.00	7500	79	667	51	424	776	4.98	13	Wheat	0.97	7280	79	649	84	726	1210	7.76
14	Maize	0.95	11351	207	803	43	467	795	6.07	14	Maize	0.73	8710	207	658	76	802	1236	9.43
15	Wheat	1.00	7500	245	667	42	509	811	5.20	15	Wheat	0.86	6440	245	577	75	877	1258	8.07
16	Maize	0.88	10606	270	762	41	550	825	6.30	16	Maize	0.62	7382	270	585	75	952	1279	9.76
17	Wheat	1.00	7500	124	667	53	604	842	5.40	17	Wheat	0.75	5650	124	510	88	1040	1301	8.34
18	Maize	0.81	9779	213	716	48	651	856	6.54	18	Maize	0.50	5954	213	506	83	1123	1320	10.08
19	Wheat	0.96	7230	126	644	56	707	871	5.59	19	Wheat	0.63	4755	126	434	91	1214	1340	8.59
20	Maize	0.74	8873	354	667	39	746	881	6.73	20	Maize	0.37	4433	354	423	75	1289	1355	10.34
21	Wheat	0.90	6732	83	602	61	807	896	5.74	21	Wheat	0.52	3884	83	360	97	1385	1373	8.80
22	Maize	0.67	7996	276	619	47	854	906	6.92	22	Maize	0.24	2929	276	340	83	1469	1387	10.59
23	Wheat	0.82	6166	27	554	67	921	920	5.90	23	Wheat	0.39	2939	27	279	103	1572	1404	9.00
24	Maize	0.58	6998	292	564	48	969	929	7.09	24	Maize	0.11	1293	292	251	85	1657	1417	10.82
25	Wheat	0.74	5564	93	503	64	1032	940	6.03	25	Wheat	0.26	1951	93	195	101	1758	1432	9.18
26	Maize	0.50	6023	416	510	40	1072	947	7.23	26	Maize	0.00	0	416	180	77	1835	1443	11.01
27	Wheat	0.67	5021	170	456	59	1131	957	6.14	27	Wheat	0.14	1017	170	115	97	1932	1456	9.33
28	Maize	0.43	5156	158	463	61	1192	967	7.38	28	Maize	0.00	0	158	180	99	2030	1468	11.21
29	Wheat	0.59	4392	207	403	58	1250	975	6.25	29	Wheat	0.00	0	207	29	96	2126	1479	9.48
30	Maize	0.34	4118	228	406	57	1307	983	7.51	30	Maize	0.00	0	228	180	95	2221	1490	11.38
31	Wheat	0.51	3790	64	352	70	1376	993	6.36	31	Wheat	0.00	0	64	29	108	2330	1502	9.63
32	Maize	0.25	3008	267	345	55	1432	1000	7.63	32	Maize	0.00	0	267	180	94	2424	1512	11.54
33	Wheat	0.42	3134	28	296	74	1506	1009	6.47	33	Wheat	0.00	0	28	29	113	2537	1523	9.76
34	Maize	0.16	1877	487	283	40	1545	1013	7.74	34	Maize	0.00	0	487	180	79	2615	1531	11.68
35	Wheat	0.34	2537	68	245	72	1617	1022	6.55	35	Wheat	0.00	0	68	29	111	2727	1541	9.88

Appendix 6.12 Simulation results for Procedure E using irrigation water with a salinity of 50 mS m^{-1} on both soils

Soil A										Soil B									
Season	**Crop**	**Yr**	**Target yield (kg/ha)**	**R_{eff} (mm)**	**IR (mm)**	**ΔEC_{sw} (mS m^{-1})**	**EC_e next (mS m^{-1})**	**D_w (mm)**	**D_{wreq} mm/day**	**Season**	**Crop**	**Yr**	**Target yield (kg/ha)**	**R_{eff} (mm)**	**IR (mm)**	**ΔEC_{sw} (mS m^{-1})**	**EC_e next (mS m^{-1})**	**D_w (mm)**	**D_{wreq} mm/day**
1	Wheat	1.00	7500	80	667	89	109	316	2.02	1	Wheat	1.00	7500	80	667	89	109	436	2.80
2	Maize	1.00	12000	310	838	1	110	318	2.43	2	Maize	1.00	12000	310	838	19	128	504	3.85
3	Wheat	1.00	7500	85	667	35	146	400	2.57	3	Wheat	1.00	7500	85	667	64	192	650	4.17
4	Maize	1.00	12000	181	838	33	179	453	3.46	4	Maize	1.00	12000	181	838	71	264	750	5.72
5	Wheat	1.00	7500	108	667	53	232	514	3.29	5	Wheat	1.00	7500	108	667	98	361	842	5.40
6	Maize	1.00	12000	261	838	38	270	548	4.18	6	Maize	0.99	11901	261	833	88	450	903	6.89
7	Wheat	1.00	7500	113	667	66	336	594	3.81	7	Wheat	1.00	7500	113	667	120	570	968	6.20
8	Maize	1.00	12000	360	838	36	372	615	4.70	8	Maize	0.84	10075	360	733	92	662	1008	7.69
9	Wheat	1.00	7500	24	667	90	462	659	4.22	9	Wheat	0.96	7173	24	640	150	812	1061	6.80
10	Maize	0.92	11021	309	785	53	515	681	5.20	10	Maize	0.66	7954	309	616	114	926	1095	8.36
11	Wheat	1.00	7500	74	667	92	607	713	4.57	11	Wheat	0.77	5787	74	522	155	1082	1135	7.28
12	Maize	0.81	9746	423	715	44	651	726	5.54	12	Maize	0.47	5591	423	487	108	1190	1160	8.85
13	Wheat	0.96	7231	79	644	98	750	753	4.83	13	Wheat	0.59	4403	79	404	164	1354	1193	7.65
14	Maize	0.71	8498	207	646	83	833	773	5.90	14	Maize	0.27	3202	207	355	150	1504	1220	9.31
15	Wheat	0.84	6278	245	563	80	913	790	5.07	15	Wheat	0.37	2753	245	263	148	1652	1243	7.97
16	Maize	0.59	7068	270	568	79	992	806	6.15	16	Maize	0.05	591	270	212	148	1800	1265	9.66
17	Wheat	0.73	5441	124	492	104	1096	824	5.28	17	Wheat	0.16	1198	124	131	174	1974	1288	8.26
18	Maize	0.46	5466	213	480	93	1189	839	6.41	18	Maize	0.00	0	0	0	0	1974	0	0
19	Wheat	0.59	4409	126	404	109	1297	856	5.48	19	Wheat	0.00	0	0	0	0	1974	0	0
20	Maize	0.31	3701	354	383	76	1374	866	6.61	20	Maize	0.00	0	0	0	0	1974	0	0
21	Wheat	0.46	3438	83	322	119	1493	881	5.65	21	Wheat	0.00	0	0	0	0	1974	0	0
22	Maize	0.17	1989	276	289	92	1585	892	6.81	22	Maize	0.00	0	0	0	0	1974	0	0
23	Wheat	0.31	2330	27	227	132	1716	907	5.81	23	Wheat	0.00	0	0	0	0	1974	0	0
24	Maize	0.00	0	0	0	0	1716	0	0.00	24	Maize	0.00	0	0	0	0	1974	0	0
25	Wheat	0.15	1148	93	127	125	1935	929	5.95	25	Wheat	0.00	0	0	0	0	1974	0	0

Appendix 6.13 Simulation results for Procedure E using irrigation water with a salinity of 100 mS m^{-1} on both soils

Soil A										**Soil B**									
Season	**Crop**	**Yr**	**Target yield (kg/ha)**	**R_{eff} (mm)**	**IR (mm)**	**ΔEC_{sw} (mS m^{-1})**	**EC_e next (mS m^{-1})**	**D_w (mm)**	**D_{wreq} mm/day**	**Season**	**Crop**	**Yr**	**Target yield (kg/ha)**	**R_{eff} (mm)**	**IR (mm)**	**ΔEC_{sw} (mS m^{-1})**	**EC_e next (mS m^{-1})**	**D_w (mm)**	**D_{wreq} mm/day**
1	Wheat	1.00	7500	80	667	179	199	283	1.81	1	Wheat	1.00	7500	80	667	179	199	391	2.51
2	Maize	1.00	12000	310	838	-8	190	267	2.04	2	Maize	1.00	12000	310	838	24	223	445	3.40
3	Wheat	1.00	7500	85	667	56	246	352	2.26	3	Wheat	1.00	7500	85	667	110	333	601	3.85
4	Maize	1.00	12000	181	838	52	298	406	3.10	4	Maize	1.00	12000	181	838	128	461	708	5.41
5	Wheat	1.00	7500	108	667	91	389	473	3.03	5	Wheat	1.00	7500	108	667	183	643	809	5.18
6	Maize	0.97	11660	261	820	65	453	509	3.89	6	Maize	0.79	9431	261	697	166	810	874	6.67
7	Wheat	1.00	7500	113	667	120	574	561	3.60	7	Wheat	0.85	6399	113	574	231	1041	943	6.05
8	Maize	0.84	10040	360	731	61	635	583	4.45	8	Maize	0.50	5945	360	506	177	1219	986	7.52
9	Wheat	0.98	7316	24	652	170	805	631	4.05	9	Wheat	0.57	4252	24	391	292	1511	1042	6.68
10	Maize	0.67	8015	309	620	98	903	655	5.00	10	Maize	0.15	1828	309	280	223	1734	1078	8.23
11	Wheat	0.79	5909	74	532	176	1080	690	4.42	11	Wheat	0.21	1545	74	160	305	2040	1120	7.18
12	Maize	0.47	5609	423	487	81	1161	704	5.37	12	Maize	0.00	0	423	0	0	2040	0	0.00
13	Wheat	0.61	4556	79	417	190	1351	733	4.70	13	Wheat	0.00	0	79	0	0	2040	0	0.00
14	Maize	0.27	3232	207	357	160	1511	754	5.76	14	Maize	0.00	0	207	0	0	2040	0	0.00
15	Wheat	0.36	2718	245	260	155	1666	773	4.95	15	Wheat	0.00	0	245	0	0	2040	0	0.00