EFFECT OF IRRIGATION WATER AND WATER TABLE SALINITY ON THE GROWTH AND WATER USE OF SELECTED CROPS

L Ehlers • JH Barnard • SB Dikgwatlhe •
LD van Rensburg • GM Ceronio •
CC du Preez • ATP Bennie

WRC Report No. 1359/1/07

Water Research Commission

Effect of Irrigation Water and Water Table Salinity on the Growth and Water Use of Selected Crops

Report to the
Water Research Commission

by

L Ehlers, JH Barnard, SB Dikgwatlhe, LD van Rensburg, GM Ceronio, CC du Preez & ATP Bennie
Department of Soil, Crop and Climate Sciences
University of the Free State
Bloemfontein

WRC Report No 1359/1/07
ISBN 978-1-77005-476-9

February 2007

EXECUTIVE SUMMARY

The general opinion is that the importance of irrigation in context of global agriculture is rapidly increasing. Unfortunately, most irrigation fields throughout the world suffer to some degree from the effects of salt accumulation in soils. An estimated 20% of the 230 million ha of irrigated land in the world is seriously affected by salinity. In South Africa an estimated 20% of the 1.3 million ha of irrigated land is salt affected. The effects of salinity in soils manifested in reduced crop growth and in severe cases, even crop failure. Salinity is associated with increased water stress and specific ion effects on crops. Therefore, secondary salinisation of irrigated land as a result of a decline in water quality cannot be ignored when sustainable crop production under irrigation is the aim.

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 optimum development and functioning of roots. The reclamation of already saline soils is accomplished through leaching with water of lower salinity, provided that drainage is adequate.

Little in this regard has been studied in South Africa. This project 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 project 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. Determine and model the salt balance for a range of irrigation water quality and soil type combinations over a three year period.

5. Quantify the leaching requirements for the two soils at five salinity levels.

In order to achieve these objectives, experiments were conducted with wheat, beans, peas and maize under controlled conditions in the laboratory, glasshouse and field with irrigation water that ranged from a low salinity of 15 mS m^{-1} to a high salinity of 600 mS m^{-1}. The influence of irrigation water salinity on seed germination and seedling vigour were tested under laboratory conditions. However, the effect of irrigation water salinity on crop growth and development in pots filled with a red sandy loam Bainsvlei soil were evaluated under glasshouse conditions. Large drainage lysimeters, filled with a yellow sandy Clovelly soil and a red sandy loam Bainsvlei soil in which shallow water tables with salinities similar to the irrigation water 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, salt accumulation in the root zone during growing seasons and modes of removal of excess salts through leaching. The results of these experiments will be addressed according to the listed objectives.

1. The laboratory experiments revealed that only the germination percentage of pea seed was reduced by deteriorating irrigation water salinity, viz. to 92% at 300 mS m^{-1}. However, increasing irrigation water salinity above 150 mS m^{-1} started to inhibit the seedling growth of all four crops as indicated by coleoptile/hipocotile and root length. In the glasshouse experiments parameters such as relative leaf area, above-ground biomass, root mass and seed yield declined with increasing salinity of the irrigation water. Peas proved to be the most sensitive crop followed by beans, maize and wheat. The field experiments simulated conditions of adequate water supply to the crops through irrigation in the presence of a water table at a depth of 1.2 m. 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 growth of wheat, maize, peas and beans started to decline when irrigating with water of 600, 450, 300 and 150 mS m^{-1}, respectively. However, the inhibition of crop growth viz. the above-ground biomass was explained better by soil water salinity.

2. Generally the water use of all four crops in the field experiments as indicated by evapotranspiration declined with deteriorating irrigation water salinity. The decline in water use despite an adequate water supply through irrigation, can be attributed to an increase of salinity that results in a decrease of osmotic potential of the soil water in the root zone. 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 findings of other researchers were therefore confirmed, namely that the effects of salinity and water stress are similar. However, 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 values mentioned earlier were exceeded.

3. In the field experiments water uptake from the shallow water tables decreased with an increase in irrigation water salinity for all four crops on both soils, probably due to a decrease in osmotic potential of the capillary zones above the water tables. 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} which is equivalent to an osmotic potential of -54 kPa. The crops less affected by the increase in salinity, or the decrease in osmotic potential of the capillary zone were wheat, followed by maize, beans and peas.

4. The determination and modelling of salt balances over a three year period in the field experiments was not realised due to rapid salt build up in both soils within a single crop growing season. Instead of these balances the focus of experiments was on salt accumulation in the root zone during a crop growing season in the presence of a 1.2 m depth water table and the removal of these accumulated salts. At the end of a crop growing season the salts were accumulated at or just below the capillary fringe of both soils, with maximum accumulation of 700 mm from the soil surface. This is the zone where most of the water is taken up by crop roots, causing an increase in the concentration of ions. A single drainage cycle removed between 2.0 and 35.0 ton salt ha^{-1} at a rate of 0.054 kg ha^{-1} mm^{-1} from the more sandy soil and between 0.8 and 13.5 ton salt ha^{-1} at a rate of 0.041 kg ha^{-1} mm^{-1} from the more clayey soil, depending on the initial salinity. Leaching of both soils with a range of saline water in the presence of differing salinity profiles revealed that soil water salinity decreased initially linearly with an increase in drainage per unit soil depth, whereafter it declined sharply with a further increase in drainage per unit soil depth. In general, efficiency of salt leaching from both soils decreased rapidly when the depletion level rose above 80% of the total actual salts removed. Equations were derived from the data to calculate: i) the salt accumulation in soils with restricted drainage during a crop growing season and ii) the amount of drainage water required for salt removal from the two soils. These equations are incorporated in the procedure given below for salinity management in irrigated soils.

5. Sustainable crop production under irrigation requires the proper management of salinity in the root zone with leaching. The amounts of water needed for leaching to manage root zone salinity are seldom estimated with complex dynamic models for several reasons. Such estimates are usually based on guidelines established from empirical relationships derived from field experiments as is the case in this study. A stepwise procedure is therefore proposed for the managing of root zone salinity. This procedure makes provision for four 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 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 threshold value; iii) where added salts can leach naturally from the root zone and the mean root zone salinity is lower than the crop threshold value; and iv) where added salts can leach naturally from the root zone and the mean root zone salinity is higher than the crop threshold value. This procedure was not yet been tested and hence is not verified.

The results from this research project 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.

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 4.3.4.2 to 4.3.4.4). There are four management options:

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 salinisation 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 less salts will also be added to the root zone. The growing season will end 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 4.3.3). 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 salinisation 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 salinisation of the unsaturated and capillary layers is 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 through the 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.

It should be clear from the above-mentioned 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. Water draining from the saturated soil towards the drainage tubes, following installation, will remove a significant amount of the salts. For example on a sandy soil with a water table at 1200 mm with a soil water EC of 777 mS m^{-1}, approximately 18 000 kg ha^{-1} salt will be removed from the root zone with the first drainage cycle. To remove 80% of the remaining salts over a depth of 1800 mm by leaching with good quality water, approximately 300 mm or 0.5 pore volume of drainage is required. More clayey soils will require more drainage to a maximum of 1 pore volume or 600 mm (Figure 6.9). When leaching salts from soils it should be kept in mind that the salinity of the irrigation water determines the equilibrium salinity of the root zone.

All these aspects were included in the proposed stepwise procedure that can be followed to formulate the best management practices for controlling root zone salinity under different conditions. As mentioned above, this procedure still needs to be tested, verified and even modified at field scale before it can be extended to optimal practice and the establishing of guidelines for managing the salt load associated with irrigation at farm and scheme level. Consequently, future research of this kind is suggested.

ACKNOWLEDGEMENTS

The successful completion of this project was possible only with the co-operation of many individuals and institutions and the authors wish to record their sincere thanks to the following:

1. The Water Research Commission for financing the project.

2. The members of the steering committee for their valuable contributions during meetings:

Mr H M du Plessis	Water Research Commission (Chairman)
Prof J G Annandale	University of Pretoria
Ms S Forbes	Free State Department of Agriculture
Dr J E Hoffman	University of Stellenbosch
Prof S Lorentz	University of KwaZulu-Natal
Mr J P Nell	ARC-Institute for Soil, Climate and Water
Mr S W J van der Merwe	Free State Department of Agriculture
Mr P S van Heerden	Consultant
Prof M F Viljoen	University of the Free State

3. The management and administration of the University of the Free State for excellent infrastructure and facilities.

4. Messrs A van Vuuren and A Welters of the CSIR for use of their facilities for water analyses.

5. Messrs C H Wessels, Z E Yokwani and T A Madito who assisted in the execution of the field trials.

6. Ms Y M Dessels and Mr E T Moeti for technical assistance regarding soil and water analyses.

7. Ms G C van Heerden for the typing of this report with great precision and efficiency.

TABLE OF CONTENTS

		PAGE
EXECUTIVE SUMMARY		iii
ACKNOWLEDGEMENTS		viii
LIST OF FIGURES		xiii
LIST OF TABLES		xviii
LIST OF PLATES		xx
LIST OF APPENDICES		xxi
1.	INTRODUCTION	1
2.	LITERATURE REVIEW	3
2.1	Introduction	3
2.2	Irrigation water quality	4
	2.2.1 Salinity	4
	2.2.2 Sodicity	5
2.3	Soil and water table salinity	7
2.4	Effect of soil and water salinity on crop growth	8
	2.4.1 Crop salt-tolerance	8
	2.4.2 Osmotic effect	10
	2.4.3 Specific ion effect and nutrition	11
	2.4.4 Specific ion effect and toxicity	12
2.5	Salt accumulation in soils	12
	2.5.1 Origin of salinity in irrigated areas	12
	2.5.2 Factors involved in salt accumulation	12
	2.5.2.1 Irrigation water quality	12
	2.5.2.2 Capillary rise	13
2.6	Salt removal from soils	14
	2.6.1 Salt movement in soil	14
	2.6.1.1 Convection	14
	2.6.1.2 Diffusion	15
	2.6.2 Leaching of salts	16
	2.6.2.1 Quantity of water for leaching	16
	2.6.2.2 Water application method	17
2.7	Predicting salt accumulation and removal	17
	2.7.1 General	17

2.7.2 Salt balance models 19
2.7.3 Capillary rise models 20
2.7.4 Models for salt leaching 20
2.7.5 Irrigation management models 21
2.7.6 Generic principles 22
2.8 Conclusions 22

3. CROP RESPONSE TO VARIOUS WATER SALINITY LEVELS UNDER LABORATORY AND GLASSHOUSE CONDITIONS 24
3.1 Introduction 24
3.2 Materials and methods 25
3.2.1 Germination experiments 25
3.2.2 Pot experiments 25
3.3 Results and discussion 27
3.3.1 Germination experiments 27
3.3.1.1 Quantitative germination data 29
3.3.1.2 Qualitative germination data 30
3.3.2 Pot experiments 30
3.3.2.1 Effect of irrigation water salinity on selected plant parameters 30
3.3.2.1.1 Relative leaf area 31
3.3.2.1.2 Relative root mass 33
3.3.2.1.3 Relative biomass 35
3.3.2.1.4 Relative seed yield 36
3.3.2.2 Effect of soil water salinity of the pots on growth and water use 38
3.3.2.2.1 Water use and salt accumulation in pots 38
3.3.2.2.2 Relative biomass 39
3.4 Conclusions 40

4. EFFECT OF IRRIGATION WATER SALINITY ON CROP YIELD AND WATER UPTAKE ON TWO APEDAL SOILS WITH SHALLOW WATER TABLES 42
4.1 Introduction 42
4.2 Materials and methods 42
4.2.1 Experimental site 42
4.2.2 Soil characteristics 44
4.2.3 Treatments 44
4.2.4 Agronomic practices 46
4.2.5 Grain and biomass yields 46
4.2.6 Soil water balance 48

4.2.7 Irrigation scheduling 49
4.3 Results and discussion 50
4.3.1 Crop yields 50
4.3.1.1 Actual crop yields as affected by irrigation water salinity 50
4.3.1.2 Relative crop yields as affected by irrigation water salinity 53
4.3.2 Evapotranspiration and water use efficiency 53
4.3.3 Water table uptake 62
4.3.4 Comparison of the salt tolerance of the different crops 69
4.3.4.1 Relationship between relative cumulative evapotranspiration and soil water salinity 69
4.3.4.2 Relationship between the relative biomass yield and soil water salinity 71
4.3.4.3 Effect of soil water salinity on the water production functions of crops 74
4.3.4.4 Effect of soil water salinity on the water table uptake of crops 75
4.4 Conclusions 76

5. SALT ACCUMULATION IN THE ROOT ZONE DURING THE GROWING SEASON OF CROPS IN THE PRESENCE OF SHALLOW WATER TABLES 80
5.1 Introduction 80
5.2 Materials and methods 80
5.3 Results and discussion 82
5.3.1 Soil water salinity profiles at beginning and end of growing season 82
5.3.2 Effect of capillary zone on salt distribution through the soil profile 91
5.3.3 Verification of the conversion factor for electrical conductivity to total dissolved salts 93
5.3.4 Comparison between salt added through irrigation water and increase in soil salinity 95
5.3.5 Prediction of salt accumulation in soils with restricted drainage 96
5.4 Conclusions 97

6. REMOVAL OF EXCESS SALTS FROM SALINE APEDAL SOILS 98
6.1 Introduction 98
6.2 Materials and methods 98
6.2.1 Experiment 1: Drainage of saturated soils 98

6.2.1.1 Measurements 99
6.2.1.2 Neutron water meter calibration 100
6.2.2 Experiment 2: Leaching with good quality irrigation water 100
6.2.3 Experiment 3: Leaching with a range of irrigation water salinities 101
6.3 Results and discussion 101
6.3.1 Drainage of saturated soils with decreasing soil water salinities 101
6.3.1.1 Salinity status of the soils 102
6.3.1.2 Effect of deteriorating soil water quality on drainage 103
6.3.1.3 Soil water content versus time relationships 104
6.3.1.4 Quantifying salt removed during a complete drainage cycle 105
6.3.2 Salt removal through leaching with good quality water 107
6.3.2.1 Water balance 107
6.3.2.2 Salt removal 109
6.3.2.3 Change in salt distribution of profiles 111
6.3.3 Salt removal by leaching with different irrigation water salinities 113
6.3.3.1 Salinity profiles and its leaching fraction 113
6.3.3.2 Leaching curves 114
6.3.3.3 Verification of the leaching curves 119
6.4 Conclusions 121

7. PROCEDURES FOR MANAGING ROOT ZONE SALINITY 123
7.1 Introduction 123
7.2 Essential information required for managing root zone salinity 123
7.3 Root zone salinity management options 128
7.4 Description of the different root zone salinity management procedures 128
7.5 Conclusions 130

8. RESEARCH OUTCOMES AND RECOMMENDATIONS 131
8.1 Introduction 131
8.2 Outcomes in relation to the project objectives 131
8.2.1 Objective 1 131
8.2.2 Objective 2 132
8.2.3 Objective 3 133
8.2.4 Objective 4 134
8.2.5 Objective 5 136
8.3 General conclusions and practical implications 137
8.4 Gaps and current knowledge 140
8.5 Requirements of future research 141
REFERENCES 142
APPENDICES 150

LIST OF FIGURES

Figure 2.1	Water uptake from water tables, as affected by water table depth and soil texture.	14
Figure 2.2	The ratio of the required salinity (Sa, mg L^{-1}) and initial salinity (Sb, mg L^{-1}) and it's relationship with the ratio with the amount of drainage (Dw, mm) and soil depth (Ds, mm).	17
Figure 3.1	Response of relative leaf area of the selected crops to different EC_i levels.	31
Figure 3.2	Response of relative root mass of the selected crops to different EC_i levels.	34
Figure 3.3	Response of relative biomass production of the selected crops to different EC_i levels.	35
Figure 3.4	Response of relative seed yield of the selected crops to different EC_i levels.	37
Figure 3.5	Relationship between irrigation water salinity (EC_i) and soil water salinity (EC_e) in the pots.	39
Figure 3.6	Soil salinity induced osmotic stress on the relative biomass production.	39
Figure 4.1	The relationship between the relative biomass yield (BM_{rel}) and irrigation water salinity (EC_i, mS m^{-1}) of wheat on both soils.	54
Figure 4.2	The relationship between the relative biomass yield (BM_{rel}) and irrigation water salinity (EC_i, mS m^{-1}) of dry beans on both soils.	54
Figure 4.3	The relationship between the relative biomass yield (BM_{rel}) and irrigation water salinity (EC_i, mS m^{-1}) of dry peas on both soils.	55
Figure 4.4	The relationship between the relative biomass yield (BM_{rel}) and irrigation water salinity (EC_i, mS m^{-1}) of maize on both soils.	55
Figure 4.5	Mean wheat daily evapotranspiration (ET, mm day^{-1}) over the growing season for all the treatments of Soil A.	58
Figure 4.6	Mean wheat daily evapotranspiration (ET, mm day^{-1}) over the growing season for all the treatments of Soil B.	58
Figure 4.7	Mean bean daily evapotranspiration (ET, mm day^{-1}) over the growing season for all the treatments of Soil A.	59
Figure 4.8	Mean bean daily evapotranspiration (ET, mm day^{-1}) over the growing season for all the treatments of Soil B.	59
Figure 4.9	Mean pea daily evapotranspiration (ET, mm day^{-1}) over the growing season for all the treatments of Soil A.	60
Figure 4.10	Mean pea daily evapotranspiration (ET, mm day^{-1}) over the growing season for all the treatments of Soil B.	60

Figure 4.11	Mean maize daily evapotranspiration (ET, mm day^{-1}) over the growing season for all the treatments of Soil A.	61
Figure 4.12	Mean maize daily evapotranspiration (ET, mm day^{-1}) over the growing season for all the treatments of Soil B.	61
Figure 4.13	Cumulative water table uptake as a function of days after planting for all the treatments of the wheat crop on Soil A.	65
Figure 4.14	Cumulative water table uptake as a function of days after planting for all the treatments of the wheat crop on Soil B.	65
Figure 4.15	Cumulative water table uptake as a function of days after planting for all the treatments of beans on Soil A.	66
Figure 4.16	Cumulative water table uptake as a function of days after planting for all the treatments of beans on Soil B.	66
Figure 4.17	Cumulative water table uptake as a function of days after planting for all the treatments of peas on Soil A.	67
Figure 4.18	Cumulative water table uptake as a function of days after planting for all the treatments of peas on Soil B.	67
Figure 4.19	Cumulative water table uptake as a function of days after planting for all the treatments of maize on Soil A.	68
Figure 4.20	Cumulative water table uptake as a function of days after planting for all the treatments of maize on Soil B.	68
Figure 4.21	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_o, -kPa) for all the crops on both soils.	70
Figure 4.22	The relationship between the relative biomass yield (BM_{rel}) and mean seasonal soil water salinity (EC_{sw}) for wheat on both soils.	72
Figure 4.23	The relationship between the relative biomass yield (BM_{rel}) and mean seasonal soil water salinity (EC_{sw}) for beans on both soils.	72
Figure 4.24	The relationship between the relative biomass yield (BM_{rel}) and mean seasonal soil water salinity (EC_{sw}) for peas on both soils.	73
Figure 4.25	The relationship between the relative biomass yield (BM_{rel}) and mean seasonal soil water salinity (EC_{sw}) for maize on both soils.	73
Figure 4.26	Relationship between the relative biomass yield (BM_{rel}) and the relative cumulative ET (Cum ET_{rel}) for all the crops and soils combined.	75
Figure 4.27	Relative water uptake from the capillary zones of water tables with different salinity levels by the experimental crops.	78

Figure 5.1	Soil water salinity profiles at the beginning and end of the wheat growing season for all the EC_i treatments of both soils.	84
Figure 5.2	Soil water salinity profiles at the beginning and end of the bean growing season for all the EC_i treatments of both soils.	86
Figure 5.3	Soil water salinity profiles at the beginning and end of the pea growing season for all the EC_i treatments of both soils.	88
Figure 5.4	Soil water salinity profiles at the beginning and end of the maize growing season for all the EC_i treatments of both soils.	90
Figure 5.5	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.	91
Figure 5.6	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.	92
Figure 5.7	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.	92
Figure 5.8	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.	93
Figure 5.9	The relationship between the EC_{sw} and TDS_{sw} measured at the end of the growing season of all the crops, for both soils.	94
Figure 5.10	The relationship between the electrical conductivity of the irrigation water (EC_i) and the total dissolved salts (TDS_i).	94
Figure 5.11	The relationship between the increase in soil water salinity and the amount of salts added through irrigation and water table uptake.	96
Figure 6.1	Comparison of the indirectly calculated cumulative drainage, using the calibrated CPN, with the directly measured values for all the lysimeters of both soils.	100
Figure 6.2	Influence of irrigation water salinity (EC_i) on the increase of soil water salinity (ΔEC_{sw}) after 612 mm irrigation.	102
Figure 6.3	Influence of electrical conductivity of the soil water (EC_{sw}) on drainage rates (DR) for both soils.	103
Figure 6.4	Water content versus time, for the 1.8 m profiles of both soils, for all the lysimeters.	105
Figure 6.5	Salt removal rate (kg salts ha^{-1} mm^{-1} drainage below 1800 mm depth) of all the lysimeters for both soils as a function of the electrical conductivity of the soil water (EC_{sw}).	107
Figure 6.6	Average water content and time of irrigation during the leaching period for both soils.	108
Figure 6.7	Relationship between measured and estimated cumulative drainage (mm) for all the lysimeters of both soils.	108

Figure 6.8	The average electrical conductivity of the soil water (EC_{sw}) over a depth of 1800 mm, for the entire leaching period for both soils.	110
Figure 6.9	Cumulative drainage plotted as a function of the fraction of actual salt removed over a depth of 1800 mm for the two soils leached with good quality water (EC_i = 75 mS m^{-1}).	111
Figure 6.10	Change in salt distribution profiles of both soils, for the various treatments, during the entire leaching period of experiment 2.	112
Figure 6.11	Change in salt distributions profiles of both soils, as affected by cumulative irrigation (mm) over the entire leaching period for experiment 3.	115
Figure 6.12	Fraction of salts removed plotted as a function of drainage per unit soil depth for the different treatments and soils.	117
Figure 6.13	Relationship between the fraction of salts removed by leaching with different qualities irrigation water and the drainage per unit soil depth (mm).	118
Figure 6.14	Statistical comparisons to the actual EC_{sw}, calculated with leaching equations, against the actual measured EC_{sw} values, of both soils using the independent data set of experiment 2.	120
Figure 6.15	Relationship between the mean silt-plus-clay percentage of the soils and the corresponding b-values for the salt leaching equations.	121
Figure 7.1	Diagram for selecting the appropriate salinity management procedure for a root zone (EC_{sw} = mean EC_{sw} of the root zone).	128

LIST OF TABLES

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.	5
Table 2.2	Salt tolerance of some agronomic crops.	9
Table 2.3	Relative susceptibility of crops to foliar injury from saline sprinkling waters.	10
Table 2.4	Concentration factors for predicting soil salinity from irrigation water salinity and the leaching fraction.	19
Table 3.1	Agronomic information regarding cultivar, planting date, planting depth, row width, seeding rate, fertilization, irrigation and sampling stage of the different experimental crops.	26
Table 3.2	Parameters used during plant growth and yield evaluation.	28
Table 3.3	The effect of water salinity on the average germination percentage, coleoptile or hypocotile length and root length of the selected crops.	29
Table 3.4	Summary of the threshold level at which salinity significantly reduced the different plant parameters of the selected crops.	32
Table 3.5	Relative leaf area (%) of selected crops at different EC_i levels.	33
Table 3.6	Relative root mass (%) of selected crops at different EC_i levels.	34
Table 3.7	Relative biomass (%) of selected crops at different EC_i levels.	35
Table 3.8	Relative yield (%) of selected crops at different EC_i levels.	37
Table 3.9	Water use efficiency (WUE, mg biomass per kg water applied) of the different crops in the pot experiments.	38
Table 3.10	Threshold EC_e (mS m^{-1}) and slope values for the selected crops according to the regression analysis of the relationship between the relative biomass and soil water salinity (EC_e) of the saline irrigation water treatments.	40
Table 4.1	Particle size distribution of Soil A and Soil B for the different depths at which they were packed in the lysimeters.	45
Table 4.2	Electrical conductivity (EC_i, mS m^{-1}) and sodium adsorption ratio (SAR) of the irrigation water that was used for the different treatments and crops.	45
Table 4.3	The amounts of different salts that were used to prepare the irrigation water quality treatments for the different crops.	47
Table 4.4	Some of the agronomic practices used for wheat, dry beans, peas and maize.	48
Table 4.5	The total amount of irrigation water applied to the different	49

	soils, crops and EC_i treatments.	
Table 4.6	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.	51
Table 4.7	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.	52
Table 4.8	Mean evapotranspiration (ET, mm) and water use efficiency (WUE, g kg^{-1}) for all the crops and EC_i treatments of both soils.	56
Table 4.9	Average cumulative evapotranspiration (ET) and uptake from the water tables (WT) for the different crops and EC_i treatments on both soils.	64
Table 4.10	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.	70
Table 4.11	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.	71
Table 4.12	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.	76
Table 4.13	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.	77
Table 5.1	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.	95
Table 6.1	Average electrical conductivity of drainage water (EC_d), cumulative drainage ($\sum D$) and cumulative salt removal ($\sum SR$) for both soils.	106
Table 6.2	Mean EC_{sw}-values of the various salinity treatments at the end of the beans growing season, and the target values set for peas at planting.	114
Table 6.3	Guidelines for approximate amount of drainage required to leach 80% of the salts from different depth with two irrigation water salinities for Soil A and B.	119

Table 6.4	Comparison of guidelines generated with the leaching equations (LE) of both soils against the recommended leaching requirement (mm 1200 mm^{-1} soil depth) of Van der Merwe (1975).	120
Table 7.1	Salt tolerance of different crops (after Rhoades & Loveday, 1990 and this report) and other relevant information.	125

LIST OF PLATES

Plate 4.1	Layout of the lysimeters and an illustration of a vertical cut through a container with a constant water table height control mechanism.	43
Plate 5.1	Ceramic cups installed from the access chamber side of the lysimeters at different depths from the soil surface.	81

LIST OF APPENDICES

Appendix 4.1	The amount of irrigation water applied at specific days after planting (DAP) for all the soils, crops and EC_i treatments.	151
Appendix 4.2	Seed and total biomass yield data for all the soils, crops and EC_i treatments.	153
Appendix 4.3	Example of a water balance sheet for the control treatment of maize on Soil A during the first 26 days after planting.	154
Appendix 5.1	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.	155
Appendix 6.1	Statistical results of the rational function for measured cumulative drainage per lysimeter regressed with time, for both soils and all EC_i treatments.	156
Appendix 6.2	Water content of the lysimeters during the entire drainage period, for both soils and all EC_i treatments.	157
Appendix 6.3	The electrical conductivity of the drainage water (EC_d), cumulative measured drainage ($\sum$ D) and the cumulative salt removed ($\sum$ SR) during the entire drainage period of all the lysimeters on both soils.	158
Appendix 6.4	Water content of the lysimeters during the entire leaching period for the EC_i treatments on both soils.	159
Appendix 6.5	The electrical conductivity of the soil water (EC_{sw}, mS m^{-1}) measured at specific times (days) during the leaching period for all the lysimters of the EC_i treatments on both soils.	161
Appendix 6.6	The full data set of the electrical conductivity of the drainage water (EC_d, mS m^{-1}) as well as the measured drainage (mm) for all the lysimeters of the EC_i treatments on both soils.	163
Appendix 6.7	The full data set of cumulative irrigation, cumulative drainage as well as the change in the electrical conductivity of the soil water (EC_{sw}, mS m^{-1}) for all the EC_i treatments on both soils.	165
Appendix 6.8	The ratios used in the leaching equations for the different treatments and soil depths of all the EC_i treatments on both soils.	166

CHAPTER 1

INTRODUCTION

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 230 million ha of irrigated land in the world is seriously affected by salinity. 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 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 lying downslope positions, where impermeable strata occur below the root zone and where the water application exceeds the 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 already 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 project 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 project 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. Determine and model the salt balance for a range of irrigation water quality and soil type combinations, over a three year period.

5. Quantify the leaching requirements for the two soils at five salinity levels.

The project focused on cases where a shallow water table is present in the lower part of the potential root zone resulting in conditions with 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 laboratory, glasshouse and field to achieve the objectives of this research project.

A thorough literature study of the issues raised in the objectives is reported in Chapter 2. The influence of various water salinity levels on seed germination and the seedling vigour of the different crops under laboratory conditions is reported in Chapter 3. In this chapter the effect of increasingly saline irrigation water on crop growth in pots under glasshouse conditions is also reported. 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 4), salt accumulation in the root zone during the growing seasons (Chapter 5) and modes of removal of excess salts through leaching (Chapter 6). All these results were combined in recommended procedures for managing root zone salinity in Chapter 7.

CHAPTER 2

LITERATURE 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 fulfill 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 paramount importance. This applies especially to processes that are associated with soil and water degradation. One of the soil degradation processes is salinisation, viz. the accumulation of salt which leads to the degradation of especially heavy-textured soils (Szabolcs, 1989). According to the Land and Plant Management Service of the FAO, salinisation of irrigated soils is a major problem. It concluded that of 230 million ha of irrigated land 20% is salt-affected and of the 1500 million ha under dryland agriculture, 2% is salt-affected in varying degrees.

The general feeling is that the importance of irrigation in world agriculture is rapidly increasing, which means that the problem of specifically secondary salinisation 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 the 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 salinisation 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 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.

It is clear that salinisation 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 salinisation. Modelling the different components involved in secondary salinisation 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).

2.2.1 Salinity

Electrical conductivity (EC) is a measure of the ability of water to conduct an electrical current and is expressed in millisiemens per meter (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 salts (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:

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

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

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 salinisation 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 90^{th} 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)

2.2.2 Sodicity

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.

$$SAR = \frac{Na^{+}}{\sqrt{(Ca^{2+} + Mg^{2+})\,2}} \quad (2.2)$$

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 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 and the 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 the 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} at the lower end, 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 (Ehlers *et al.*, 2003). Shallow water tables in or just below the root zone cause rapid salinisation of soil layers above the water table, 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 salinisation as a potential hazard where sub-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 build-up 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 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 evapotranspiration from a water table with a salinity of 600 mS m^{-1} and up to 49% of its evapotranspiration from a water table when the salinity increased to 1000 mS m^{-1}.

This was confirmed by Blaine & Kite (1984) who investigated the 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. 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 salinisation 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. 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, 1977a):

$$Y_r = 100 - b\,(EC_e - a) \qquad (2.3)$$

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)

		Electrical conductivity of saturated soil extract		
Common name	**Botanical name**	**Threshold $mS\ m^{-1}$**	**Slope % of $mS\ m^{-1}$**	**Rating ***
Bean	*Phaseolus vulgaris*	100	19	S
Cotton	*Gossypium hirsutum*	770	5.2	T
Maize	*Zea mays*	170	12	MS
Pea	*Pisum sativum*	-	-	S
Peanut	*Arachis hypogaea*	320	29	MS
Potato	*Solanum tuberosum*	170	12	MS
Wheat	*Triticum aestivum*	600	7.1	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 treasuring 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 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	Grape	Alfalfa	Cauliflower
Apricot	Pepper	Barley	Cotton
Citrus	Potato	Cucumber	Sugarbeet
Plum	Tomato	Safflower	Sunflower
		Sesame	
		Sorghum	
		Maize	

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 of 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 than 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 damage 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 it 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 $SO_4^{=}$ and to a greater extent, Cl^- diminished the rate of NO_3^- absorption with 83% at 0.2 M NaCl.

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 liter. 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 salinisation 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 risen, due to the degree of excessive irrigation which exceeds the drainage of the soil. High water tables in irrigated agriculture gave rise to problems of salinity and waterlogging in most of the irrigation schemes. This secondary salinisation 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 the 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 options can 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 Gharmarnia *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 meters. 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, will depend 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 texture. When water table depth increases, the contribution of the water table as a percentage of ET will decrease. This effect of water table depth on water table contribution will be influenced by the salinity levels of the water table (Sepashah & 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 salinisation problems especially at high water table salinity levels (Streutker *et al.*, 1981).

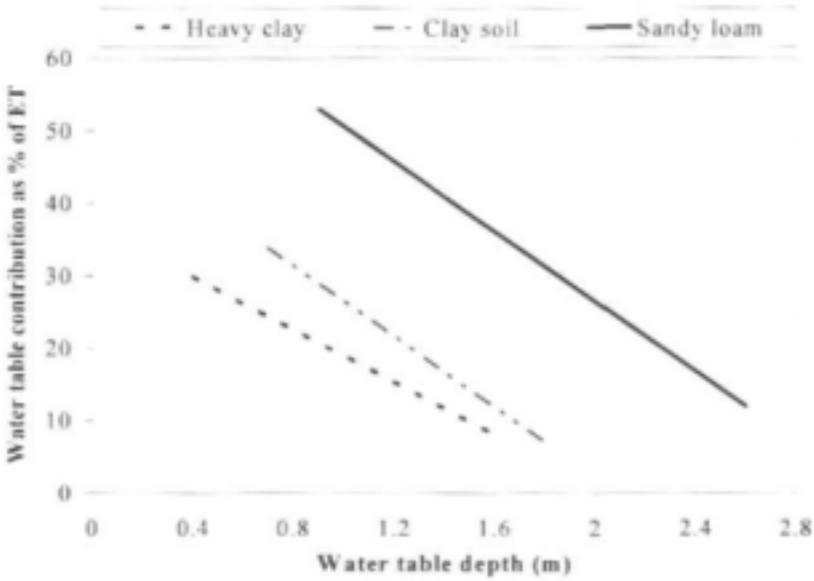

Figure 2.1 Water uptake from water tables, as affected by water table depth and soil texture (Grismer & Gates, 1988).

2.6 Salt removal from soils

2.6.1 Salt movement in soil

According to the miscible displacement theory, salt will move in the soil in response to 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 lower salt concentration of the macro pores and the higher salt concentration of the micro pores. As a result of this, salt ions diffused from the stagnant micro pores into the mass flow stream through the macro pores. Equation 2.4 describes the process:

$$q_s = q_c + q_d \qquad (2.4)$$

where q_s is the total solute flux, q_c the convective solute flux, and q_d the diffusion 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).

2.6.1.1 Convection

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

$$q_c = Jw \,.\, Cl \qquad (2.5)$$

where Jw is the water flux and Cl the solute concentration. Equation 2.5 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. This extra motion that must be considered is often called hydrodynamic dispersion. It results from the interaction between large and small pores through the local velocities that connect them. The solute convection can then be described by Equation 2.6.

$$\text{Total convection} = Jw \cdot Cl + Jlh \qquad (2.6)$$

where Jlh 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 off solute movement. During unsaturated conditions, hydrodynamic flow ceases and diffusion becomes the dominant mechanism in solute movement (Herald, 1999).

2.6.1.2 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 can be calculated from Fick's first law:

$$F = - D . dC / dx \qquad (2.7)$$

Equation 2.7 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 the diffusion coefficient relating F to dC / dx, which can be measured experimentally.

Rewriting Equation 2.7 for unsaturated conditions gives Equation 2.8:

$$F = -Ds . \theta . dC / d x \qquad (2.8)$$

where θ is the volumetric soil water content and -Ds the diffusion coefficient in soil 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, should be added to Equation 2.8.

$$Ds = -D.\ \theta.\ f.\ dC / dx \qquad (2.9)$$

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).

2.6.2 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.

2.6.2.1 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 (Sa/Sb) to the depth of drainage water per unit depth of soil (Dw/Ds). These curves illustrate the effect of soil type and the quantity of water required to achieve the same degree of leaching.

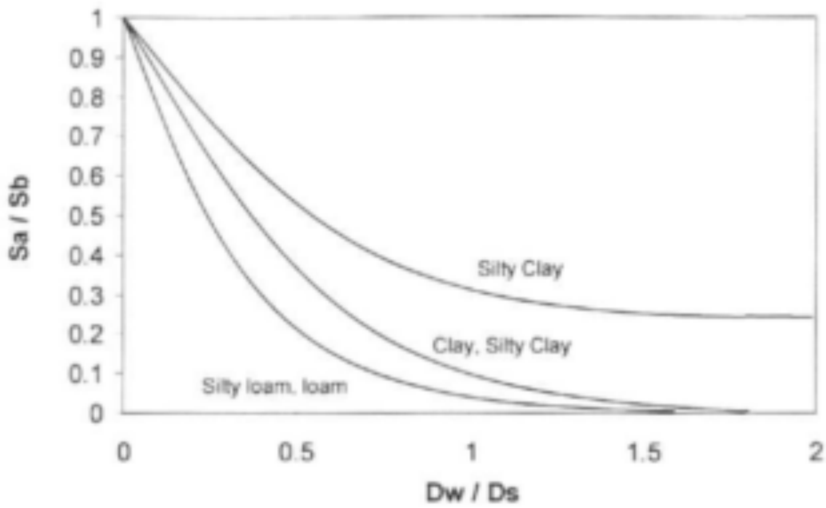

Figure 2.2 The ratio of the required salinity (Sa, mg L^{-1}) and initial salinity (Sb, mg L^{-1}) and its relationship with the ratio between the amount of drainage (Dw, mm) and soil depth (Ds, mm) (Dieleman, 1963).

2.6.2.2 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 Predicting salt accumulation and removal

2.7.1 General

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

The main focal points of this study, as illustrated in the preceding discussion are the processes in the unsaturated zone. Consequently, modelling will also be aimed at salt accumulation and removal in the unsaturated root zone. Here simpler single-process oriented models, i.e. models for infiltration, root water uptake, leaching or solute transport can be very useful in modelling soil salinity.

A number of hydrosalinity models have been developed to examine and manage soil water and solute movement. However, little general use has been made of these models beyond their initial development and testing, due to the intensive data requirements of these more physically based models (Herald, 1999). These so-called research models are generally not suitable for management purposes due to their intensive data requirements. The strength of these models is that they comprehensively integrate the knowledge of the processes controlling water and solute movement. Management models are less intensive and quantitative in their ability to predict solute and water movement under field conditions.

Developers of hydrosalinity models have adopted either one of two common approaches, namely the capacity approach and the thermodynamic approach. The capacity approach is where a soil layer retains water to a defined upper limit before draining to a deeper layer in the soil profile. Information on saturated hydraulic conductivity and hydraulic gradients is usually not required. This approach assumes steady state soil salinity conditions.

In the thermodynamic approach, water and solute transport are explained in terms of differences in potential chemical energy within the soil. These models assume transient state conditions and the Richards equation is generally used to describe soil water movement. Although limited to conditions of steady-state water flow in homogeneous soils, the analytic solutions of the classical convective dispersive equation have been widely used in solute modelling. The use of this equation to represent solute transport in models is subjected to large spatial differences in the relationship between water flux, water content and the apparent diffusion coefficient (Herald, 1999).

Ideally, a well-designed salinity model should, apart from water and solute subroutines, also include a chemical interaction and a crop growth subroutine. The chemical composition of soil water depends on reactions such as dissolution, precipitation, adsorption and exchange. It will then be further modified by the chemical composition of the irrigation water and the extent to which evapotranspiration concentrates it. A common approach in modelling ion exchange is to apply the mass action principle to a specific ion (Du Preez *et al.*, 2000).

2.7.2 *Salt balance models*

According to Ayers & Westcott (1985) Equation 2.10 is strictly speaking not a salt balance. However, it is included because of its simplistic nature. The equation predicts the soil salinity (EC_e, mS m^{-1}) expected after several years of irrigation with water of salinity (EC_i, mS m^{-1}):

$$EC_e \text{ (mS m}^{-1}\text{)} = EC_i \text{ (mS m}^{-1}\text{)} \,.\, CF \qquad (2.10)$$

where CF is the concentration factor that can be found in Table 2.4.

Table 2.4 Concentration factors for predicting soil salinity from irrigation water salinity and the leaching fraction (Ayers & Westcott, 1985)

Leaching fraction (LF)	**Applied water needed (% of ET)**	**Concentration factor (CF)**
0.05	105.3	3.2
0.10	111.1	2.1
0.15	117.6	1.6
0.20	125.0	1.3
0.25	133.3	1.2
0.30	142.9	1.0
0.40	166.7	0.9
0.50	200.0	0.8
0.60	250.0	0.7
0.70	333.3	0.6
0.80	500.0	0.6

Empirical models like the general salt balance of Aragües (1996) and the specific salt balance of Szabolcs (1986) are mathematical functions that were fitted to experimental field observations. These models may be beneficial in the short term but extrapolation of results is in many cases unreliable because the dynamic physical processes are excluded. Du Preez *et al.* (2000) used these models to predict long term salt accumulation for sites studied along the lower Vaal River. The Aragües model indicated that 78% to 87% of salts added as a result of farming practices leached out of the root zone. On the basis of the Szabolcs model it was concluded that irrigation spanning another 50 years would increase the salt content of soils at two-thirds of the sites.

Estimations based on the SWB model (Annandale *et al.*, 1998) confirmed these results, depending on soil type and irrigation practices. The model was originally developed for irrigation scheduling, but in addition to the soil water balance, the salt balance can also be simulated on the basis of this model.

2.7.3 Capillary rise models

Salt accumulation in irrigated soils is the consequence of saline irrigation water and water tables at shallow depths. Research conducted by Ehlers *et al.* (2003) was tested according to the SWB (Soil Water Balance) and SWAMP (Soil Water Management Program) models to predict the contribution of root accessible water tables towards crop water requirements. The upward flow rate and height, which regulates the supply rate from a water table, is controlled by the hydraulic properties of the soil layers above the water table.

The finite difference water redistribution approach was used in SWB and the upward cascading approach in SWAMP. Both models showed a positive correlation between measured and simulated results. To get accurate simulations the soil hydraulic properties required as inputs need to be accurately measured for a specific site because the water fluxes used to simulate water redistribution are sensitive to soil hydraulic properties. Both these models can be used to predict the upward flow of water from water tables at different depths but they do not distinguish between saline and non-saline water tables.

Another model is the transient state analytical model (TSAM) that was modified by Jorenush & Sepaskhah (2003). The modification involves the inclusion of variable root depths, non-uniform water uptake patterns and a more complete water balance equation. This model accurately predicted the capillary rise and salinity of different soil layers for irrigated conditions at various water table depths and salinity levels.

2.7.4 Models for salt leaching

Moolman (1993) conducted a review on water and solute transport models (e.g. Burns, Addiscott, TETrans, Rose, Shaffer, Jury and Wagenet-Hutson) simulating leaching processes in the unsaturated zone. He concluded that the more mechanistic models are superior to the simpler non-mechanistic, capacity type models. The alleged superiority might not be as conclusive when the models are used to predict responses in large irrigated areas. All reported comparisons between models in this review were conducted on small plots, where the influence of spatial variability of rate parameters on the outcome of the study, is expected to be less than would be the case in larger areas. None of the models reviewed can effectively describe the movement of chemicals under conditions of macro-pore flow and when models are applied to larger areas other factors might be of greater importance than the hydraulic variables of the field soils. Hutson *et al.* (1988) demonstrated, according to Moolman (1993), that it was not the hydraulic properties that determined the distribution of the applied chemicals but rather the sorption processes and nett water fluxes which are a function of surface boundary conditions.

Herald (1999) gave a summary of hydrosalinity models, tested with field data representative of the lower Coerney River irrigation area. Of these, three were management models which varied in complexity from the very simple Leaching Requirement model (LR), to the SODICS and the more complex PEAK leaching models. The research model, LEACHC, is considerably more detailed and physically based than the above-mentioned management models. All the tested models gave average comparisons between measured and simulated results. It was concluded by Herald (1999) that the results were unsatisfactory because they excluded macro-pore flow.

Water moving through structured clay topsoils flows through the macro-pores, and very little moves through the matrix of the clay in the aggregates. An empirical model was developed by Armstrong *et al.* (1998) to predict leaching, using the cumulative depth of drainage water, the size of aggregates, the storm duration and the storm frequency. This model showed a positive correlation between the predicted and measured salt leaching in aggregated soils under laboratory conditions. In the field, the formation of a crust, due to water drop impact, complicated the matter. When a protective mulch was applied the prediction was once again validated.

A more complicated two-domain model (MACRO) of water and solute transport in macro-porous soils was used to predict chloride leaching in drained and irrigated marsh soils in Marismas, Spain. MACRO is a mechanistic solute transport model, which incorporates a physically based preferential flow model in which total soil porosity is divided into two flow domains, namely macro-pores and micro-pores. It was found that the model performed poorly when bypass flow was not taken into account (Andreu *et al.*, 1994).

2.7.5 Irrigation management models

Irrigation management is a very important component of salinity control. WATSKED is a versatile, simple, user-friendly model for irrigation scheduling and can be used for sprinkle, drip or flood irrigation. Although the model is designed for irrigation with saline water it is yet to be tested for this application. WATSKED determines leaching fractions needed to bring soil layers to threshold salinity levels when saline water is used for irrigation. It also predicts the timing of leaching and the minimum amount of irrigation water required to leach salts from soil layers to a desired level. The model was tested by Theiveyanathan *et al.* (2004) and performed well under freshwater sprinkle irrigation and freshwater flood irrigation of *Eucalyptus* plantations

The model SWAP, developed by the Water Resources Group of Wageningen University, is another model applicable to irrigation management. Among the model options are irrigation scheduling, drainage designing, assessing percolation, waterlogging and long-term salinisation and transfer of substances such as solutes, nitrogen and pesticides. A simulation study by Singh (2004) utilizing this model revealed that it was possible to use saline water of up to 1400 mS m^{-1} alternatively with better quality water for a cotton-wheat crop rotation. In all situations pre-sown irrigation must be conducted with water of salinity between 30 and 40 mS m^{-1}.

In recent years models developed for salinity control take into account different irrigation systems and scheduling practices. It is obvious that modelling for the purpose of salinity control will be influenced by all the processes affecting secondary salinisation.

2.7.6 Generic principles

WAVES is a model that predicts the dynamic interactions within the soil-vegetation-atmosphere system, on a daily time step. Results from WAVES simulations of plant growth, evapotranspiration, water table uptake, salt accumulation, and the impacts on lucerne growth were compared with measurements made in lysimeters at Griffith, New South Wales, Australia by Zhang *et al.* (1999). With minimal calibration WAVES was able to reproduce both daily and seasonal variations within all the above parameters. There was a decline of 36% in transpiration, 42% in leaf area growth, and 67% in upward flux from the water table after the salinity of the water table increased from 10 to 1600 mS m^{-1}.

SALTMED is another model that contains established water and solute transport, evapotranspiration and crop water uptake equations. The model can be used for a variety of irrigation systems, soil types, soil stratifications, crop and trees, water management strategies, leaching requirements, and water qualities. Data from the literature was used by Ragab (2002) to run the model for five applications. The model was able to illustrate the effect of irrigation systems, soil types and irrigation water salinity levels on soil water and salinity distribution, leaching requirements, and crop yields. Unfortunately, the model did not perform as well as one would expect. It was concluded that the model benefiting from the Windows™ environment, was friendly and easy to use. However, it is a physically based model using the inputs for well known water and solute transport, evapotranspiration and water uptake equations.

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

2.8 Conclusions

A major factor contributing towards land degradation is soil and water salinisation. In an assessment of South Africa's water quality situation it is evident that the country's 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.

The effects of salinity on agricultural crops are manifested in 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. When Na^+ on the exchange complex becomes excessive, permeability and tilth are deleteriously affected if the concentration of salts in the infiltrating water is below some threshold value.

Shallow water tables typically develop in irrigated lands usually in down-slope positions, when the portion of applied water exceeds the 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 and 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. This approach will minimize off-site pollution.

CHAPTER 3

CROP RESPONSE TO VARIOUS WATER SALINITY LEVELS UNDER LABORATORY AND GLASSHOUSE CONDITIONS

3.1 Introduction

The fitness of water for various uses in the protection of aquatic ecosystems, is described by its physical, chemical and aesthetic properties and is controlled by constituents that are either dissolved or suspended in the water (Department of Water Affairs and Forestry, 1996). The composition of dissolved or suspended constituents determines the quality of irrigation water, and is therefore an important consideration when evaluating the salinity conditions of any irrigated area (Richards, 1954). According to Russell (1973) the yield of a wide variety of crops is reduced by saline conditions and the tolerance of plants to overcome this abiotic stress is quantified in terms of survival rate or the plants' growth abilities in these conditions.

Water losses occur through evaporation and transpiration from the soil which cause a rise in the salt concentration of the soil solution in the root zone of 2 to 5 times higher than that of the irrigation water (Shainberg & Oster, 1978; Chabbra, 1996). The build up of salts in the water causes a drop in the osmotic potential of the water, but could also cause a build up of potentially toxic ions (Abrol *et al*, 1988; Läuchli & Epstein, 1990). When growth inhibition or depression is caused by a decrease in the osmotic potential it is termed an osmotic effect, but when caused by specific ions that lead to nutrient imbalances or toxicity it is termed a specific ion effect. Saline conditions could also adversely influence plant growth as a result of the high pH levels, the poor physical condition of the soil and the inhibition of nutrient uptake (FSSA, 2003).

The adverse effects of salt-affected soils on plant growth are manifested in the form of decreased germination, a decrease in leaf expansion and ultimately leaf area, stomatal conductance, biomass accumulation and eventually seed yield (Katerji *et al.*, 1996, Abid *et al.*, 2001; Cramer *et al.*, 2001; Saqib *et al.*, 2004a).

Excessive water salinity is a constant threat to the sustainability of irrigated crop production (Ramoliya & Pandey, 2001). It is imperative to know the salt tolerance of different crops when saline irrigation water is to be used, or where salt build up occurs in soils. According to the FSSA (2003) crops have been grouped into four categories of sensitivity to saline conditions, namely sensitive, moderately tolerant and tolerant. The criteria used to establish the threshold of tolerance for the different crops were set at a yield loss of 10%.

The objectives of this chapter are to use laboratory and glasshouse experiments to: i) quantify the effect of irrigation water salinity on the establishment, growth and yield of crops; ii) compare the response of selected crops to different irrigation water salinities; and iii) determine at what level of deteriorating irrigation and soil water salinity the crops show an inhibition.

3.2 Materials and methods

The irrigation water for the field trials was also used for the laboratory and glasshouse trials which are described below. A proper description of the preparation and composition of this irrigation water for the different treatments is given in Section 4.2.3 and therefore not repeated here.

3.2.1 Germination experiments

The germination experiments consisted of five different saline water qualities, viz. 15 - control, 75, 150, 225 and 300 mS m^{-1} for beans and peas, and 15 - control, 150, 300, 450 and 600 mS m^{-1} for maize and wheat. Anchor-germination paper was used where 15 seeds were evenly distributed on a pencil line 100 mm from the top of the germination paper. Another paper was placed on top and wetted with 50 ml of the specific treatment water. The germination papers were rolled and each inserted into a 1 L Erlenmeyer flask. Five replicates were used. To prevent the dehydration of the germination paper the top of each flask was covered with a polyethylene bag followed by incubation at a temperature of 25°C. Three days later the first observations were made followed by daily inspections for a period of five days. During this period, germination percentage (%), coleoptile/hypocotile length (mm) and root length (mm) were measured.

3.2.2 Pot experiments

Asbestos pots (0.34 x 0.34 x 0.35 m) with a volume of 40.5 L were used. A gravel layer of approximately 30 mm was placed at the bottom of each pot to facilitate drainage during leaching of the pots prior to planting. A cloth was placed on the gravel layer, separating the soil and gravel, to prevent the soil from penetrating the gravel and blocking the drainage tube. Each pot was filled with 70 kg of a red sandy loam Bainsvlei topsoil (particle size distribution: coarse sand = 0.3%; medium sand = 6.4%; fine sand = 83.3%; silt = 2.0% and clay = 8.0%) after the soil had been dried and sieved through a 2 mm sieve. The pots were leached with 25 L of the specified water salinity solutions before planting. Thereafter for the rest of the growing season the amount of water applied to keep each pot well watered was recorded. Five salt concentrations (15 - control, 75, 150, 225 and 300 mS m^{-1}) for beans and peas (one season) and five concentrations (15 - control, 150, 300, 450 and 600 mS m^{-1}) for maize and wheat (two seasons) were used. For the second season, in the wheat trial, an additional 1200 mS m^{-1} treatment was added because of a lack of response to the treatments during the first season. Three days after saturating the pots, fertilizers were uniformly applied on the surface of the soil and incorporated to a depth of 100 mm. Some relevant agronomic information is summarised in Table 3.1.

Table 3.1 Agronomic information regarding cultivar, planting date, planting depth, row width, seeding rate, fertilization, irrigation and sampling stage of the different experimental crops.

Parameter	Beans	Peas	Maize	Wheat
Cultivar	Teebus	Solara	PAN 6335	SST 806
Planting date	4 February 2005	22 July 2004	6 February 2003 (yr 1) 28 November 2004 (yr 2)	17 July 2003 (yr 1) 16 June 2004 (yr 2)
Planting depth	30 mm	30 mm	30 mm	30 mm
Row width	100 mm	-	-	-
Seeding rate	3 plants pot^{-1}	3 plants pot^{-1}	3 plants pot^{-1}	1.2 g pot^{-1}
Fertilization:				
Nitrogen Pre-plant	0.173 g pot^{-1} (15 kg ha^{-1})	0.312 g pot^{-1} (27 kg ha^{-1})	2.509 g pot^{-1} (217 kg ha^{-1})	0.948 g pot^{-1} (82 kg ha^{-1})
Top dressing	0.798 g pot^{-1} (69 kg ha^{-1})	0.231 g pot^{-1} (20 kg ha^{-1})	-	1.191 g pot^{-1} (103 kg ha^{-1})
Total	0.971 g pot^{-1} (84 kg ha^{-1})	0.543 g pot^{-1} (47 kg ha^{-1})	2.509 g pot^{-1} (217 kg ha^{-1})	2.139 g pot^{-1} (185 kg ha^{-1})
Phosphorous	0.260 g pot^{-1} (22.5 kg ha^{-1})	0.462 g pot^{-1} (40 kg ha^{-1})	0.566 g pot^{-1} (49 kg ha^{-1})	0.474 g pot^{-1} (41 kg ha^{-1})
Potassium	0.347 g pot^{-1} (30 kg ha^{-1})	0.613 g pot^{-1} (53 kg ha^{-1})	-	0.231 g pot^{-1} (20 kg ha^{-1})
Irrigation	106 L pot^{-1}	97 L pot^{-1}	54 L pot^{-1} (yr 1) 54 L pot^{-1} (yr 2)	140 L pot^{-1} (yr 1) 145 L pot^{-1} (yr 2)
Sampling stages 1	5 WAE*	5 WAE	2 WAE	Tillering
2	Flowering	Flowering	4 WAE	Flag leaf
3	Maturity	Maturity	6 WAE	Maturity

*Weeks after emergence

All experiments were laid out in a complete randomised design with a factorial combination consisting of two main factors, viz. five EC_i levels [15, 75, 150, 225 and 300 mS m^{-1} (beans and peas) or 15, 150, 300, 450 and 600 mS m^{-1} (maize and wheat)] and three growth stages [beans and peas = 5 WAE (weeks after emergence), flowering and maturity; maize = 2, 4 and 6 WAE; and wheat = tillering, flag leaf and maturity] replicated thrice. These experiments were conducted over two seasons but the data pertaining to beans and peas was only available for one season each as a result of *Sclerotinia sclerotiorum* on beans and either a soil born disease or fungal infection of the pea seed.

Various plant parameters were measured as indicated in Table 3.2, but only leaf area, root mass, above ground biomass and seed yield were selected and discussed in this chapter. For more detail on the results see the dissertation of Dikgwatlhe (2006).

Leaf area was measured with the LICOR 3000 leaf area meter and expressed per square centimeter (cm^2). For this measurement the compound leaves, without the petiole, of beans and peas as well as the leaf blade of wheat and maize without the leaf sheath were sampled. Roots were washed from the pots, dried at 60°C for 72 hours, weighed and expressed in gram (g). The seed yield was obtained through weighing the harvested seeds after these had been dried to a constant moisture content and expressed in grams (g). All parameters were expressed per plant for beans, peas and maize and per m^2 for wheat.

Experimental data was analysed with the NCSS (Number Cruncher Statistical System) statistical package (Hintze, 1998). The least significant difference (LSD) was calculated at $P \leq 0.05$ to compare the means using the Tukey - Kramer multiple comparison tests (Gomez & Gomez, 1984). Though the experiment was a complete randomised design with a factorial combination the different sampling stages were analysed separately.

3.3 Results and discussion

3.3.1 Germination experiments

Quantitative and qualitative plant parameters were used to describe the effect of deteriorating water salinity on germination, *viz.* germination percentage (quantitatively) and coleoptile/hypocotile length and root length (qualitatively) as shown in Table 3.3.

Table 3.2 Parameters used during plant growth and yield evaluation.

Growth stage	Beans	Peas	Maize	Wheat
1	Leaf area (cm^2 $plant^{-1}$) Root length (mm mm^{-2}) Root mass (g $plant^{-1}$) Biomass (g $plant^{-1}$)	Leaf area (cm^2 $plant^{-1}$) Root length (mm mm^{-2}) Root mass (g $plant^{-1}$) Biomass (g $plant^{-1}$)	Leaf count Stem diameter (mm) Plant height (mm) Leaf area (cm^2 $plant^{-1}$) Root length (mm mm^{-2}) Root mass (g $plant^{-1}$) Biomass (g $plant^{-1}$)	Plant height (mm) Leaf area (cm^2 m^{-2}) Number of tillers Root length (mm mm^{-2}) Root mass (g m^{-2}) Biomass (g m^{-2})
2	Leaf area (cm^2 $plant^{-1}$) Root length (mm mm^{-2}) Root mass (g $plant^{-1}$) Biomass (g $plant^{-1}$)	Leaf area (cm^2 $plant^{-1}$) Root length (mm mm^{-2}) Root mass (g $plant^{-1}$) Biomass (g $plant^{-1}$)	Leaf count Stem diameter (mm) Plant height (mm) Leaf area (cm^2 $plant^{-1}$) Root length (mm mm^{-2}) Root mass (g $plant^{-1}$) Biomass (g $plant^{-1}$)	Plant height (mm) Leaf area (cm^2 m^{-2}) Number of tillers Root length (mm mm^{-2}) Root mass (g m^{-2}) Biomass (g m^{-2})
3	Root length (mm mm^{-2}) Root mass (g $plant^{-1}$) Biomass (g $plant^{-1}$) Number of pods $plant^{-1}$ Seed yield (g $plant^{-1}$)	Root length (mm mm^{-2}) Root mass (g $plant^{-1}$) Biomass (g $plant^{-1}$) Number of pods $plant^{-1}$ Seed yield (g $plant^{-1}$)	Leaf count Stem diameter (mm) Plant height (mm) Leaf area (cm^2 $plant^{-1}$) Root length (mm mm^{-2}) Root mass (g $plant^{-1}$) Biomass (g $plant^{-1}$)	Plant height (mm) Number of tillers Root length (mm mm^{-2}) Root mass (g m^{-2}) Biomass (g m^{-2}) Number of ears m^{-2} Seed yield (g m^{-2}) Seed mass ear^{-1} (g) 100 seed weight (g)

Table 3.3 The effect of irrigation water salinity on the average germination percentage, coleoptile or hypocotile length and root length of the selected crops

Plant parameter	Treatment (EC_i mS m^{-1})					LSD $_{(0.05)}$
	15*	75	150	225	300	
Beans:						
Germination (%)	100a	100a	100a	100a	93a	ns
Hypocotile length (mm)	139a	127a	121b	110b	104b	16.85
Root length (mm)	177a	157a	150b	127b	126b	26.19
Peas:						
Germination (%)	100a	100a	100a	100a	92b	4.18
Hypocotile length (mm)	130a	126a	121a	112a	109a	ns
Root length (mm)	158a	158a	155a	138a	125a	ns
	15	150	300	450	600	
Maize:						
Germination (%)	98a	98a	97a	97a	97a	ns
Coleoptile length (mm)	149a	135a	131b	117b	110bc	16.80
Root length (mm)	182a	170a	160a	137b	133b	29.69
Wheat:						
Germination (%)	100a	99a	97a	99a	100a	ns
Coleoptile length (mm)	150a	145a	147a	128a	136a	ns
Root length (mm)	112a	109a	108a	103a	98a	ns

*Control

3.3.1.1 Quantitative germination data

Comparing the germination percentage of the different crops showed that, with the exception of peas, no significant differences were obtained with the selected range of EC_i levels. At a level of 300 mS m^{-1} the germination percentage of peas was significantly reduced to 92%. No significant reduction in the germination percentage of beans was obtained although the germination percentage was reduced to 93% at 300 mS m^{-1}. These findings are also supported by those of Steppuhn *et al.* (2001) who found that increased soil salinity reduced the emergence of peas and beans. The germination percentage of maize and wheat proved not to be affected by the deteriorating irrigation water salinity. It is important to mention that germination percentage is only a quantitative measurement and does not reflect the quality of the germinated seedlings.

3.3.1.2 Qualitative germination data

The coleoptile/hypocotile length as well as the root length of the germinating seedlings were measured and evaluated to establish whether the quality of the seedlings was markedly affected by the selected EC_i treatment levels. Interesting results were obtained regarding this aspect as both coleoptile/hypocotile and root length showed a continuous decrease in length with an increase in the EC_i levels of the wetting solution for all crops (Table 3.3). For example, the germination of beans was apparently not affected by the salinity of the irrigation water, but both qualitative parameters showed a significant reduction in growth at levels of 150 mS m^{-1} and higher. This is a clear indication that the quality or vigour of the seedlings was reduced by the deteriorating water salinity, producing weaker seedlings. The reduction in hypocotile and root length also corresponds with the findings of Steppuhn *et al.* (2001) and Bayuelo-Jimenez *et al.* (2002). The performance of peas suggests that the roots (21% reduction in length) are more sensitive to deteriorating water salinity than the hypocotiles (16% reduction in length), though no significant differences were obtained. The quality of maize seedlings on the other hand was slightly affected by reductions in the coleoptile and root length. The coleoptile length was reduced by 12% at 300 mS m^{-1} and the root length by 25% at 450 mS m^{-1} in comparison to the control. Wheat seedlings showed to be the most tolerant of the crops investigated, as both the quality parameters did not significantly affect germination. According to Maas and Hoffman (1977b) and Maas (1990) wheat is classified as moderately tolerant to saline conditions.

Although the germination percentage of beans and maize was not significantly affected, the quality of the seedlings was affected with a reduction in the coleoptile/hypocotile and root lengths. This could lead to poorly established seedlings that may eventually die off as a result of primary stress (salt) or secondary stress (nutrient uptake, water uptake or susceptibility to disease).

Germination and seedling emergence are two indispensable parameters for the establishment of crops and are of utmost importance in crops that do not have a favourable compensation ability such as wheat compared to the other selected crops. Therefore, a reduction of 10% in the stand or establishment of seedlings could lead to significant economic losses.

3.3.2 Pot experiments

3.3.2.1 Effect of irrigation water salinity on selected plant parameters

The statistical results of all above- and below-ground plant parameters are presented in Table 3.4. Results for beans and peas were obtained during one season of growth, but for maize and wheat the observations were obtained over two seasons. Apparently it seems that conditions were slightly better during the second growing season compared to the first growing season of wheat. This could mainly be ascribed to the fact that the planting date of the second season was one month earlier than for the first season, therefore the second season's growth period was longer. However, when expressing the salinity response of wheat to its maximum response within a particular season, the results showed no significant difference in its response between seasons. Therefore, the data of the two seasons was combined for analysis. The same applied to maize though no apparent difference was observed for all parameters between the different seasons.

As shown in Figures 3.1 to 3.4, the discussion on the reaction of growth and yield parameters will be in terms of relative values, which are the treatment values divided by the control value. In all four figures the level of first significant difference compared to the control, is indicated by a vertical line. The leaf area and root mass results for the second growth stage and the above-ground biomass and seed yield for the third growth stage for beans, peas and wheat are presented. Maize was grown for only six weeks and therefore all parameters used are for the six weeks after emergence stage.

3.3.2.1.1 Relative leaf area

According to the regression functions fitted to the relative leaf area at the EC_i treatments, the relative leaf area of all crops declined as a result of an increase in water salinity (Figure 3.1). The mean maxima were 141 508, 4 587, 1 501 and 396 cm² for wheat, maize, beans and peas, respectively (Table 3.5). Significant reduction in leaf area was obtained from EC_i levels of 225 mS m^{-1} for both beans and peas and of 300 mS m^{-1} for both maize and wheat compared to the control treatment.

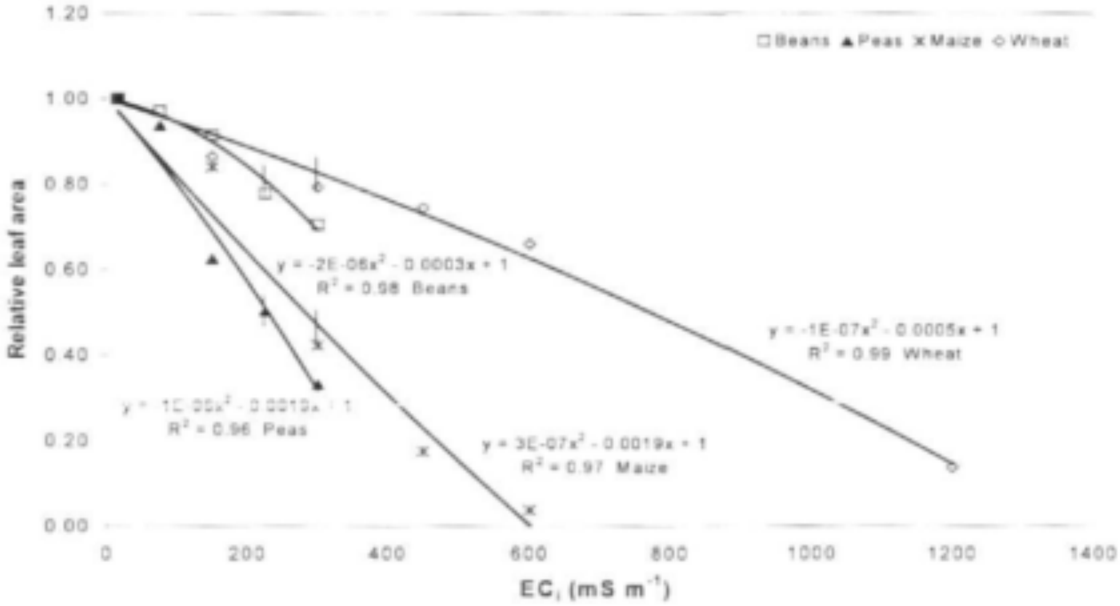

Figure 3.1 Response of relative leaf area of the selected crops to different EC_i levels. The vertical line (I) refers to the first significant difference ($P \leq 0.05$) compared to the control.

Table 3.4 Summary of the threshold level at which salinity significantly reduced the different plant parameters of the selected crops

Growth stage	Beans	EC_i level ($mS\ m^{-1}$)	Peas	EC_i level ($mS\ m^{-1}$)	Maize	EC_i level ($mS\ m^{-1}$)	Wheat	EC_i level ($mS\ m^{-1}$)
1	Leaf area	* (150)	Leaf area	* (225)	Leaf count	* (300)	Plant height	* (150)
	Root length	* (150)	Root length	* (300)	Stem diameter	* (300)	Leaf area	* (300)
	Root mass	* (225)	Root mass	* (300)	Plant height	* (300)	Number of tillers	* (300)
	Biomass	* (300)	Biomass	* (225)	Leaf area	* (300)	Root length	* (300)
					Root length	* (300)	Root mass	* (300)
					Root mass	* (450)	Biomass	* (300)
					Biomass	* (300)		
2	Leaf area	* (225)	Leaf area	* (225)	Leaf count	* (300)	Plant height	* (150)
	Root length	* (150)	Root length	* (150)	Stem diameter	* (300)	Leaf area	* (300)
	Root mass	* (225)	Root mass	* (225)	Plant height	* (150)	Number of tillers	* (300)
	Biomass	* (150)	Biomass	ns	Leaf area	* (300)	Root length	* (300)
					Root length	* (300)	Root mass	* (300)
					Root mass	* (300)	Biomass	* (300)
					Biomass	* (150)		
3	Root length	* (300)	Root length	* (150)	Leaf count	* (450)	Plant height	* (300)
	Root mass	* (150)	Root mass	* (150)	Stem diameter	* (450)	Number of tillers	* (450)
	Biomass	* (300)	Biomass	* (225)	Plant height	* (300)	Root length	* (300)
	Pods $plant^{-1}$	* (300)	Pods $plant^{-1}$	* (225)	Leaf area	* (300)	Root mass	* (150)
	Seed yield	* (300)	Seed yield	* (75)	Root length	* (150)	Biomass	* (300)
					Root mass	* (150)	Number of ears	* (450)
					Biomass	* (150)	Seed yield	* (300)
							Seed mass ear^{-1}	* (600)
							100 seed weight	* (450)

*Significantly different from the control at $P \leq 0.05$.

Table 3.5 Relative leaf area (%) of selected crops at different EC_i levels

Crop	Average* (cm²)	EC_i level (mS m^{-1})							
		15	75	150	225	300	450	600	1200
Wheat	141 508	100	96	92	88	84	75	66	26
Maize	4 587	100	86	72	59	46	21	0	-
Beans	1 501	100	97	91	83	73	-	-	-
Peas	396	100	85	69	52	44	-	-	-

*Average maximum leaf area for the control (15 mS m^{-1})

The relative leaf area at the different EC_i levels has been summarised in Table 3.5. Comparing the reduction in relative leaf area as a result of increasing water salinity indicated that peas are the most sensitive crop with regard to relative leaf area followed by maize, beans and wheat. This tendency was valid for all EC_i levels. At 300 mS m^{-1} the leaf area of peas was reduced to 33% compared to reductions of 46, 73 and 84% for maize, beans and wheat respectively. One has to bear in mind that the data collected for maize was not for the full growth cycle but only for the very early vegetative stage of growth and development at 6 weeks. It is well known that salinity and leaf area are usually inversely related (Maas & Hoffman, 1977b) and the results obtained for these experiments confirmed this. Decline in leaf area as a result of increasing salinity were also reported by Katerji *et al.* (1996) and Abid *et al.* (2001) on maize; Passioura & Munns (2000) on wheat and Steppuhn *et al.* (2001) on canola, field pea, dry bean and durum wheat.

3.3.2.1.2 Relative root mass

Root mass, expressed relative to the control value, declined with increasing water salinity as illustrated in Figure 3.2 for the selected crops. The regression lines in Figure 3.2 represent the relatives values for the second growth stage of beans, peas and wheat and those of maize at 6 WAE. The control values used to calculate the relative values were 151.8 g m^{-2} for wheat and 17.5, 1.2 and 0.9 g plant^{-1} for maize, beans and peas, respectively (Table 3.6). Significant differences were obtained for EC_i levels of higher than 225 mS m^{-1} for both beans and peas and from 150 mS m^{-1} for maize and 300 mS m^{-1} for wheat, compared to the control treatment.

The relative root mass percentages, compared to the control, at the different EC_i levels have been summarised in Table 3.6. A comparison of the relative root mass indicated that peas are the most sensitive crop with regard to reduction in root mass followed by maize, beans and wheat. This tendency was valid for all EC_i levels. The root mass of peas was reduced by 73% at 300 mS m^{-1}, while that of maize, beans and wheat was reduced by 57, 55 and 40% respectively. The results of these experiments support the findings of Cordovilla *et al.* (1999) who also reported a reduction in root dry weight as a result of deteriorating water quality due to salinity.

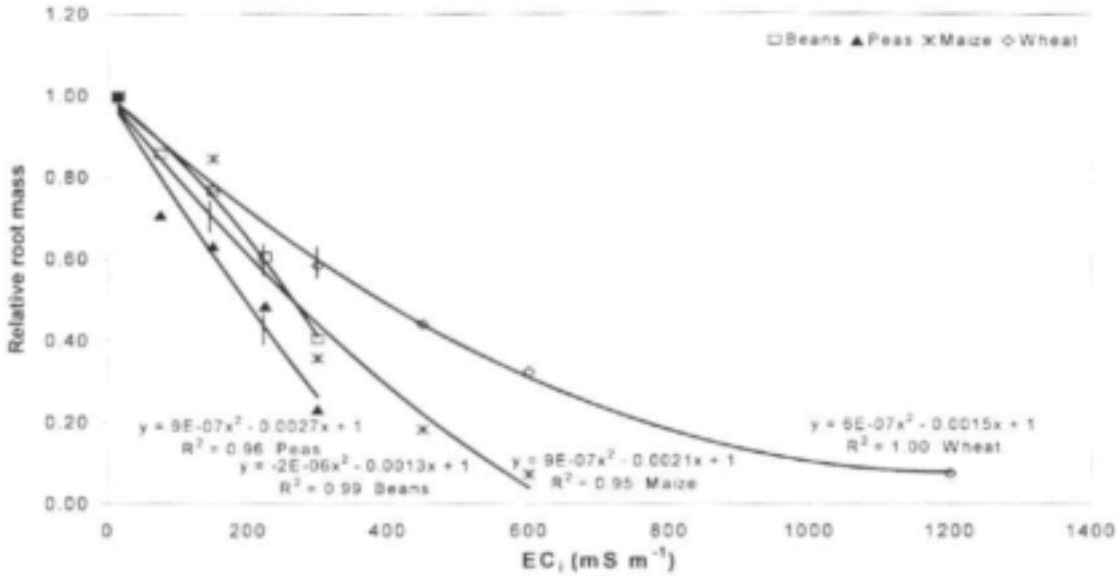

Figure 3.2 Response of relative root mass of the selected crops to different EC_i levels. The vertical line (I) refers to the first significant difference ($P \leq 0.05$) compared to the control.

Munns & Rawson (1999) and Saqib *et al.* (2004b) also found a reduction in root mass with increasing salinity at different growth stages. Excess salinity in the root zone also adversely affects already established plants through a reduction of root growth (Rhoades & Loveday, 1990). Accordingly salt stress conditions may induce morphological and structural changes in roots that could lead to a reduction in the rate of root elongation. Saline conditions can promote desiccation of root cells, where the roots die from their tips backwards, and this is escalated in dryer parts of the root medium (Rhoades & Loveday, 1990; Saqib *et al.*, 2004b).

Table 3.6 Relative root mass (%) of selected crops at different EC_i levels

Crop	Average * (g)	EC_i level (mS m^{-1})							
		15	75	150	225	300	450	600	1200
Wheat	151.8	100	89	79	69	60	45	32	6
Maize	17.5	100	85	71	57	45	24	6	-
Beans	1.2	100	89	76	61	43	-	-	-
Peas	0.9	100	80	62	44	27	-	-	-

*Average maximum root mass measured in the control (15 mS m^{-1})

3.3.2.1.3 *Relative above-ground biomass*

A decline in the relative above-ground biomass of all crops was observed as a result of increasing water salinity (Figure 3.3). The relative biomass values in Figure 3.3 were calculated using the maximum biomass obtained over the seasons in the control treatments. These values were 1781.9 g m^{-2} for wheat, and 35.4, 44.8 and 13.4 g $plant^{-1}$ for maize, beans and peas, respectively (Table 3.7). Significant reductions in dry biomass were obtained from EC_i values of 225 mS m^{-1} for peas; 300 mS m^{-1} for beans; 150 mS m^{-1} for maize and 300 mS m^{-1} for wheat, compared to the control treatment.

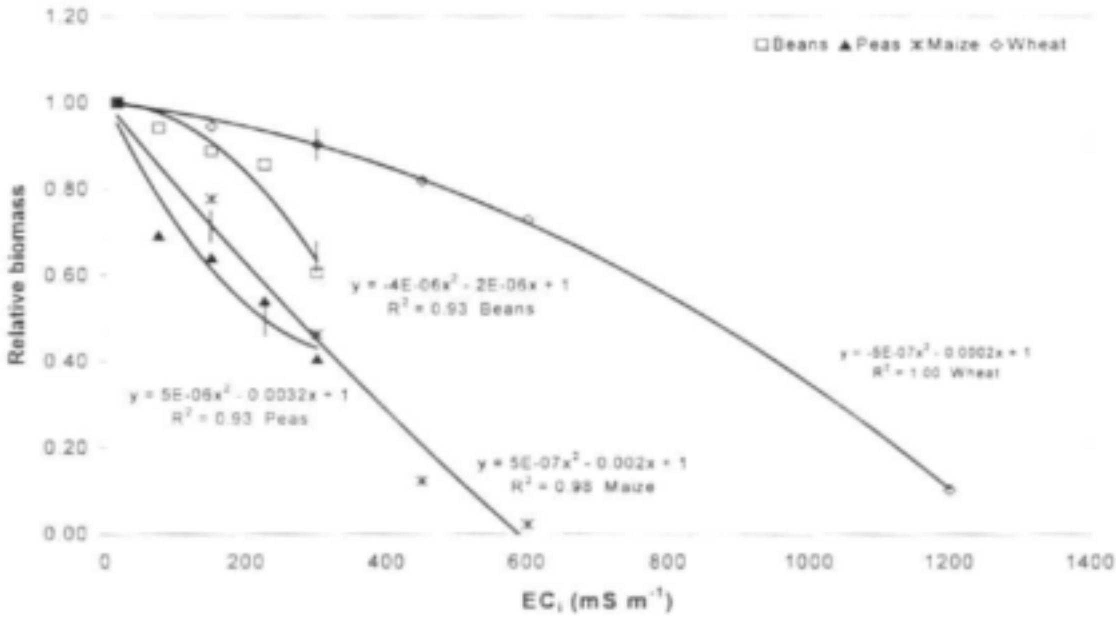

Figure 3.3 Response of relative biomass production of the selected crops to different EC_i levels. The vertical line (I) refers to the first significant difference ($P \leq 0.05$) compared to the control.

Table 3.7 Relative biomass (%) of selected crops at different EC_i levels

Crop	Average *(g)	EC_i level (mS m^{-1})							
		15	75	150	225	300	450	600	1200
Wheat	1781.9	100	98	96	93	89	81	70	4
Maize	35.4	100	85	71	58	44	20	0	-
Beans	44.8	100	98	91	80	64	-	-	-
Peas	13.4	100	79	63	53	49	-	-	-

*Average maximum biomass for the control (15 mS m^{-1})

The relative above-ground biomass at the different EC_i levels, calculated from the data obtained in these experiments, has been summarised in Table 3.7. A comparison of the relative biomass demonstrated that peas were the most sensitive crop in terms of biomass reduction followed by maize, beans and wheat. This tendency was valid for all EC_i levels. Biomass of maize at 300 mS m^{-1} was reduced by 56%, while that of peas, beans and wheat was reduced by 51, 36 and 11% respectively.

The addition of salts that occurs during the growing season, resulting from irrigation, decreases the osmotic potential of the soil solution. According to Chabbra (1996) this decline in the osmotic potential decreases the physiological availability of water because of a smaller difference between the osmotic potential of plant root cells and the sum of the osmotic and matric potential of the soil solution. As a result plants are not able to maintain their turgor, which results in wilting. This could eventually result in the reduction of photosynthesis and eventually a reduction in biomass production. Abid *et al.* (2001) also observed a reduction in biomass production with a decrease in water quality due to salinity. Saqib *et al.* (2004a) also found that the straw weight of wheat was significantly reduced by saline conditions and this is attributed to a reduction in total biomass production. Finally, the findings of Munns (2002a) reveal that the reduction on growth and ultimately biomass production could be ascribed to internal plant injury caused by metabolic disturbances as a result of salinity.

3.3.2.1.4 Relative seed yield

The relative seed yield of all crops except maize which was only grown for 6 weeks, declined with increasing water salinity (Figure 3.4). The actual seed yields of the control treatments, used to express the relative values were 7.6 g $plant^{-1}$, 25.3 g $plant^{-1}$ and 912.2 g m^{-2} for peas, beans and wheat, respectively (Table 3.8). Significant differences were obtained from EC_i levels of 75 mS m^{-1} and 300 mS m^{-1} for beans and wheat, respectively. Using the regression coefficients, the first significant estimated reductions in relative seed yield were 29% for peas at 75 mS m^{-1}, 45% for beans at 300 mS m^{-1}, and 15% for wheat at 300 mS m^{-1} (Figure 3.4).

Crop yield is usually markedly reduced before visual symptoms of salinity damage become apparent (Lantzke & Calder, 2002). Through salinity the formation of viable reproductive organs in annuals are affected with a reduction in the number of florets per ear, the time of flowering and ultimately the yield of cereals (El-Hendawy *et al.*, 2005). A recent study by Saqib *et al.* (2004a) also showed that the wheat yield was reduced as a result of a significant reduction in the number of spikelets per spike, spikes per plant and spike length. In the case of peas and beans salinity impairs germination, inhibits nodulation, inhibits plant development and as a result reduces the final yield (Maas, 1990; Steppuhn *et al.*, 2001). This phenomenon corresponds with results obtained during drought stress (Munns & Rawson, 1999). According to Saqib *et al.* (2004a) growth depression results from a water deficit, ion imbalance and ion toxicity and as a result seed yield is significantly reduced in high saline substrate conditions.

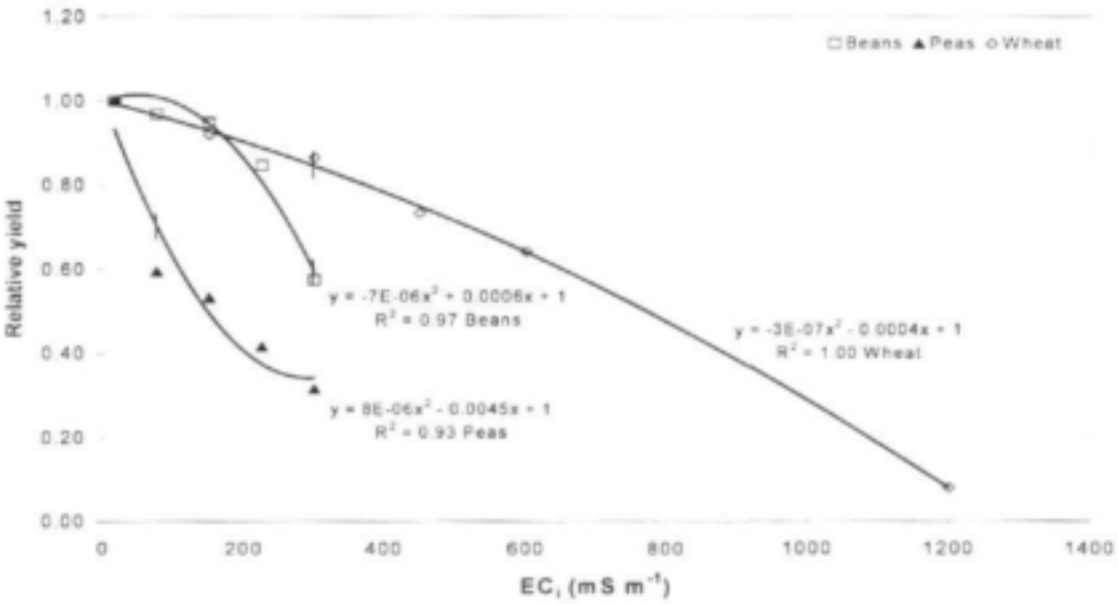

Figure 3.4 Response of relative seed yield of the selected crops to EC_i levels. The vertical line (I) refers to the first significant difference ($P \leq 0.05$) compared to the control.

Table 3.8 Relative yield (%) of selected crops at different EC_i levels

Crop	Average* (g)	EC_i level (mS m^{-1})							
		15	75	150	225	300	450	600	1200
Wheat	912.2	100	97	93	89	85	76	65	9
Beans	25.3	100	100	93	78	55	-	-	-
Peas	7.6	100	71	50	39	37	-	-	-

*Average maximum yield obtained at the control (15 mS m^{-1})

Various soil, water and environmental factors interact to determine the salt tolerance of plants (Maas, 1990), therefore complicating the ability to predict plant responses on an absolute basis. Thus by expressing the data on a relative basis plants can be compared to provide general salt tolerance guidelines (Maas, 1990). With regard to relative yield, it has been established that soil salinity expressed in terms of EC_e does not reduce yield significantly until a threshold has been exceeded. Beyond the threshold the reduction in yield is almost linear (Maas & Hoffman, 1977a,b). This tendency could to some extent be seen in Figure 3.4 for beans and to a lesser degree for wheat. The reason is because all the growth parameters in this section were related to EC_i. Fortunately the EC_e of the soil in the pots was also measured. The effect of EC_e, which relates better to EC_{sw}, determined in the field experiments, will be discussed for relative biomass production in Section 3.3.2.2.

3.3.2.2 Effect of soil water salinity of the pots on growth and water use

Soil samples were taken from the pots after leaching with the irrigation water, at the beginning of each experiment and after harvesting. The electrical conductivity of the saturated paste was determined and the mean of the two values was expressed as EC_e in mS m^{-1}.

According to common practice EC_e can be converted to EC_{sw} by multiplying EC_e with a factor varying between 1.5 and 2 depending on the soil water content. The EC_{sw} values in this study were determined in soil water extracted with ceramic cups from the soil. Significant amounts could only be extracted after the soils in the lysimeters were saturated. It can therefore be assumed that the EC_e values of the pot experiments would be comparable with the EC_{sw} values of the lysimeter experiments.

3.3.2.2.1 Water use and salt accumulation in pots

Crop canopies grown in experimental pots tend to form a larger canopy area in relation to soil surface area, especially where long thin pots are used. Converting the total water use of the crops as given in Table 3.1 from L pot^{-1} to mm gives apparently abnormally high values of 917, 839, 467 and 1232 mm for beans, peas, maize and wheat, respectively. This can mainly be explained by the exclusion of plant competition from adjacent plants that is normally absent in glasshouse trials in comparison to field trials. The large canopy drew water from a small surface area of the pot. This phenomenon tends to accelerate the process of salinisation in the pots. The salinisation factor can be derived from the slopes of the linear regression of EC_i versus EC_e for the different crops in Figure 3.5. Accordingly, it seems that the EC_e in the pots increased with factors of 1.9, 2.0, 2.2 and 3.2, relative to the EC_i in the maize, beans, wheat and pea experiments, respectively. It must be kept in mind that maize was only grown for 6 weeks. Water use efficiency has been expressed in g biomass per kg water applied and the results are summarised in Table 3.9.

Table 3.9 Water use efficiency (WUE, mg biomass per kg water applied) of the different crops in the pot experiments

Crop	Total biomass ($g\ pot^{-1}$)	Water applied ($kg\ pot^{-1}$)	WUE ($g\ kg^{-1}$)
Beans	134.4	106.0	1.268
Peas	40.2	97.0	0.414
Maize	106.2	54.0	1.967
Wheat	206.0	142.5	1.446

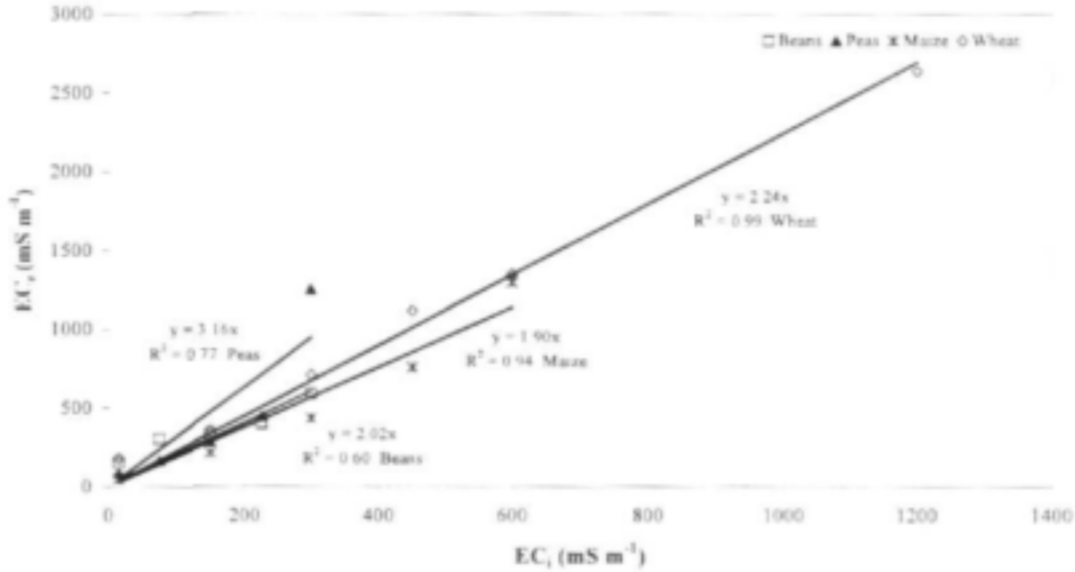

Figure 3.5 Relationship between irrigation water salinity (EC_i) and soil water salinity (EC_e) in the pots.

3.3.2.2.2 Relative biomass

The relative biomass of the selected crops is related to EC_e as shown in Figure 3.6. The regression analysis is based on the soil water salinity levels (EC_e) and the non-stress treatments were also included in the regressions. Threshold EC_e values and slopes required for Equation 2.3 were determined by the regression analysis summarised in Table 3.10.

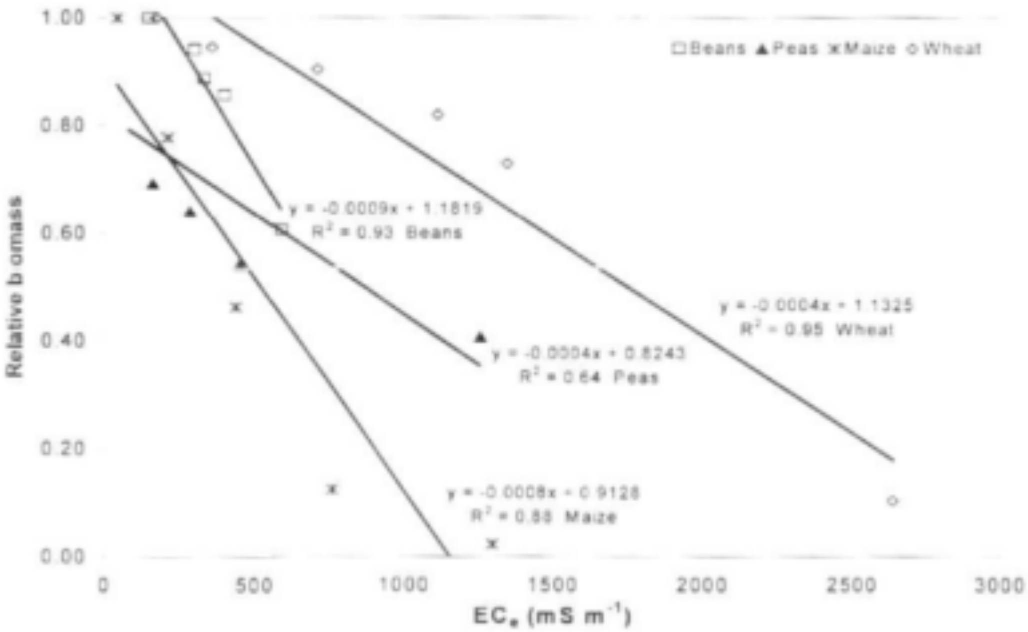

Figure 3.6 Soil salinity induced osmotic stress on the relative biomass production. Note that non-stress treatments were included in the regression.

The relative biomass of the selected crops proved to be negatively influenced with an increase in soil water salinity as indicated by EC_e (Figure 3.6). A comparison of the slopes of the regression lines demonstrated that beans were the most sensitive crop compared to the other selected crops with regard to soil water salinity. The slopes indicate that with an increase in soil water salinity the relative biomass was adversely affected and reduced at a constant rate that varied between 0.0004 and 0.0009 per unit EC_e for the selected crops.

Table 3.10 Threshold EC_e (mS m^{-1}) and slope values for the selected crops according to the regression analysis of the relationship between the relative biomass and soil water salinity (EC_e) of the saline irrigation water treatments

Crop	Threshold EC_e(mS m^{-1})	Slope (b)
Beans	202	-0.0009
Peas	*	-0.0004
Maize	*	-0.0008
Wheat	331	-0.0004

*Negative value

3.4 Conclusions

All the measured plant growth parameters were negatively affected by increasing irrigation water salinity. The degree of reduction of the different parameters differed among the different crops as a result of differences in salt tolerance.

Quantitative and qualitative germination data revealed that though the germination percentage of beans and maize was not significantly affected, the quality of the seedlings was affected in the form of a reduction in both the coleoptile/hypocotile and root length. This could lead to poorly established seedlings that may eventually die off as a result of primary stress (salt) or secondary stress (nutrient uptake, water uptake or susceptibility to disease) resulting in an uneven stand. Germination and seedling emergence are two indispensable parameters for the establishment of crops and are of utmost importance in crops that do not have a favourable compensation ability such as wheat.

Growth and yield parameters such as the relative leaf area, root mass, biomass and seed yield all declined with an increase in the EC levels of irrigation water. Peas proved to be the most sensitive crop followed by beans, maize and wheat. With regard to the relative seed yield both the leguminous crops, beans and peas, were severely affected at 225 mS m^{-1} with a 22 and 61% reduction, respectively. This shows that these crops are more sensitive to saline conditions compared to a moderately tolerant crop, such as wheat, with a reduction of 11% at 225 mS m^{-1}.

Salts accumulated in the pots during the experiments to levels where the average electrical conductivity of the soil solution (EC_e, mS m^{-1}) was 2 to 3 times higher than that of the irrigation water (EC_i). The mean relative biomass per plant or per square meter for the replications and soils per treatment decreased linearly with increasing salinity of the soil solution.

The important purpose of these experiments was to quantify the effect of irrigation water salinity (EC_i) on the establishment, growth and yield of wheat, maize, beans and peas. Furthermore, the aim of the study was to compare the response of these selected crops to the deteriorating water salinity and to determine and/or confirm at what level (EC_i) the crops showed a significant degree of reduction in growth and/or yield. These objectives were obtained and can be used to assist with decision making on the EC_i levels to be used in the field trials of the selected crops.

CHAPTER 4

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

4.1 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 salinisation 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.

4.2 Materials and methods

4.2.1 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 cut through a lysimeter with a constant water table height control mechanism are shown in Plate 4.1.

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.

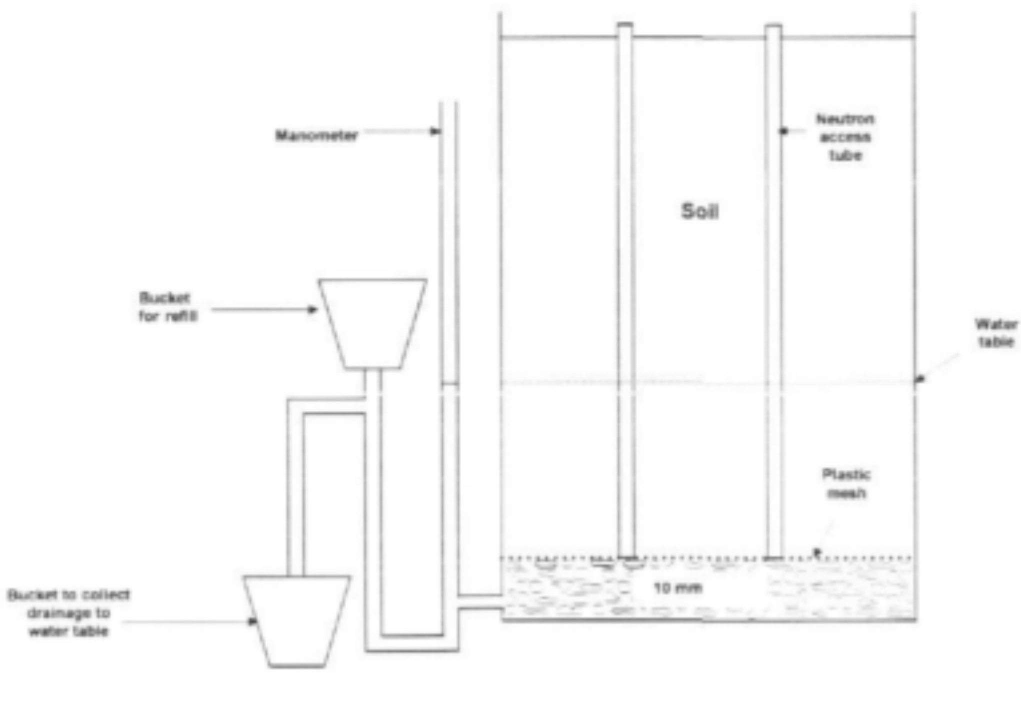

Plate 4.1 Layout of the lysimeters and an illustration of a vertical cut through a container with a constant water table height control mechanism.

For this experiment five 2 500 L 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 poli-ethylene 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.

4.2.2 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 4.1.

4.2.3 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. In each of the replicated lysimeters for 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 that is used for irrigation, at the bottom of the lysimeters once a day. The treatments that were chosen for the different crops are presented in Table 4.2.

Sodium chloride (NaCl), calcium chloride ($CaCl_2$), magnesium sulfate ($MgSO_4$), sodium sulfate (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 salt (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 4.1 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

It was pointed out earlier in this report, 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 study (Section 5.3.3) where the value of the constant was determined as 7.568 for the soil water and 7.831 for the irrigation water.

Table 4.2 Electrical conductivity (EC_i, mS m^{-1}) and sodium adsorption ratio (SAR) of the irrigation water 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

Table 4.3 gives the amount of the different salts that were used to prepare the irrigation water salinity treatments for the different crops. Calcium (Ca^{2+}) and magnesium (Mg^{2+}) was used in a ratio ranging between 1.2 and 1.6, whereas the sulfate (SO_4^{2-}) 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).

4.2.4 Agronomic practices

All the agronomic practices were managed with the objective to create optimum conditions for crop growth, allowing for maximum root water uptake and yield. Some of these practices for the different crops are given in Table 4.4. 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.

4.2.5 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 it just above the soil surface. After drying it at 70°C for three days in a ventilated oven, it was weighed and threshed to determine the 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.

Table 4.3 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

Table 4.4 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})		

4.2.6 Soil water balance

For the calculation of evapotranspiration the following components of the soil water balance (Equation 4.1) were measured weekly, throughout the growing season for each of the lysimeters.

$$ET = I \pm \Delta W + Q - D \qquad (4.1)$$

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.

4.2.7 *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 liter, as well as the time of application, expressed as days after planting (DAP), for all the crops and treatments are presented in Appendix 4.1. A summary of the total amount of irrigation water applied to all the soils, crops and treatments is given in Table 4.5..

Table 4.5 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	liter	EC_i (mS m^{-1})	mm	liter
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	liter	EC_i (mS m^{-1})	mm	liter
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

4.3 Results and discussion

4.3.1 Crop yields

4.3.1.1 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 4.2. 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 4.6.

1. Wheat

From Table 4.6 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 as was the case in the glasshouse experiment where the maximum EC_i treatment was 1200 mS m^{-1} (Section 3.3.2).

2. Beans

There was a significant decrease in seed yield with an increase in irrigation water salinity (Table 4.6). 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 4.7.

Table 4.6 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 (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 4.7 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 4.7 were calculated from the values presented in Appendix 6.1. 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}.

3. 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 4.6 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.

4. 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 4.6). 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.

4.3.1.2 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 4.1 to 4.4 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 the glasshouse experiments, 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.

4.3.2 Evapotranspiration and water use efficiency

The mean cumulative evapotranspiration (ET, mm) and water use efficiency (WUE, g seed kg water^{-1}) results for all the soils, crops and treatments are summarized in Table 4.8. 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 4.3. The data sheets are available on request from the authors. The mean daily evapotranspiration of the crops over the growing season for all treatments is displayed in Figures 4.5 to 4.12.

1. 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 4.5 for Soil A and Figure 4.6 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.

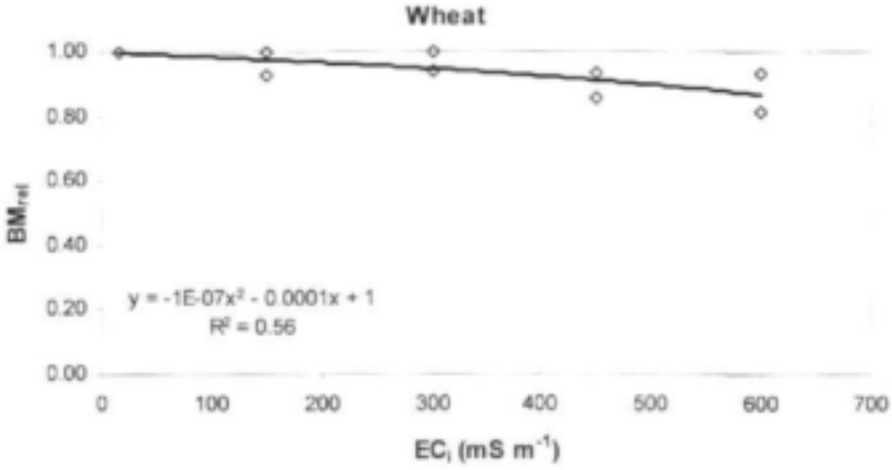

Figure 4.1 The relationship between the relative biomass yield (BM_{rel}) and irrigation water salinity (EC_i, mS m^{-1}) of wheat on both soils.

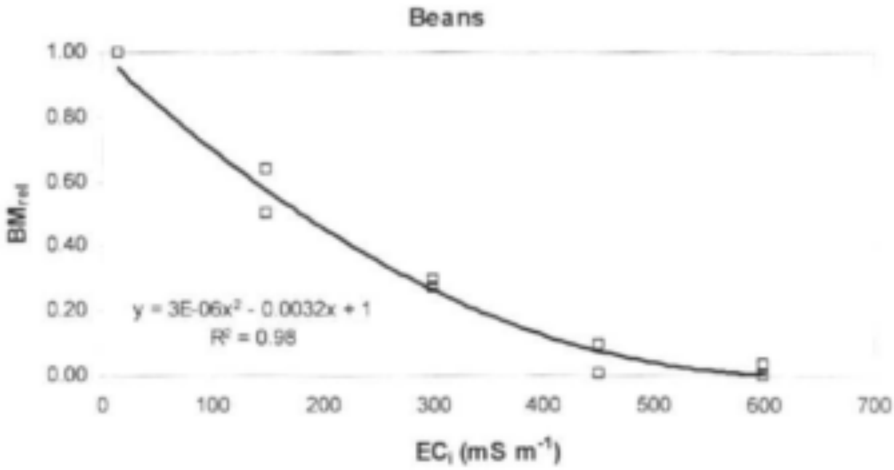

Figure 4.2 The relationship between the relative biomass yield (BM_{rel}) and irrigation water salinity (EC_i, mS m^{-1}) of beans on both soils.

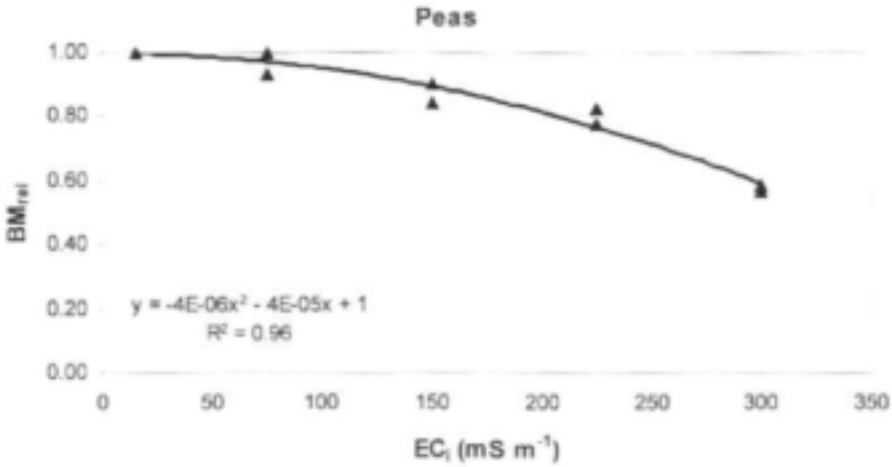

Figure 4.3 The relationship between the relative biomass yield (BM_{rel}) and irrigation water salinity (EC_i, mS m^{-1}) of peas on both soils.

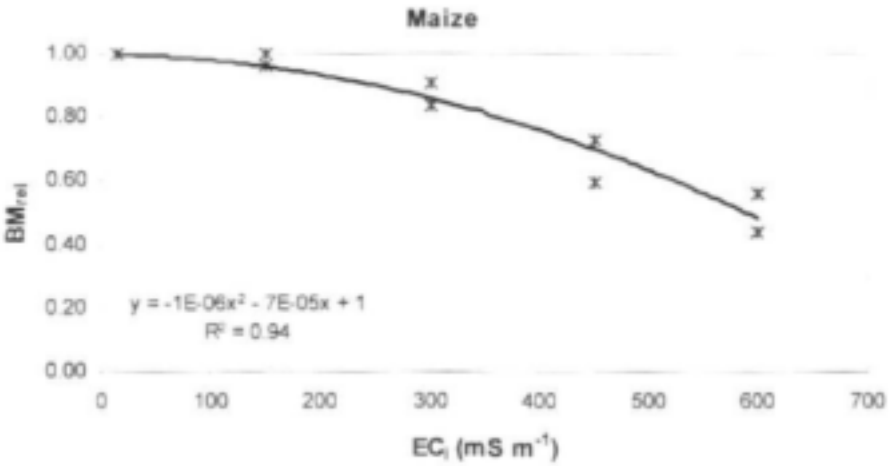

Figure 4.4 The relationship between the relative biomass yield (BM_{rel}) and irrigation water salinity (EC_i, mS m^{-1}) of maize on both soils.

Table 4.8 Mean evapotranspiration (ET, mm) and water use efficiency (WUE, g kg^{-1}) for all the crops and ECi treatments of 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*	*nss*		***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. As was illustrated in Section 3.3, rapid decline in yield, water use and WUE can be expected beyond 600 mS m^{-1}.

2. 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 4.7 for Soil A and in Figure 4.8 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 4.3.1.1.

3. 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 4.9 and 4.10 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.

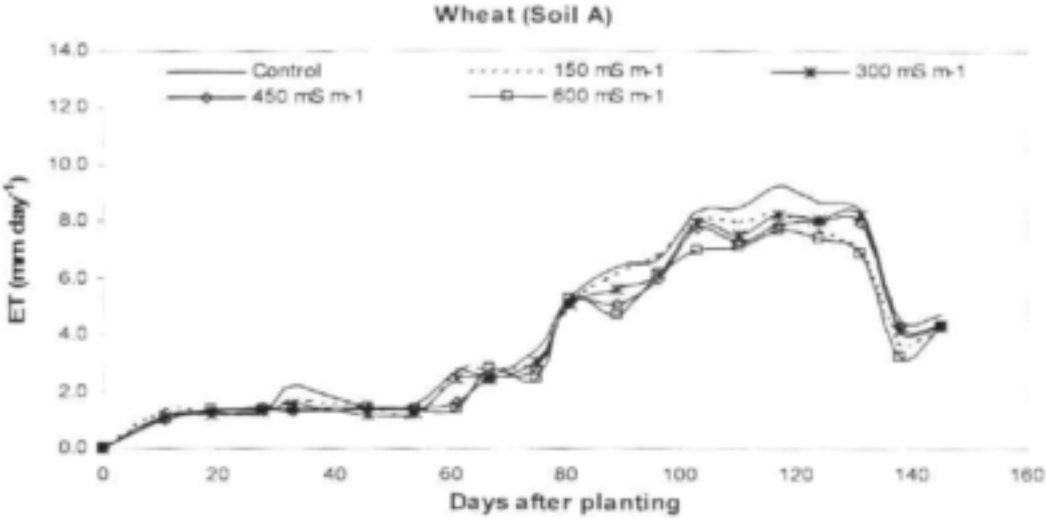

Figure 4.5 Mean wheat daily evapotranspiration (ET, mm day^{-1}) over the growing season for all the treatments of Soil A.

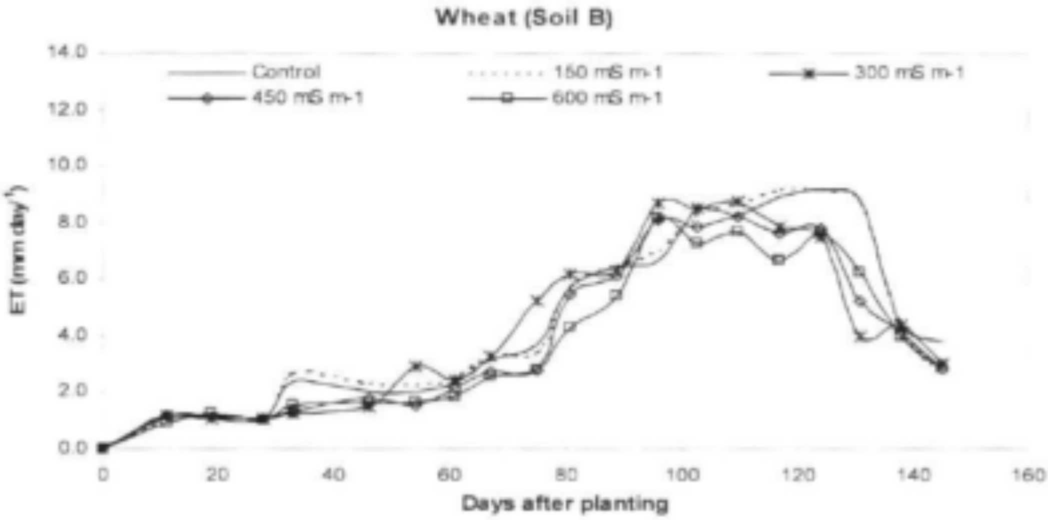

Figure 4.6 Mean wheat daily evapotranspiration (ET, mm day^{-1}) over the growing season for all the treatments of Soil B.

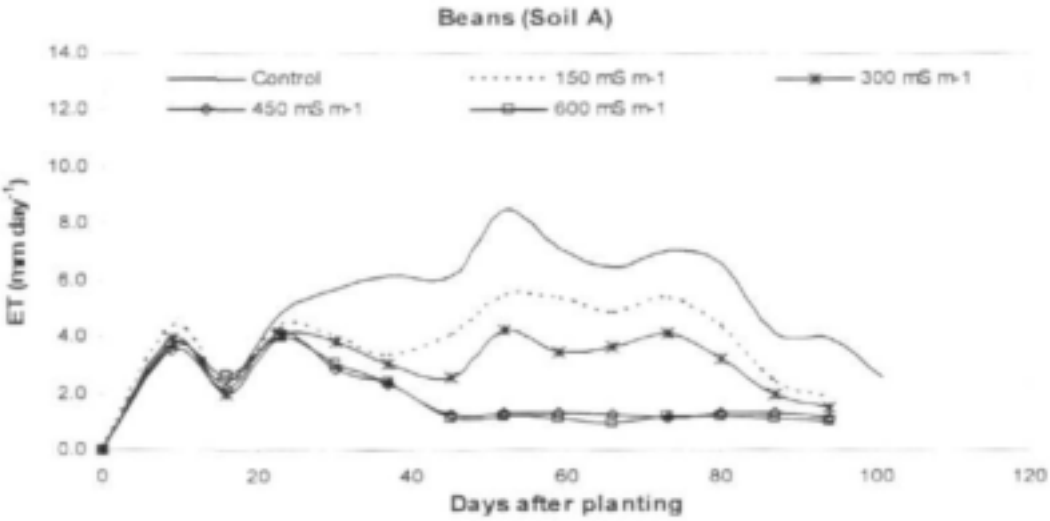

Figure 4.7 Mean bean daily evapotranspiration (ET, mm day^{-1}) over the growing season for all the treatments of Soil A.

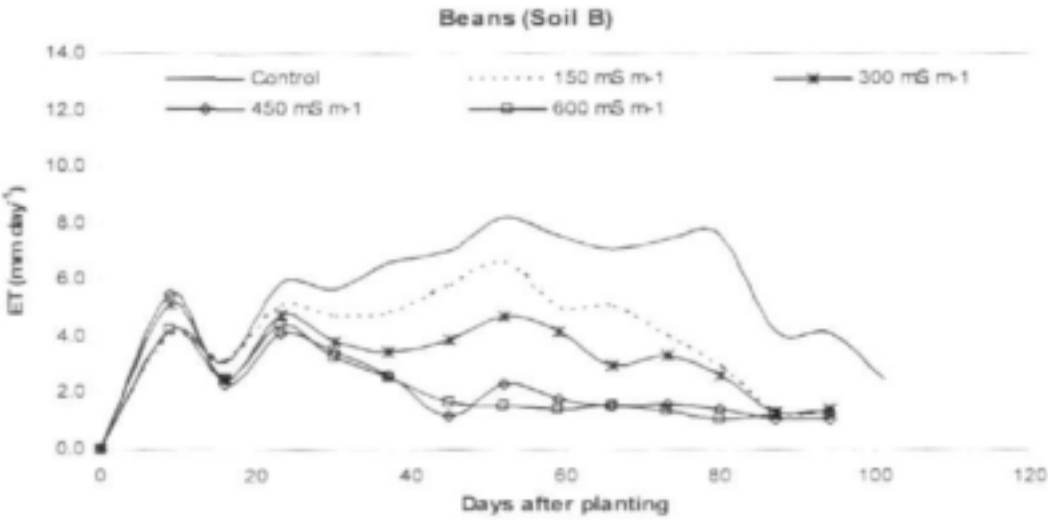

Figure 4.8 Mean bean daily evapotranspiration (ET, mm day^{-1}) over the growing season for all the treatments of Soil B.

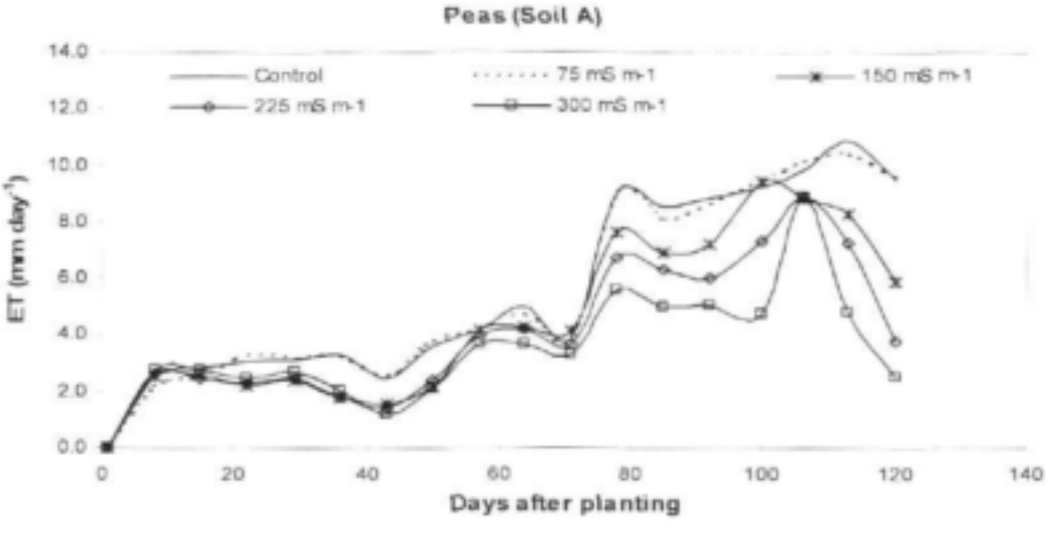

Figure 4.9 Mean pea daily evapotranspiration (ET, mm day^{-1}) over the growing season for all the treatments of Soil A.

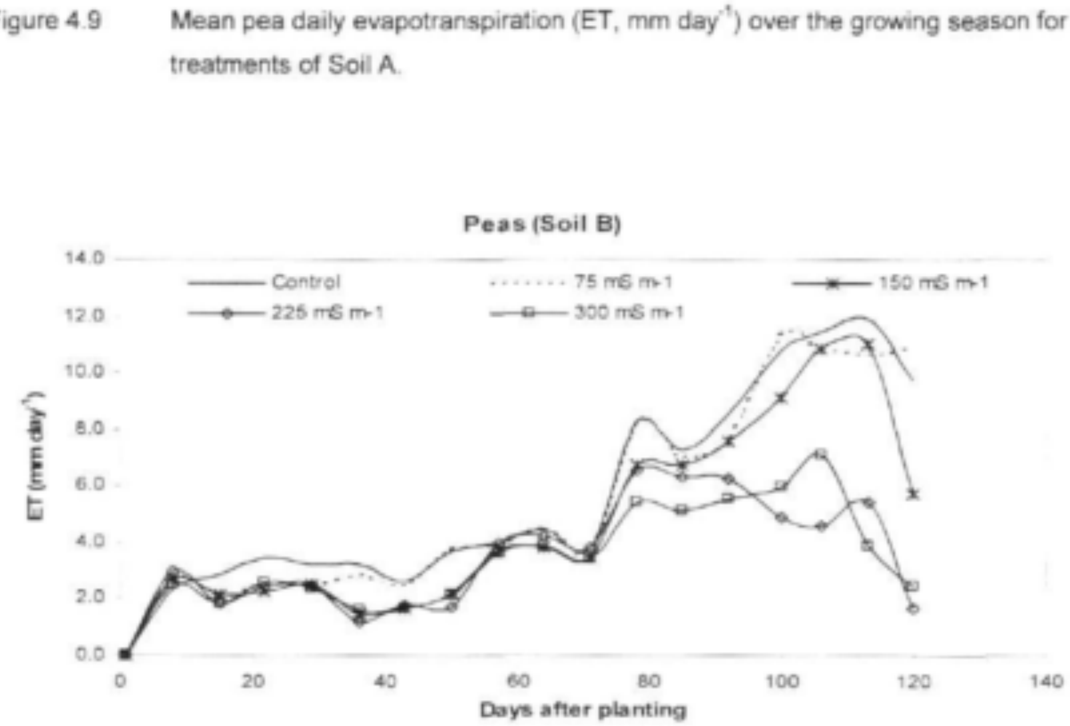

Figure 4.10 Mean pea daily evapotranspiration (ET, mm day^{-1}) over the growing season for all the treatments of Soil B.

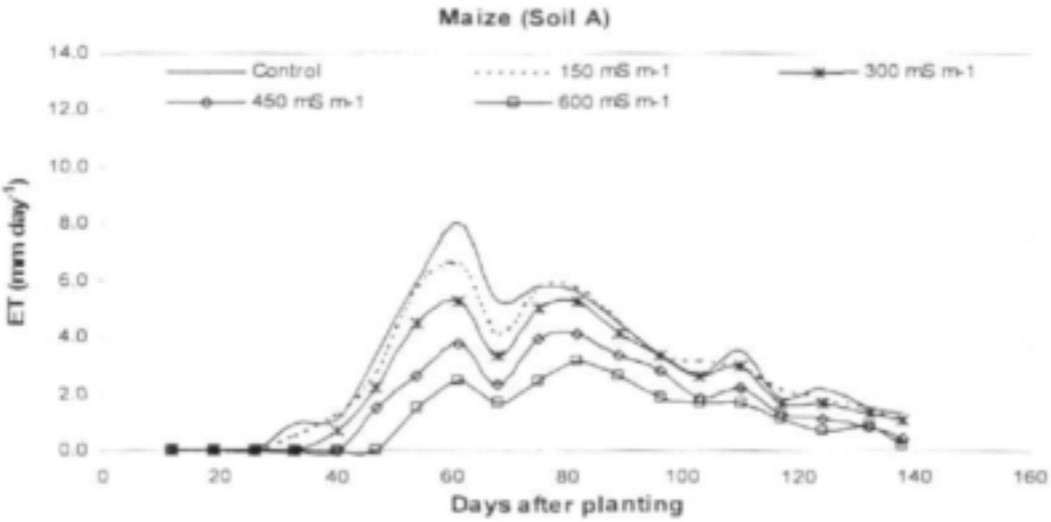

Figure 4.11 Mean maize daily evapotranspiration (ET, mm day^{-1}) over the growing season for all the treatments of Soil A.

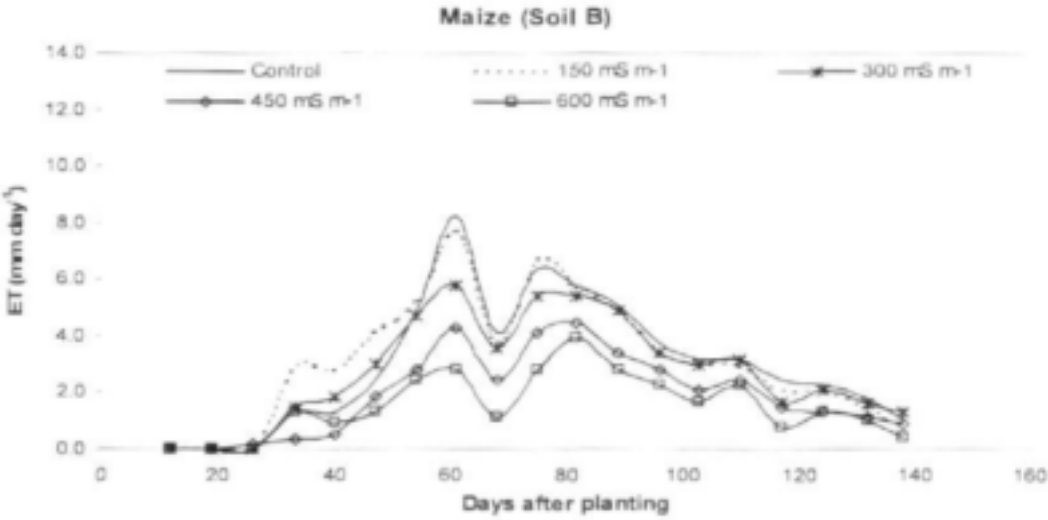

Figure 4.12 Mean maize daily evapotranspiration (ET, mm day^{-1}) over the growing season for all the treatments of Soil B.

As shown in Table 4.8 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}.

4. 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 4.11 and 4.12 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 4.8 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.

4.3.3 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 4.9. The cumulative uptake from the water tables over the growing season are also illustrated in Figures 4.13 and 4.14 for wheat, Figures 4.15 and 4.16 for beans, Figures 4.17 and 4.18 for peas and Figures 4.19 and 4.20 for maize.

1. 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 4.13 for soil A and Figure 4.14 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).

2. *Beans*

From Table 4.9 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 4.7. Inspection of Figures 4.15 and 4.16 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.

3. *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 4.17 and 4.18, 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.

4. *Maize*

The results in Table 4.9 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 4.9 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

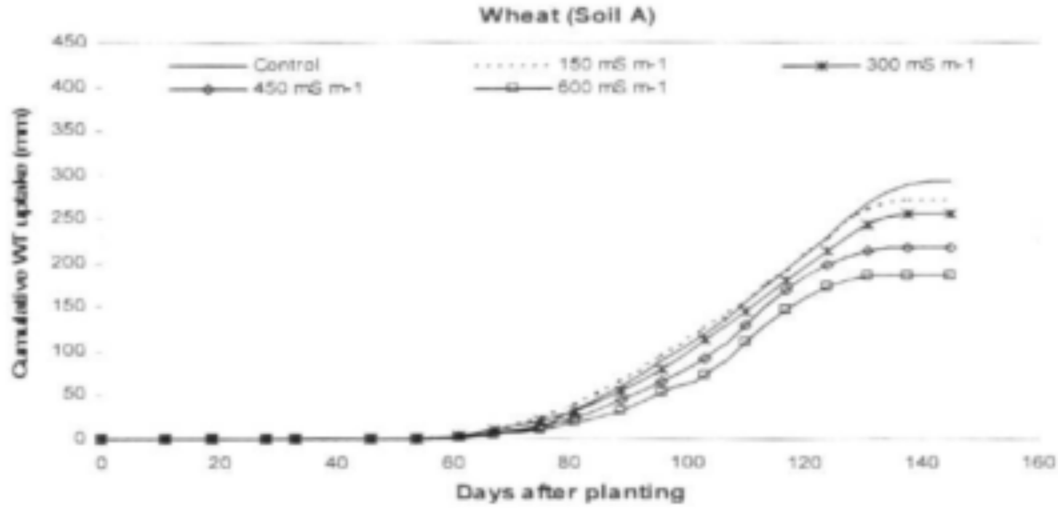

Figure 4.13 Cumulative water table uptake as a function of days after planting for all the treatments of the wheat crop on Soil A.

Figure 4.14 Cumulative water table uptake as a function of days after planting for all the treatments of the wheat crop on Soil B.

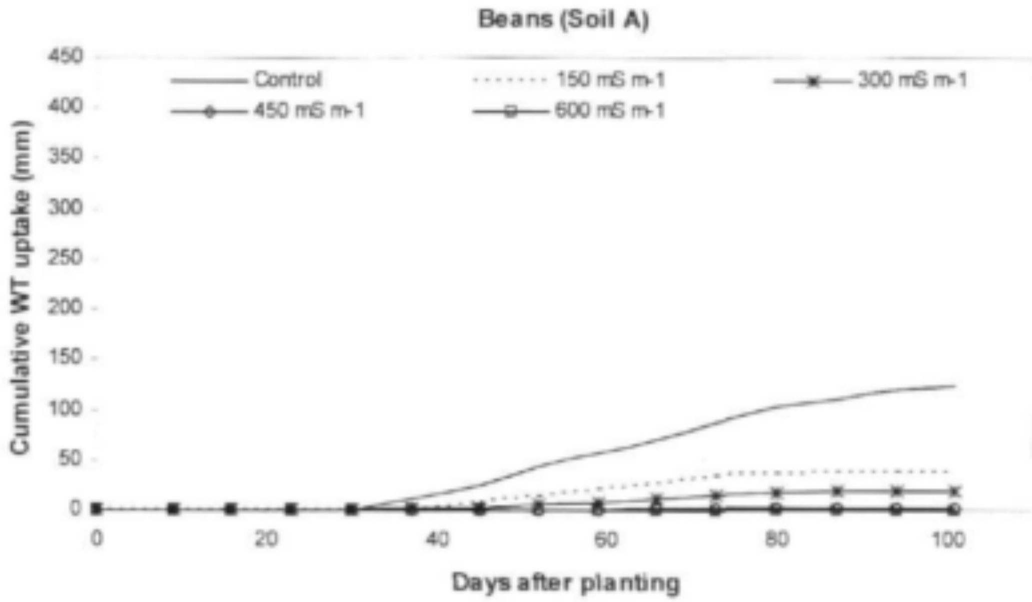

Figure 4.15 Cumulative water table uptake as a function of days after planting for all the treatments of beans on Soil A.

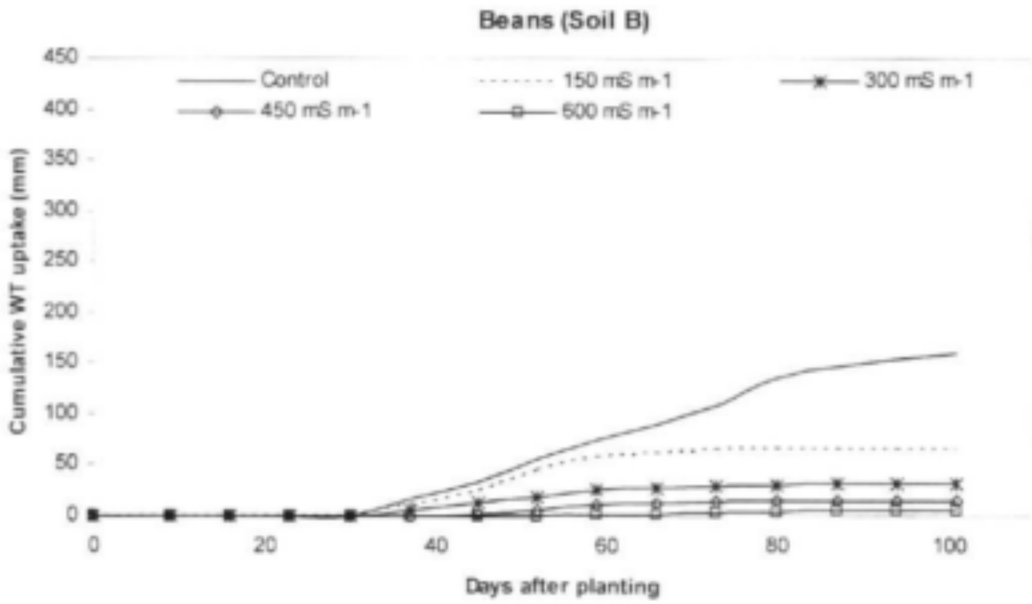

Figure 4.16 Cumulative water table uptake as a function of days after planting for all the treatments of beans on Soil B.

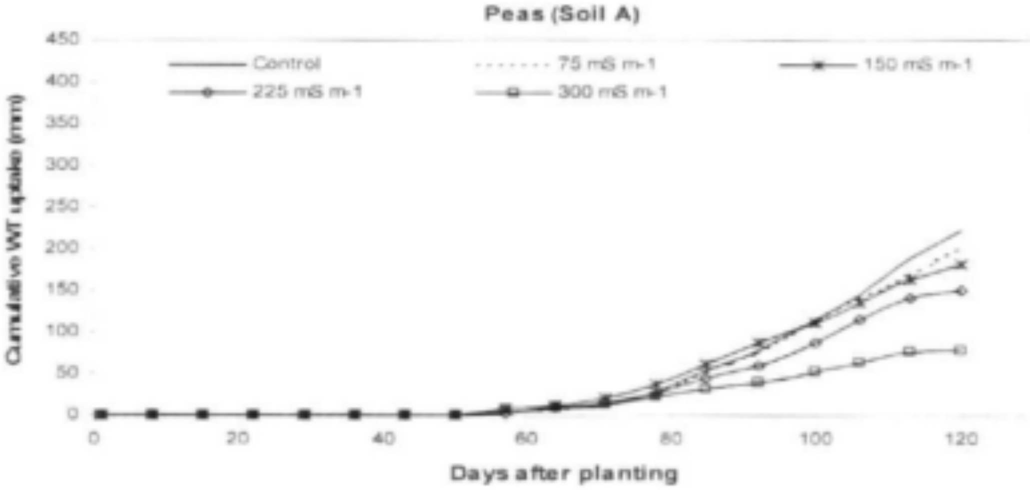

Figure 4.17 Cumulative water table uptake as a function of days after planting for all the treatments of peas on Soil A.

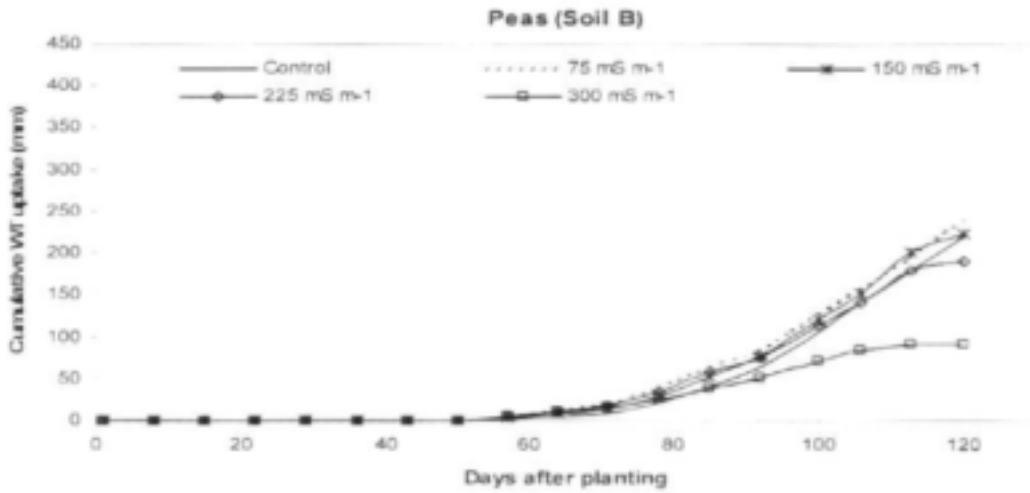

Figure 4.18 Cumulative water table uptake as a function of days after planting for all the treatments of peas on Soil B.

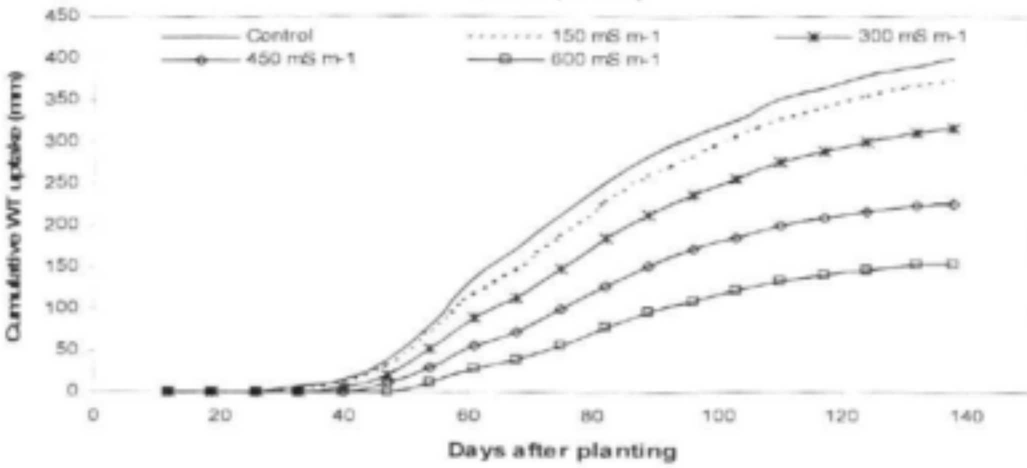

Figure 4.19 Cumulative water table uptake as a function of days after planting for all the treatments of maize on Soil A.

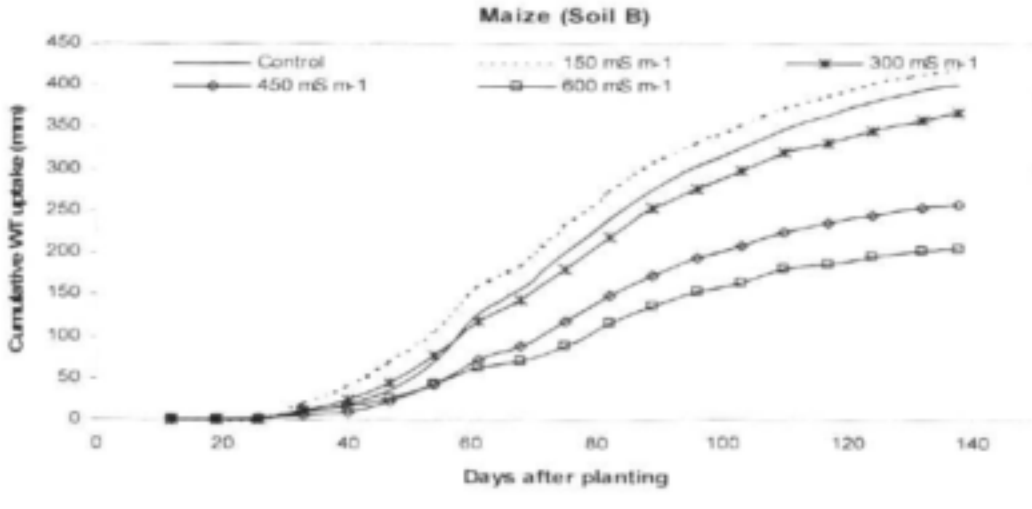

Figure 4.20 Cumulative water table uptake as a function of days after planting for all the treatments of maize on Soil B.

Figures 4.19 and 4.20 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.

4.3.4 Comparison of the salt tolerance of the different crops

4.3.4.1 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 4.21, 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 4.10.

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) the classification based on growth and yield, namely that wheat is moderately salt tolerant, maize moderately salt sensitive and beans and peas salt sensitive.

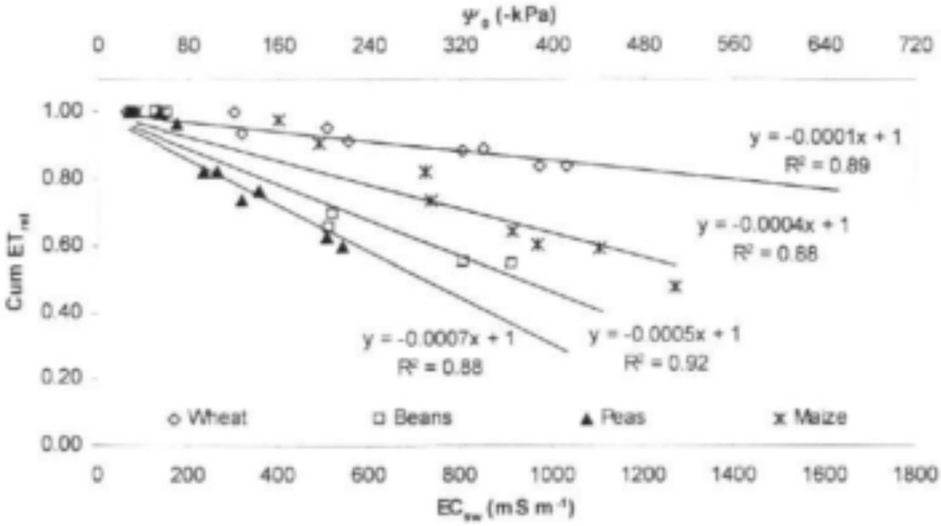

Figure 4.21 The relationship between the relative cumulative ET (Cum ET_{rel}) and soil water salinity (EC_{sw}, mS m^{-1}) as affected by osmotic potential (Ψ_o, -kPa) for all the crops on both soils.

Table 4.10 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

4.3.4.2 Relationship between the relative biomass yield and soil water salinity

For the 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 4.10) 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 4.11. The biomass yield response of the different crops to soil salinity as characterized by linear functions are illustrated in Figures 4.22 to 4.25.

Table 4.11 *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*		
	Glasshouse	Field	R & L**	Glasshouse	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)

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 values reported by Rhoades & Loveday (1990) of 170 mS m^{-1} and 130 mS m^{-1} by Katerji *et al.* (2003).

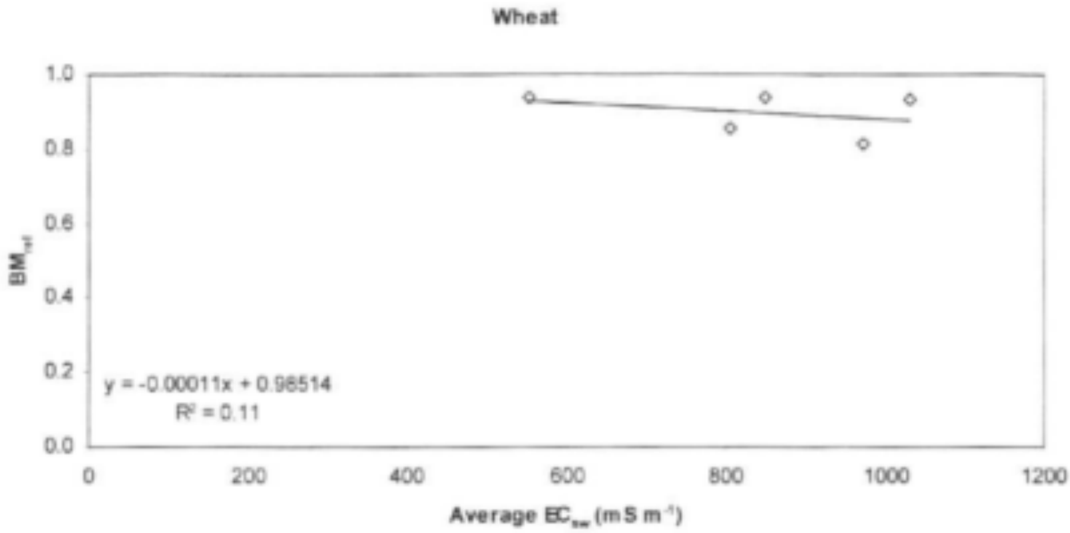

Figure 4.22 The relationship between the relative biomass yield (BM_{rel}) and mean seasonal soil water salinity (EC_{sw}) for wheat on both soils.

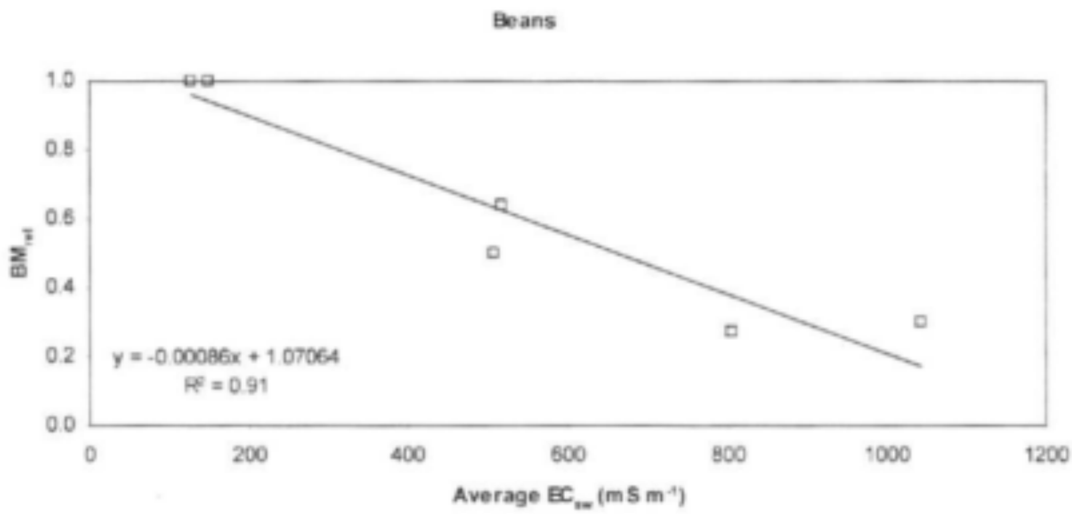

Figure 4.23 The relationship between the relative biomass yield (BM_{rel}) and mean seasonal soil water salinity (EC_{sw}) for beans on both soils.

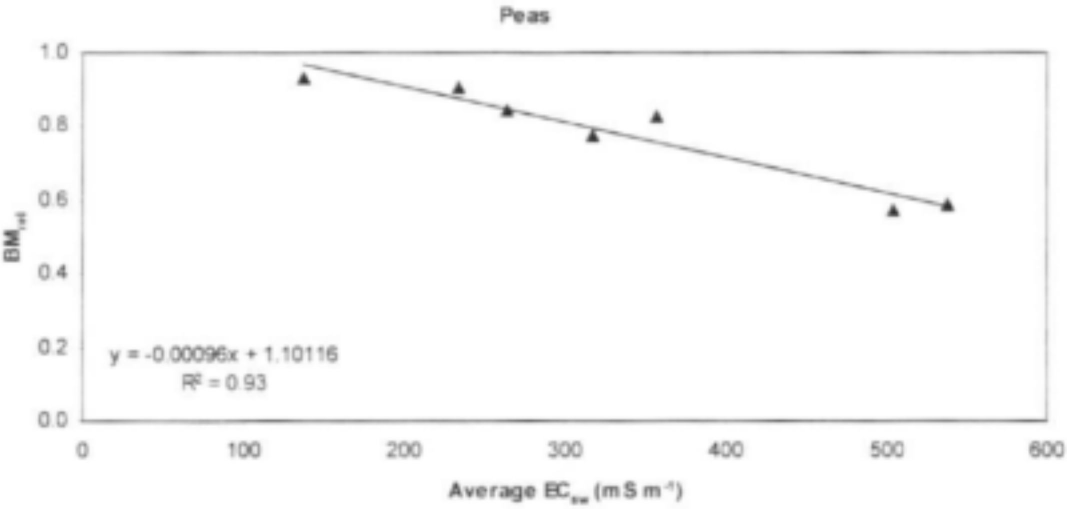

Figure 4.24 The relationship between the relative biomass yield (BM_{rel}) and mean seasonal soil water salinity (EC_{sw}) for peas on both soils.

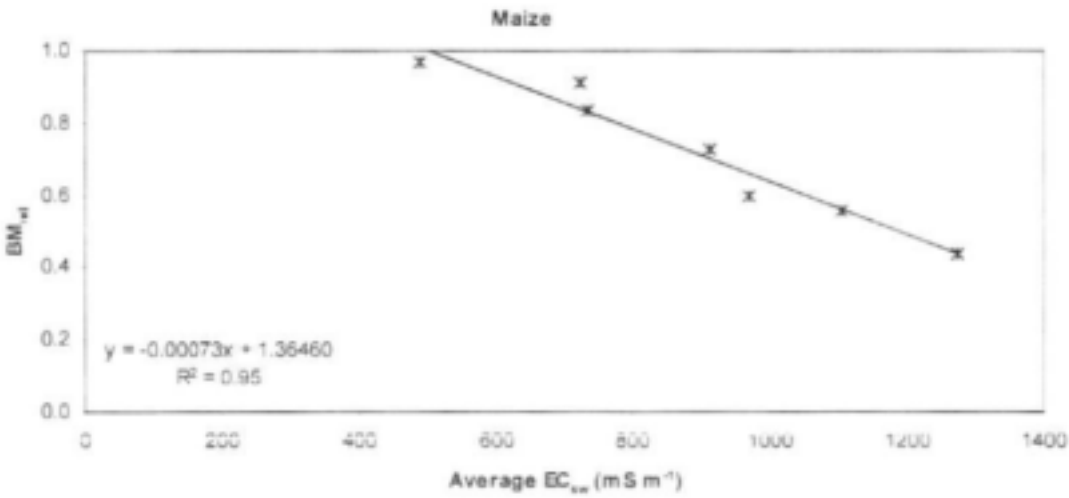

Figure 4.25 The relationship between the relative biomass yield (BM_{rel}) and mean seasonal soil water salinity (EC_{sw}) for maize on both soils.

According to Maas (1990), the parameters in Table 4.11 can be used to estimate the relative yield (Y_r) with Equation 4.2 for soil salinities exceeding the threshold value of any crop.

$$Yr = 1 - b\,(EC_{sw} - a) \tag{4.2}$$

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

b = Slope expressed in fractions of 1 per mS m^{-1}

EC_{sw} = Mean electrical conductivity of the soil water taken from the root zone expressed in mS m^{-1}

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

4.3.4.3 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 potential (matric plus osmotic) of the soil water. The corresponding decrease in the potential difference 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):

$$1 - \frac{Ya}{Ym} = b\left[1 - \left(\frac{ETa}{ETm}\right)\right] \tag{4.3}$$

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

b = 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 give a linear relationship between relative evapotranspiration and relative yield as illustrated by Figure 4.26 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.

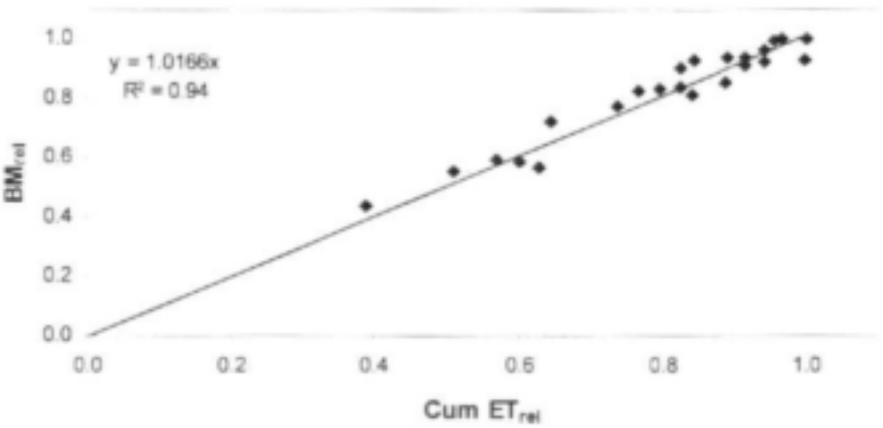

Figure 4.26 Relationship between the relative biomass yield (BM_{rel}) and the relative cumulative ET (Cum ET_{rel}) for all the crops and soils combined.

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

The uptake of water from the water tables (WT) is presented in Table 4.9 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 4.12 and 4.13 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 4.13), 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 4.27, 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 (Annandale *et al.*, 1999) 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 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 rizosphere.

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 7.2.

Table 4.12 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

4.4 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.

Table 4.13 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

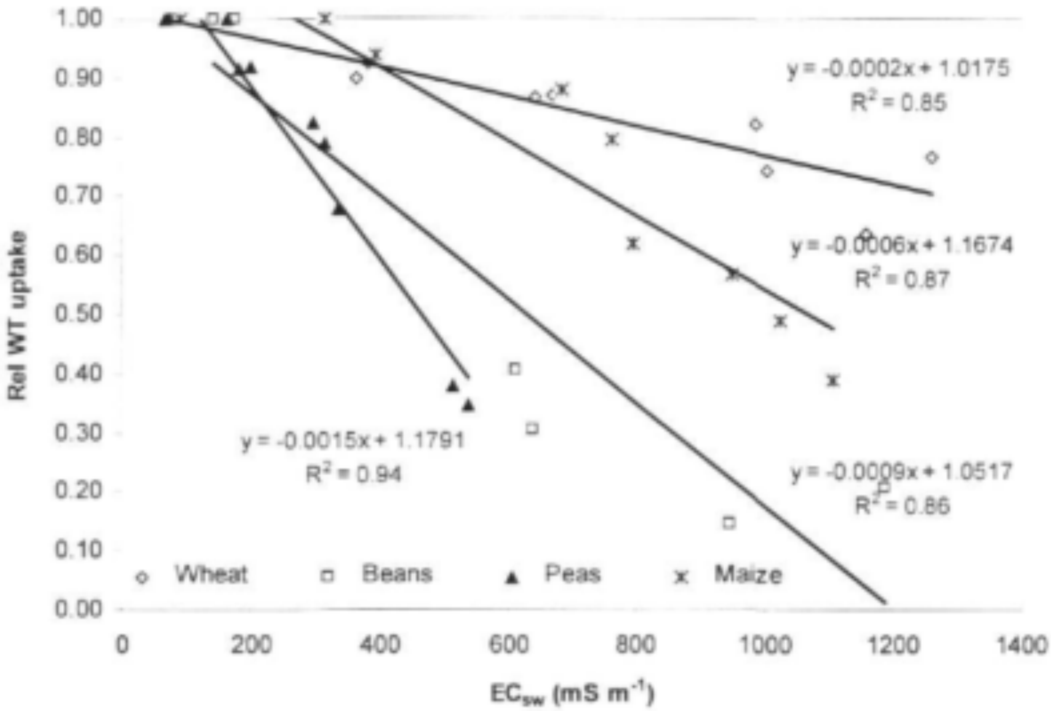

Figure 4.27 Relative water uptake from the capillary zones of water tables with different salinity levels by the experimental crops.

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 comparative 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 will probably 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 contents 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 becomes possible to compare these results with those published in the relevant 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 relative 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 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 glasshouse experiment threshold value for wheat 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 5

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

5.1 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 4). 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, irrigation water salinity and 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, at a range of irrigation water salinities and in the presence of shallow saline water tables.

5.2 Materials and methods

The lysimeter unit used for obtaining data for this study is described in Section 4.2.1. 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 5.1). 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.

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_d of the leachate 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 5.1 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 the 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 salts (TDS) and sodium adsorption ratio (SAR) of the soil water if necessary.

5.3 Results and discussion

5.3.1 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 5.1. Figures 5.1 to 5.4 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 5.1) are the same as for the beginning of the bean growing season.

1. 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 5.1 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.

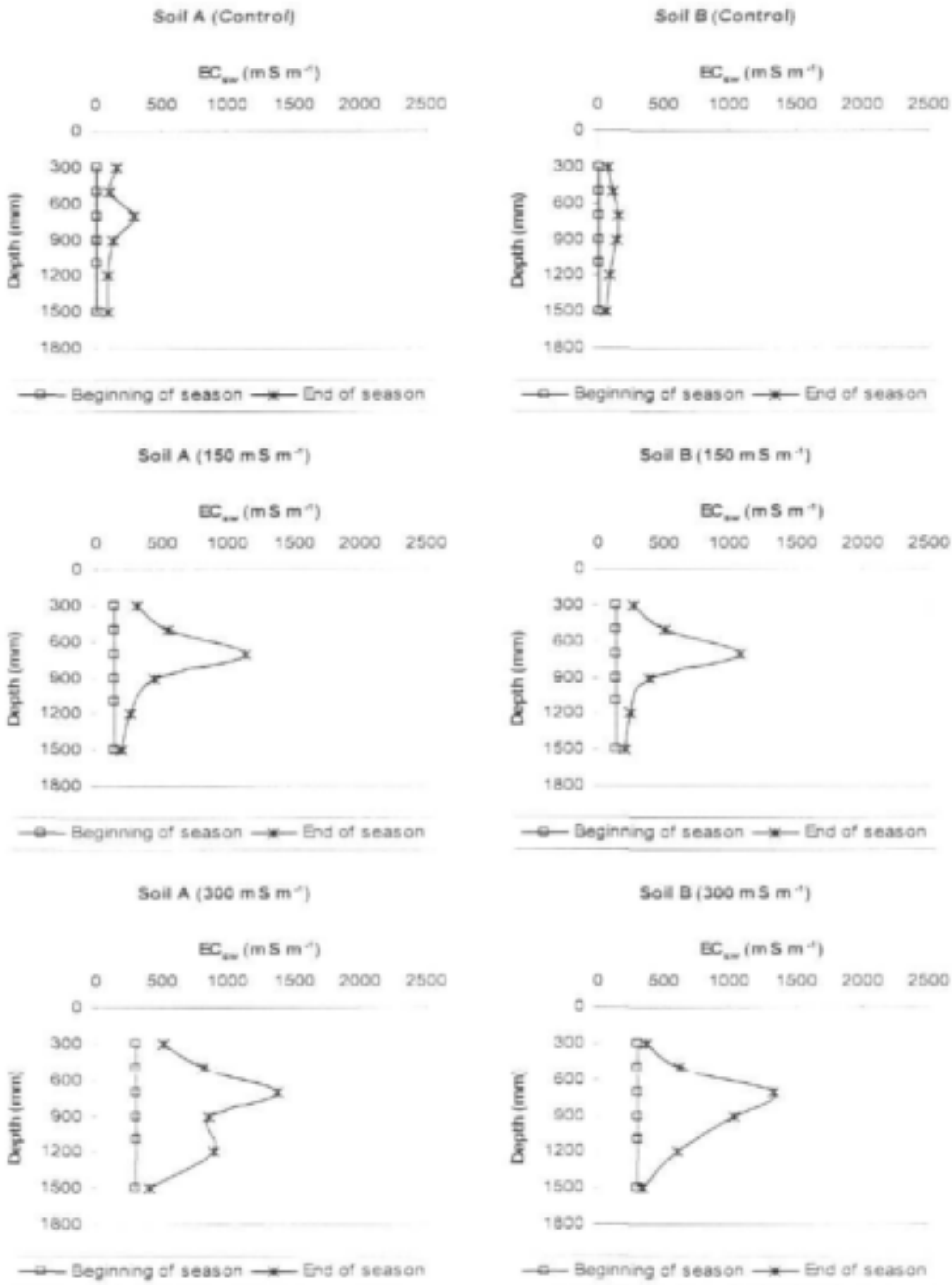

Figure 5.1 continue

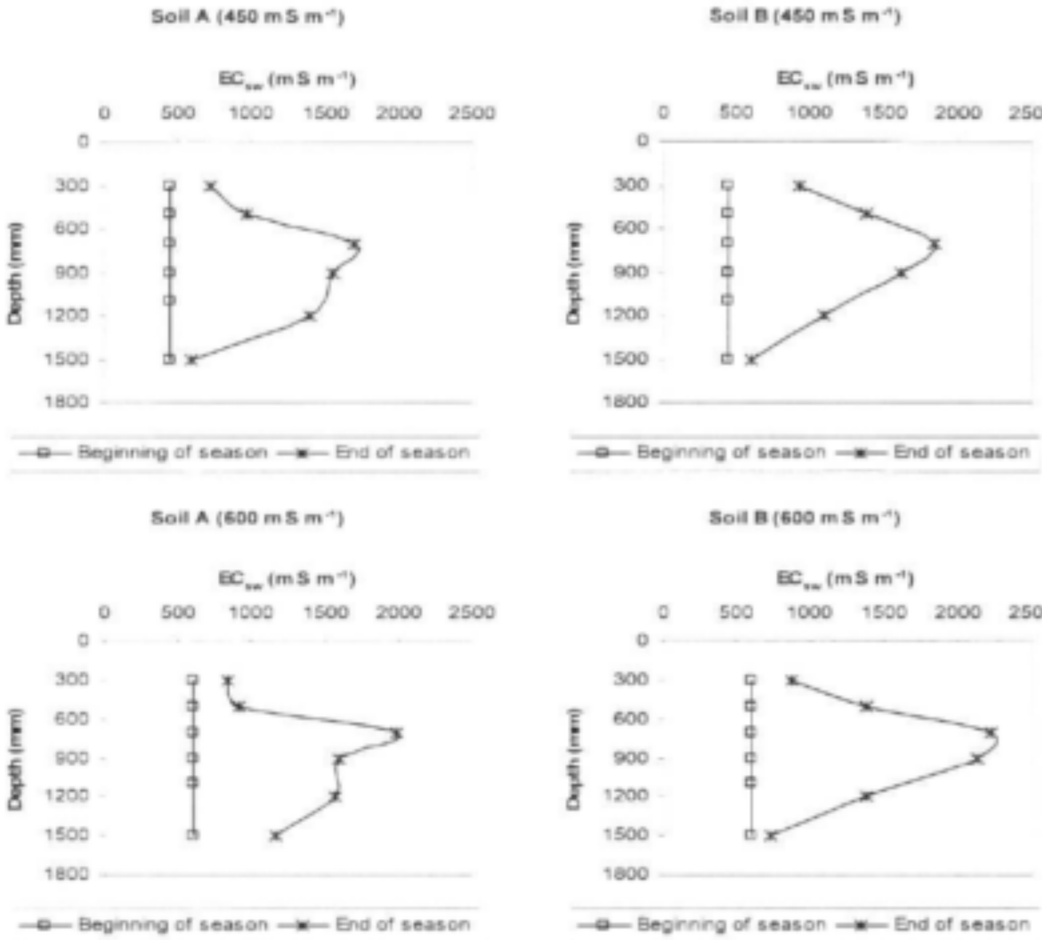

Figure 5.1 Soil water salinity profiles at the beginning and end of the wheat growing season for all the EC_i treatments of both soils.

2. 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 5.2.1) 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 5.2, was directly related to the salinity level of the added irrigation water, as surface or sub-surface irrigation. As explained in Section 4.3.1, the high salinity levels in the top soil negatively affected the germination and establishment of beans. As illustrated in Figure 5.2 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 the salts can be observed in all the treatments on Soil A and in the 150, 450 and 600 mS m^{-1} treatments on Soil B (Figure 5.2).

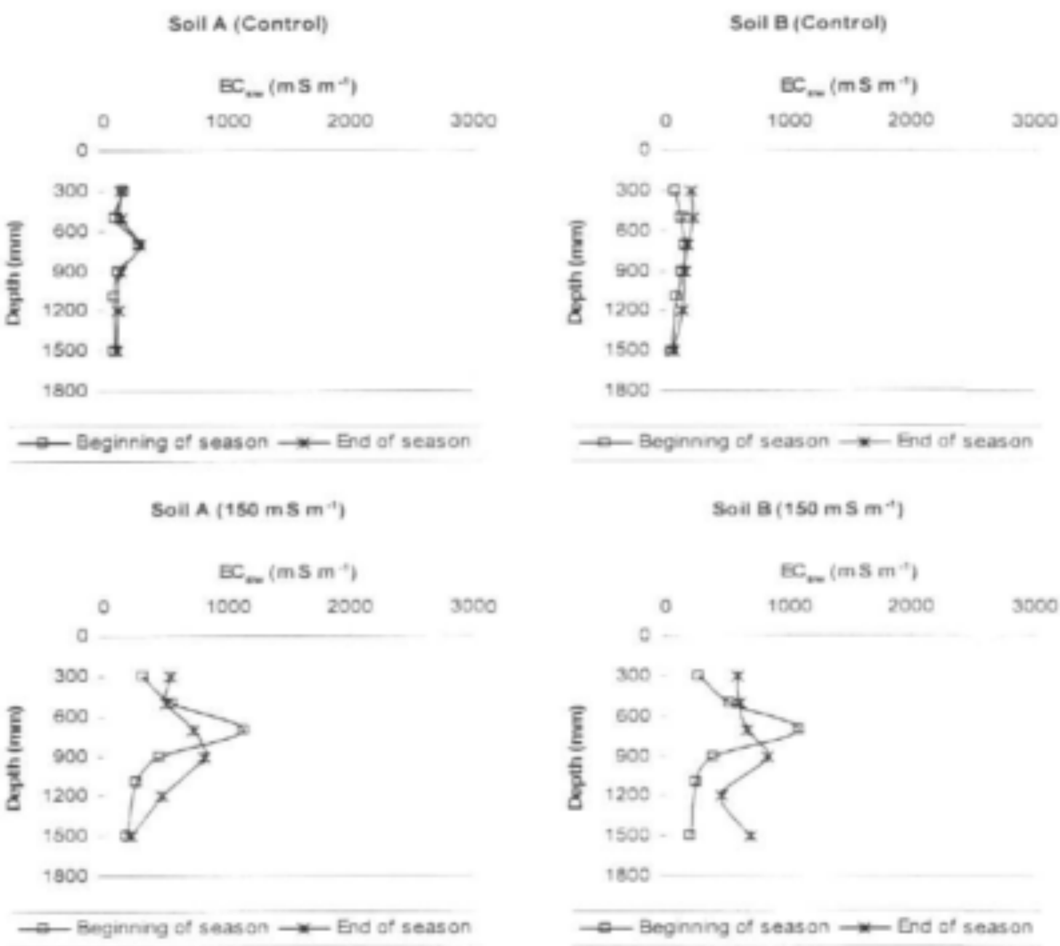

Figure 5.2 continue

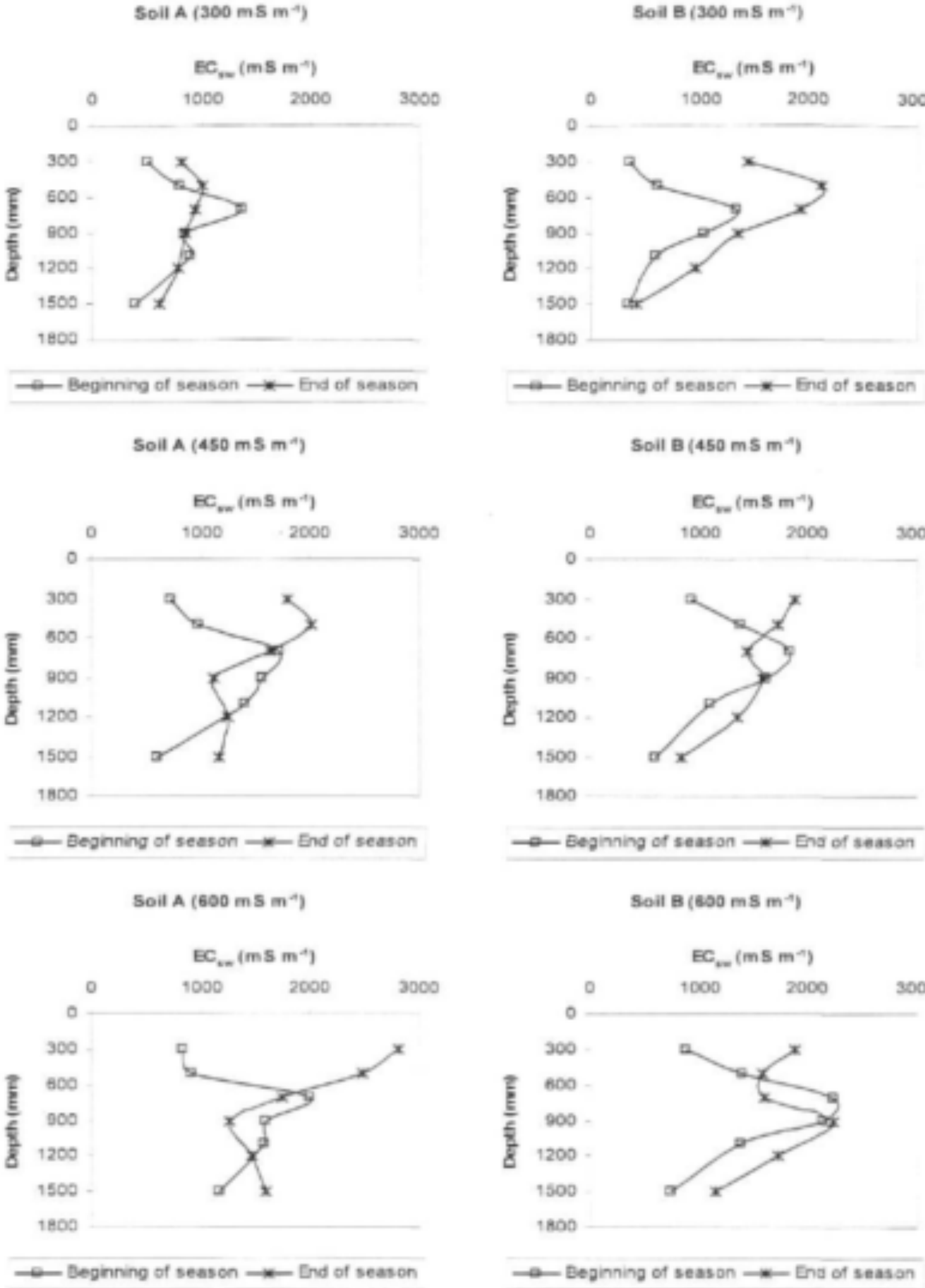

Figure 5.2 Soil water salinity profiles at the beginning and end of the bean growing season for all the EC_i treatments of both soils.

3. **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 5.3 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.

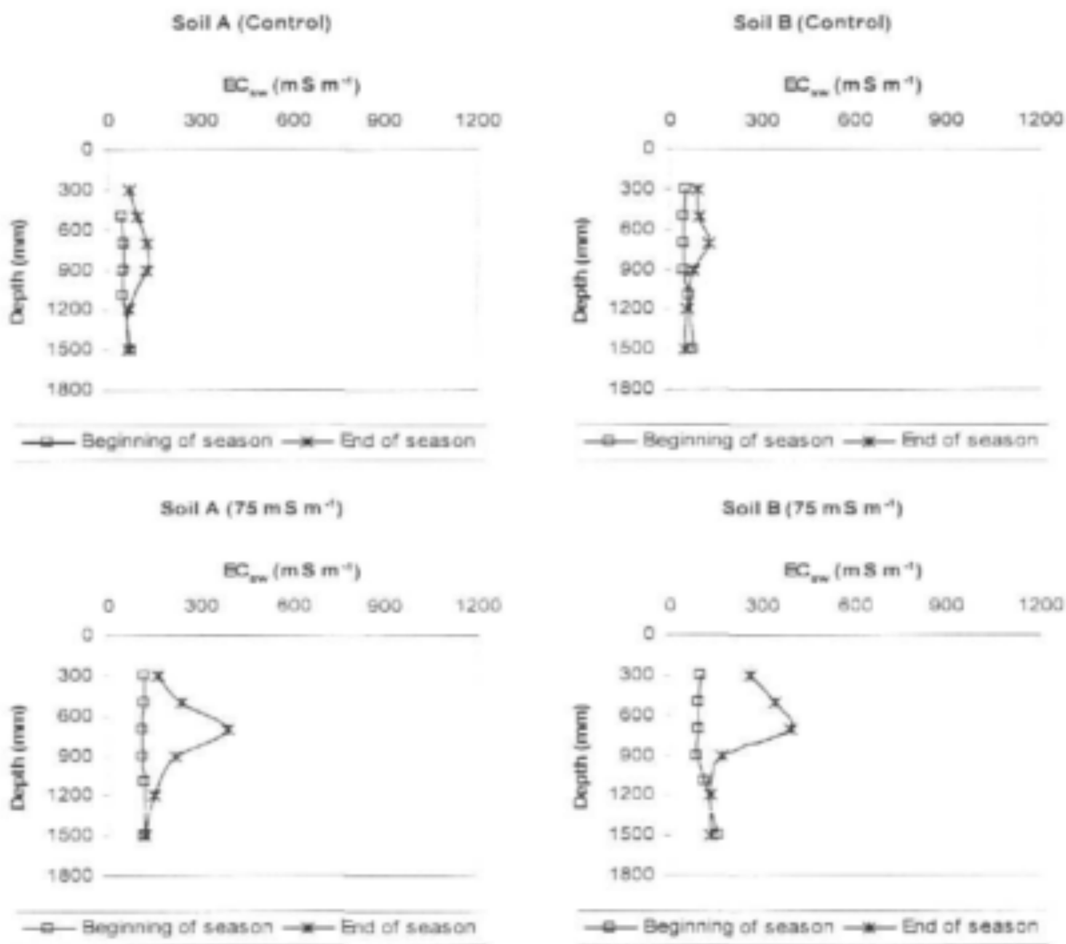

Figure 5.3 continue

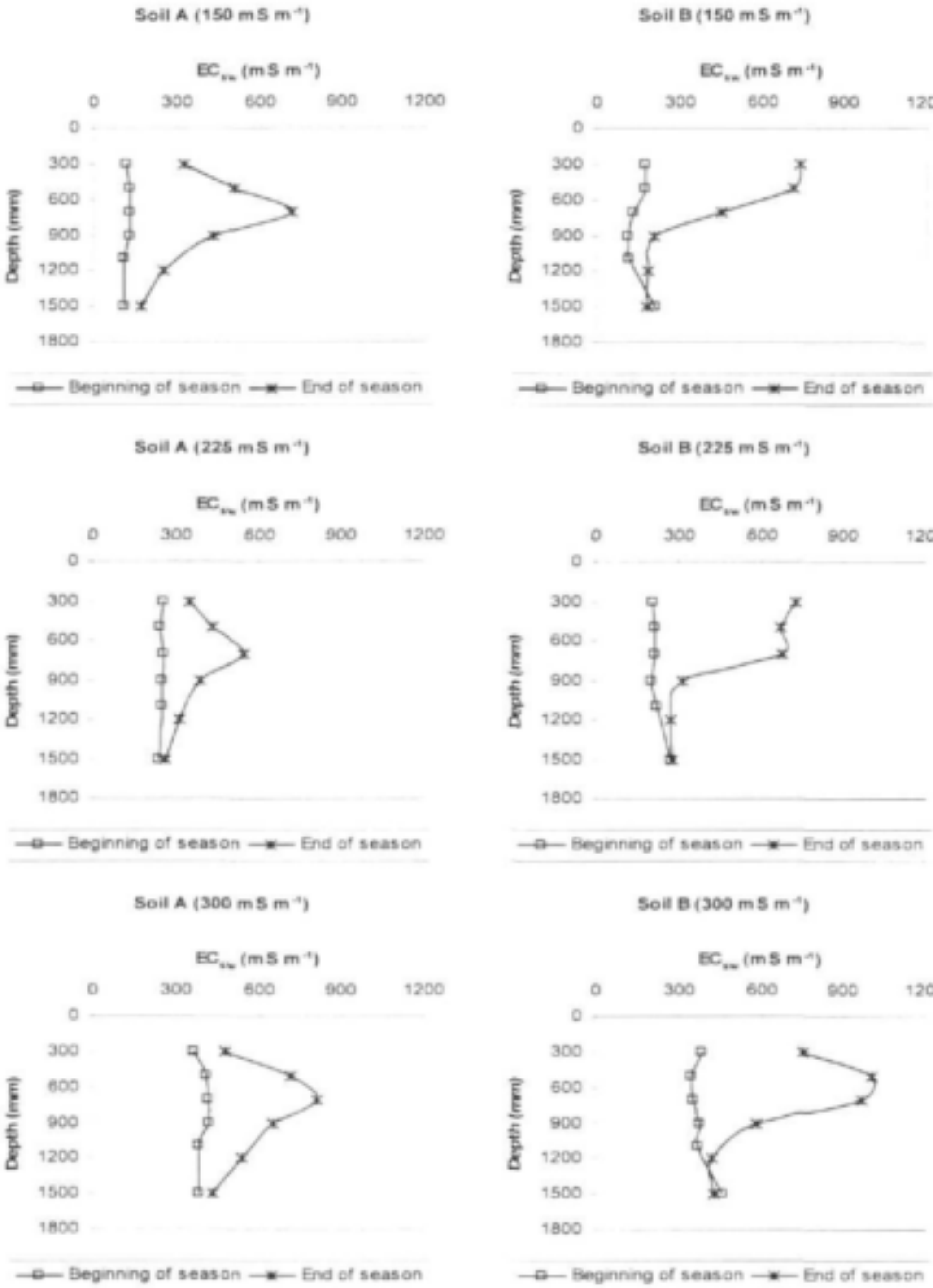

Figure 5.3 Soil water salinity profiles at the beginning and end of the pea growing season for all the EC_i treatments of both soils.

4. Maize

The salinity levels at the beginning (after leaching) and end of the maize growing season are illustrated in Figure 5.4 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}.

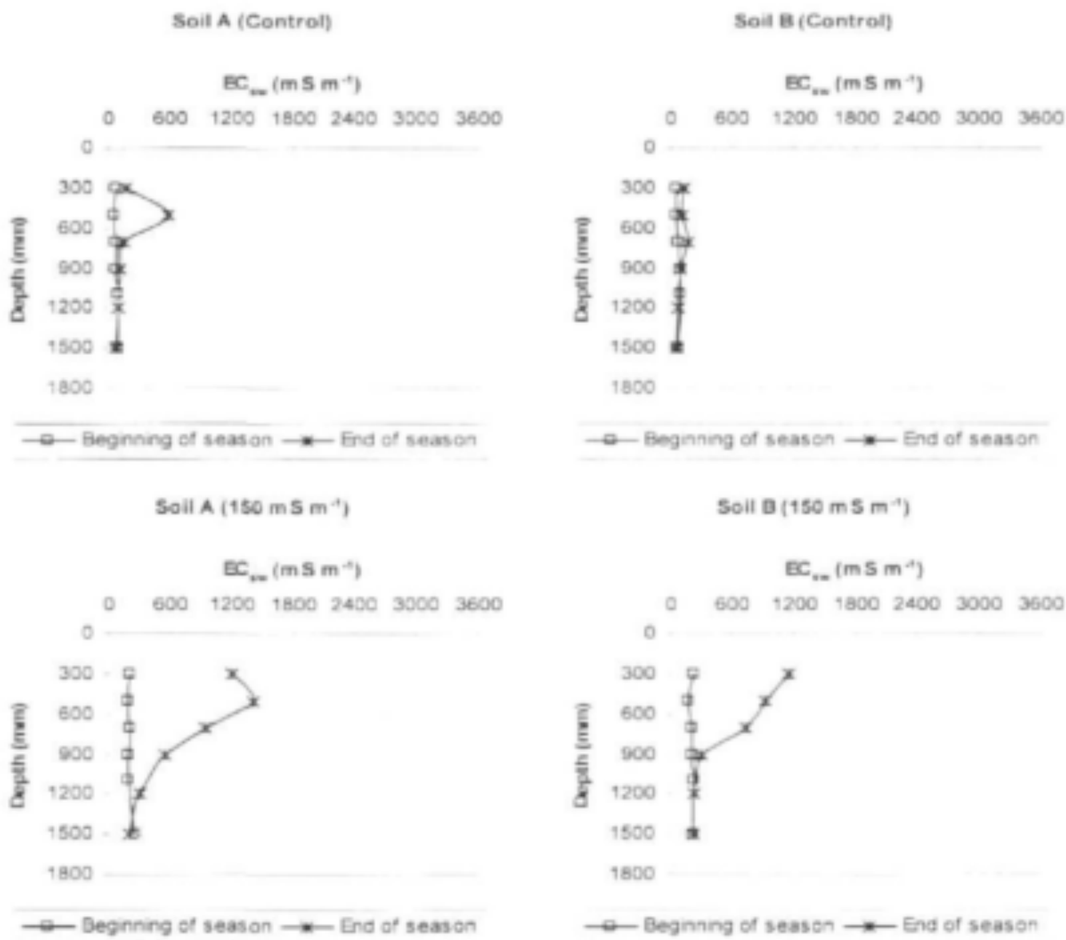

Figure 5.4 continue

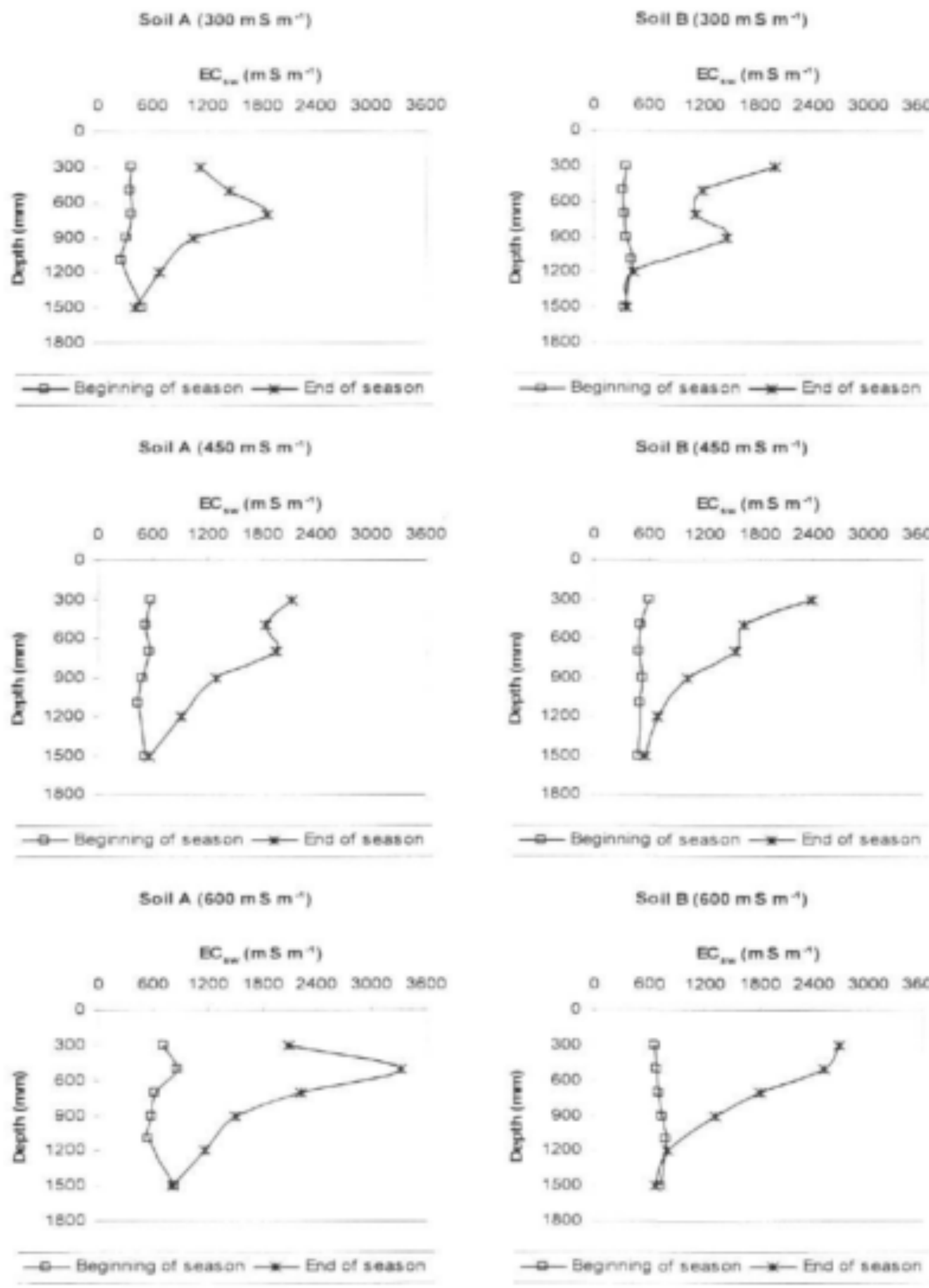

Figure 5.4 Soil water salinity profiles at the beginning and end of the maize growing season for all the EC_i treatments of both soils.

5.3.2 *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 causes rapid salinisation of soil layers above the water table in the capillary zone, where leaching is restricted. Ehlers *et al.* (2003) gave an equation for the relationship between the height of capillary rise above a water table, and the silt-plus-clay contents of different soils. Using the average silt-plus-clay contents of 8.25% and 16% for Soils A and B respectively, one can 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 5.5 to 5.8 presents the 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 whereas 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 4. 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.

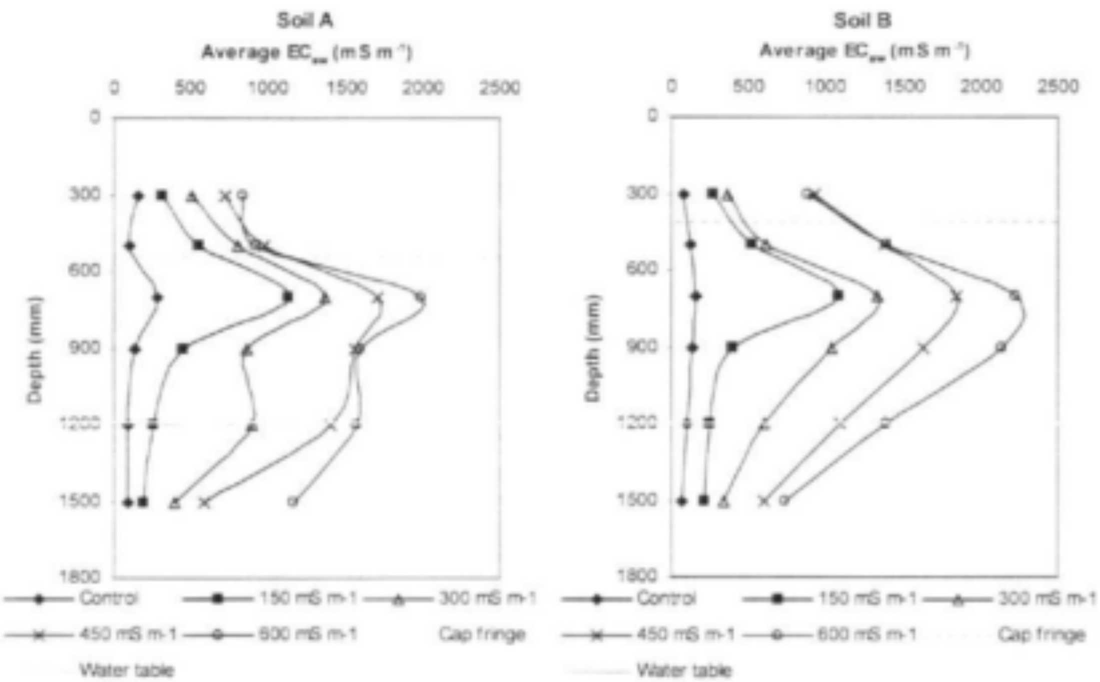

Figure 5.5 Salt distribution profiles (EC_{sw}, mS m^{-1}) at the end of the wheat growing season for all the EC_i treatments of Soil A and B.

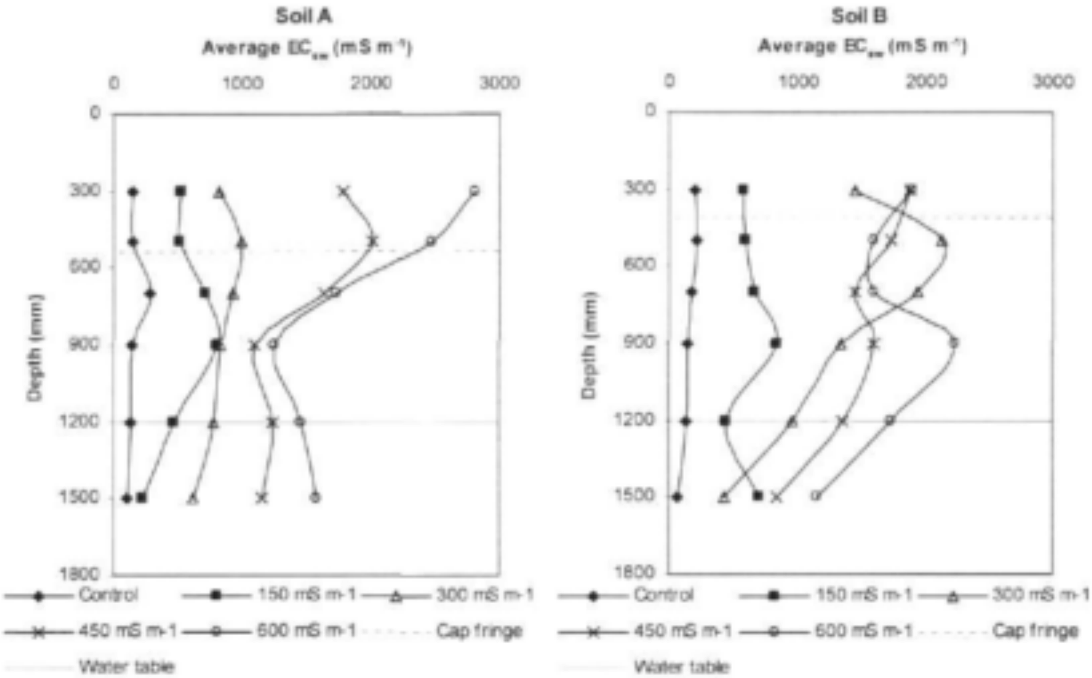

Figure 5.6 Salt distribution profiles (EC_{sw}, mS m^{-1}) at the end of the bean growing season for all the EC_i treatments of Soil A and B.

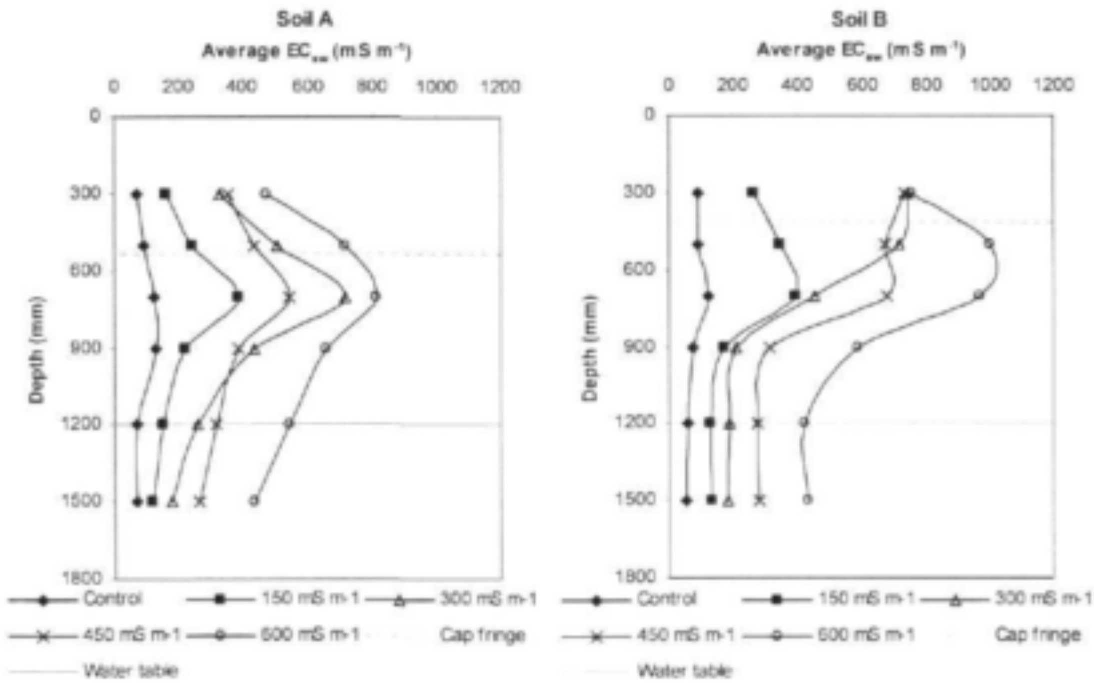

Figure 5.7 Salt distribution profiles (EC_{sw}, mS m^{-1}) at the end of the pea growing season for all the EC_i treatments of Soil A and B.

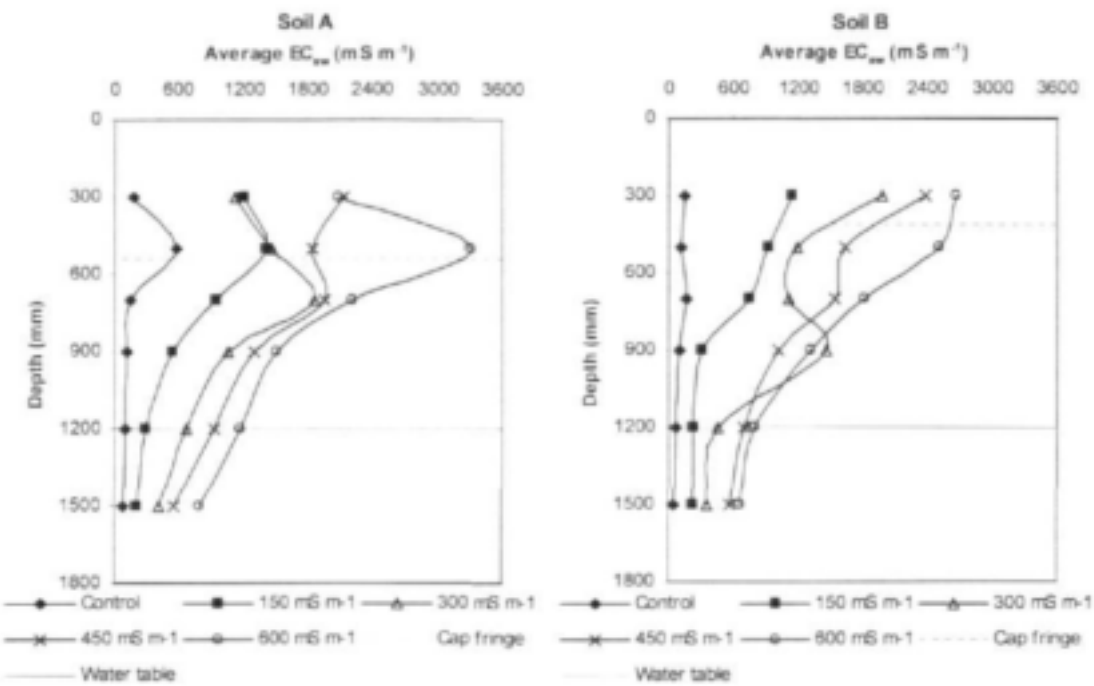

Figure 5.8 Salt distribution profiles (EC_{sw}, mS m^{-1}) at the end of the maize growing season for all the EC_i treatments of Soil A and B.

5.3.3 Verification of the conversion factor for electrical conductivity to total dissolved salts

The total dissolved salts (TDS, mg L^{-1}) was 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 4.2.3. 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 5.9). The same principle can be applied to convert the electrical conductivity of the irrigation water (EC_i) to total dissolved salts (TDS_i). Using the EC_i and TDS_i values as presented in Table 4.3, a constant of 7.831 was obtained, as shown in Figure 5.10.

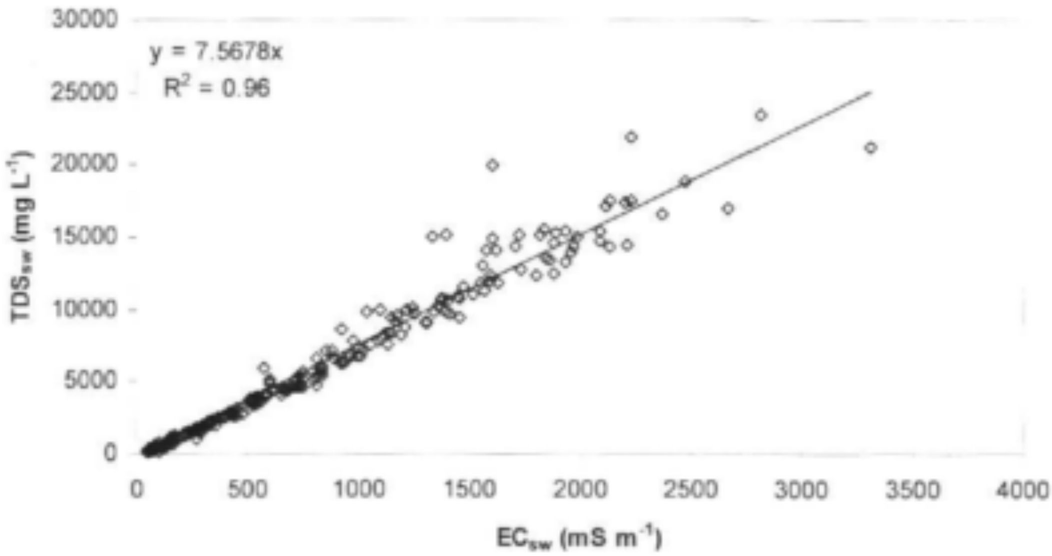

Figure 5.9 The relationship between the EC_{sw} and TDS_{sw} measured at the end of the growing season of all the crops, for both soils.

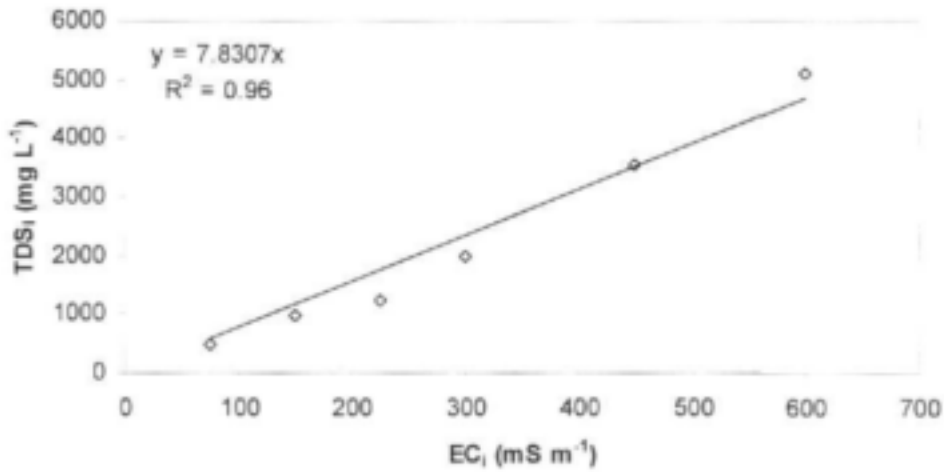

Figure 5.10 The relationship between the electrical conductivity of the irrigation water (EC_i) and the total dissolved salts (TDS_i).

5.3.4 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 as the amount 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 5.1). 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 5.10 illustrates the relationship between the increase in the mean EC_{sw} over a depth of 1800 mm (Table 4.10) and the amount of salt added through irrigation. The relationship indicates that for every 1000 kg of salt added through irrigation water, the mean EC_{sw} will increase with 37 mS m^{-1} over a depth of 1800 mm, irrespective of soil type.

Table 5.1 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 (liter)	TDS (mg L^{-1})	Salt added (kg ha^{-1})	ΔEC_{sw}	Soil	Treatment	IRR + WT (liter)	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 (liter)	TDS (mg L^{-1})	Salt added (kg ha^{-1})	ΔEC_{sw}	Soil	Treatment	IRR + WT (liter)	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

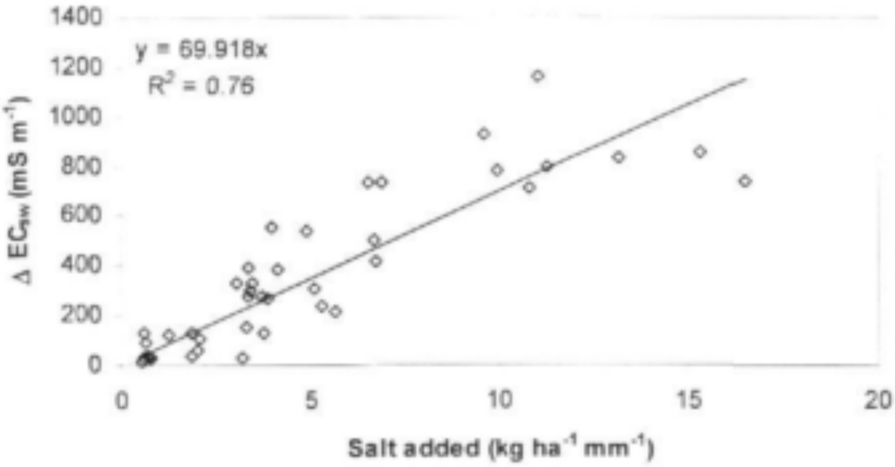

Figure 5.11 The relationship between the increase in soil water salinity and the amount of salts added through irrigation and water table uptake.

5.3.5 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 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 5.11) to obtain the estimated increase in the mean EC_{sw} of the root zone (Equation 5.1). 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} per 1800 mm) can be predicted after each irrigation cycle using Equation 5.1. The application of Equation 5.1 will be discussed in Chapter 7. Under saturated soil conditions it can be assumed that ΔEC_{sw} will be comparable to ΔEC_e. See explanation in Section 3.3.2.2.

$$\Delta EC_{sw} = [(EC_i \times \text{Cum IR} \times 0.0783)/z] \times 69.918 \qquad (5.1)$$

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)

5.4 Conclusions

When soils with restricted drainage are irrigated with salt containing water, the salts added through irrigation will accumulate in the root zone. The amount of salt in the irrigation water determines the long term salt accumulation and distribution in a soil profile. In the presence of shallow water tables, it was found that most of the salt will accumulate within the capillary zone, especially in the upper half.

It was also found that the yield of crops, which are sensitive to soil salinity, will be reduced when grown on these soils. This reduction in yield will be determined by the rate at which salts accumulate within the root zone. The accumulation of salts in soils with limited drainage, can be predicted for any known quality and quantity of irrigation water, using Equation 5.1. This allows for the prediction of the decline in yield of different crops (Section 4.3.4.2).

CHAPTER 6

REMOVAL OF EXCESS SALTS FROM SALINE APEDAL SOILS

6.1 Introduction

Poor management of irrigated land will inescapably lead to the build up of salts in the root zone due to removal of water by the crops or transpiration and evaporation from the soil surface (Van der Merwe, 1975). Sustainable utilization of this land depends heavily on the drainage strategies employed. On-farm drainage strategies are influenced by many processes related to water and solute movement as explained in standard soil physical text books (Marshall *et al.*, 1996; Hillel, 1998; Jury & Horton, 2004). Basic knowledge of the processes as well as the factors that influence salt build up is important for formulating strategies on salt removal and disposal. The main aim of this chapter is to focus on the removal of salts from apedal soils. Although sodic soils are excluded from the scope of this project it is still acknowledged as an important field of study, mainly due to the structural breakdown of soils and corresponding loss in hydraulic conductivity (Van der Merwe, 1975). The two soils to be studied represent deep Clovelly and Bainsvlei soil types (Soil Classification Working Group, 1991). The orthic A on a red or yellow-brown apedal B horizon sequence are commonly used for irrigation, especially in the arid bioclimatic zones of South Africa. These soils also tend to form water tables in lower lying landscapes where over-irrigation is practised. If not artificially drained it quickly becomes unproductive due to capillary rise of water and salts into the root zone. Under-irrigation however leads to the accumulation of salts, especially where overhead irrigation systems, such as centre pivot and linear irrigation systems are used (Du Preez *et al.*, 2000). This chapter will specifically address (i) the effect of salinity on the drainage characteristics of apedal soils, (ii) salt removal as affected by irrigation water of a high quality; and (iii) development of leaching equations that includes variables such as rooting depth, initial soil water salinity and irrigation water salinity that can be applied in the management of salinity.

6.2 Materials and methods

All the experiments were conducted at the Field Research Facility of the Department of Soil, Crop and Climate Science, University of the Free State at Kenilworth near Bloemfontein. Consult Section 4.2.1 for a description and layout of the lysimeter unit that was used.

6.2.1 Experiment 1: Drainage of saturated soils

After harvesting of the maize trial, the soils in the lysimeters were saturated over a period of two days with the same quality of irrigation water used in the trial. As reported in Section 4.2.3 there were five irrigation water quality treatments, viz. T1 = 15, T2 = 150, T3 = 300, T4 = 450 and T5 = 600 mS m^{-1}. The average amount of water applied to saturate the soils was 267 mm for Soil A and 211 mm for

Soil B. Soil water was then extracted through ceramic suction cups that were installed at different depths as described in Section 5.2.1. The electrical conductivity of the soil water (EC_{sw}, mS m^{-1}) from the suction cups was measured with an Ecoscan electrical conductivity meter. These water samples were further analyzed for dissolved cations (Ca, Mg, Na and K) and anions (Cl, SO_4) using standard procedures (The Non Affiliated Soil Analysis Work Committee, 1990).

6.2.1.1 Measurements

Plastic covers were placed on the soil surface of the lysimeters to prevent water loss through evaporation. The manometer and bucket connected to the bottom of the lysimeters were disconnected in order to allow the water to drain from the soil. Drainage water was collected in 10 L buckets, via the drain-outlet of each lysimeter. The number of buckets and time intervals were recorded on a 24 hour basis throughout the entire measuring period of 27 days.

The cumulative drainage volume (mm) per lysimeter was regressed against time (days), using the rational function ($y = a + bx^{-1} + cx + dx^2$) of the software package Curve Expert of Hyams (1995). The statistical results are summarized in Appendix 6.1 for each lysimeter of both soils. It can be assumed that this method provides an accurate description of cumulative drainage as the R^2 values are constantly higher than 0.98 for all the lysimeters. The resulting cumulative drainage curves were then used to calculate drainage rates on a daily basis. During the entire drainage period the electrical conductivity of the drainage water (EC_d, mS m^{-1}) was measured daily.

Volumetric soil water content was measured with a CPN 503 DR hydroprobe neutron water meter (NWM) at 300 mm intervals to a depth of 1800 mm from the soil surface. Water content measurements were done three times during the first 24 hours, twice during the second 24 hours, after which only one measurement was taken every other day until the 27^{th} day after saturation. Drainage (D, mm) was calculated indirectly from the change in soil water content measurements (ΔW, mm) made with the NWM assuming that precipitation, evaporation, transpiration and runoff were zero (Equation 6.1):

$$D = -\Delta W = -(W_i - W_{i-1}) \qquad (6.1)$$

where i is a specific time (days) of measurement.

Drainage obtained with Equation 6.1 was plotted as cumulative drainage versus cumulative time and then regressed with the above-mentioned rational function.

6.2.1.2 Neutron water meter calibration

It was not possible to calibrate the NWM with the standard procedure of gravimetric soil water and bulk density measurements. An indirect method was applied as an alternative procedure. In this procedure the directly measured cumulative drainage was compared with the drainage calculated indirectly using Equation 6.1. The measured and calculated drainage were then plotted against each other to determine the deviation from a 1:1 fit. The slope of the original calibration function of the NWM (Equation 6.2) was adjusted with small increments, and the procedure repeated until the best fit was observed.

$$\theta = 18.68CR - 0.779 \tag{6.2}$$

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

The best fit for Soil A was obtained with a slope of 21 for T1 and T2, and 23 for T3, T4 and T5. In the case of Soil B a slope of 21 for T1, and 22 for T2, T3, T4 and T5 gave the best fit. The 1:1 cumulative drainage graphs, presented in Figure 6.1 for both soils, showed good correspondence between the direct and indirect methods. The R^2 values were above 0.85 for both soils and the slopes were close to 1. For future use of the indirect method the adjusted slopes can be used.

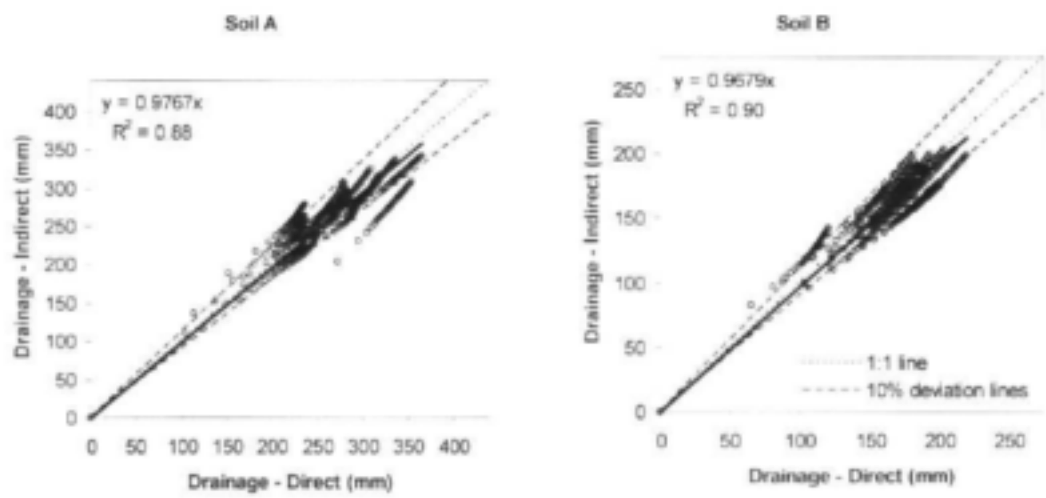

Figure 6.1 Comparison of the indirectly calculated cumulative drainage, using the calibrated CPN, with the directly measured values for all the lysimeters of both soils.

6.2.2 Experiment 2: Leaching with good quality irrigation water

The layout of experiment 2 was similar to experiment 1 except that all the treatments were irrigated with water of the same quality, viz, 75 mS m^{-1}. The soil water salinity of the treatments, at the end of experiment 1, was taken as the starting point for soil water salinities of experiment 2. At this stage the average EC_{sw} for T1, T2, T3, T4 and T5 were 85, 261, 315, 521 and 671 mS m^{-1} for Soil A and 83, 271, 467, 547 and 1014 mS m^{-1} for Soil B, respectively.

Before irrigation started with the 75 mS m^{-1} water, the water content of the soil was near the drained upper limit (DUL). Both soils were irrigated by flooding the surface with a depth of 50 mm water per irrigation event. Two irrigations per week were applied for seven weeks giving a total of 700 mm. The amount of water that drained from the bottom of each lysimeter was measured directly and calculated indirectly by using the data from the NWM measurements. Direct measurements were made daily by opening the drained-outlet at the bottom of the lysimeter every morning and closing it every evening. The measured volume of drainage water was converted to depth (mm). Drainage water from every lysimeter was stored in a separate container, it was thoroughly stirred daily and the electrical conductivity measured as described earlier (EC_d, mS m^{-1}). The soil surface of the lysimeters was covered with a plastic sheet to prevent evaporation (E), except for 2-3 hours per day when the soil water measurements were made or when irrigations were applied. For the entire period the lysimeter unit was covered by a rain shelter to prevent rain from entering the lysimeters and to restrict E during measurements.

6.2.3 Experiment 3: Leaching with a range of irrigation water salinities

For the third experiment leaching of the lysimeters with a range of irrigation water salinities was done between harvesting of the bean crop and planting of the peas. This period stretched over 9 weeks from May to July 2004. The salts accumulated in the soil over two growing seasons, viz that of wheat and beans. The profiles were leached with the following irrigation water salinities: T1 = 15, T2 = 75, T3 = 150, T4 = 225, T5 = 300 mS m^{-1}. Six irrigations were given during the leaching period, which amounted to 848 mm for Soil A and 911 mm for Soil B. Soil water was extracted through the suction cups and the EC_{sw} was determined as explained for experiment 1. Drainage was measured manually over the entire period, following the same procedure as described for experiment 2. Unfortunately the electrical conductivity of the drainage water was not measured, so it was impossible to calculate the salts removed.

6.3 Results and discussion

6.3.1 Drainage of saturated soils with decreasing soil water salinities

As described in Section 6.2.1 experiment 1 was designed to simulate conditions where saturated soils, containing different amounts of salts, are drained artificially.

6.3.1.1 Salinity status of the soils

The composition of the salts in the irrigation water was selected to represent the quality of the lower Vaal River system. The sodium adsorption ratio (SAR) of all the water treatments were below 5, while the EC_i of the water increased from treatment T1 (15 mS m^{-1}) to T5 (600 mS m^{-1}). During the maize experiment no drainage occurred as a constant water table was maintained at 1.2 m from the soil surface. On average a total of 612 mm was irrigated during the maize experiment, which inevitably lead to the build-up of salts in the profiles. The average EC_{sw}-values during the growing season of maize for T1 to T5 were 139, 489, 734, 968 and 1272 mS m^{-1} for Soil A, and 84, 400, 721, 912 and 1105 mS m^{-1} for Soil B (Table 4.10).

According to Gupta & Abrol (1990), soils with an EC_e < 400 mS m^{-1} are classified as non-saline. Saline soils have EC_e values > 400 mS m^{-1} and SAR values < 15, while sodic soils have SAR values > 15. Following these criteria, treatment T1 of both Soil A and Soil B, represent the non-saline soils, while treatments T2 to T5 of both soils represent the saline soils. None of the treatments for both soils have SAR values above 15.

From the clear relationship (R^2 > 0.78) between the electrical conductivity of the irrigation water and the increase in ΔEC_{sw} during the maize season as displayed in Figure 6.2, it can be concluded that 612 mm irrigation almost doubled the EC_{sw} over the growing season.

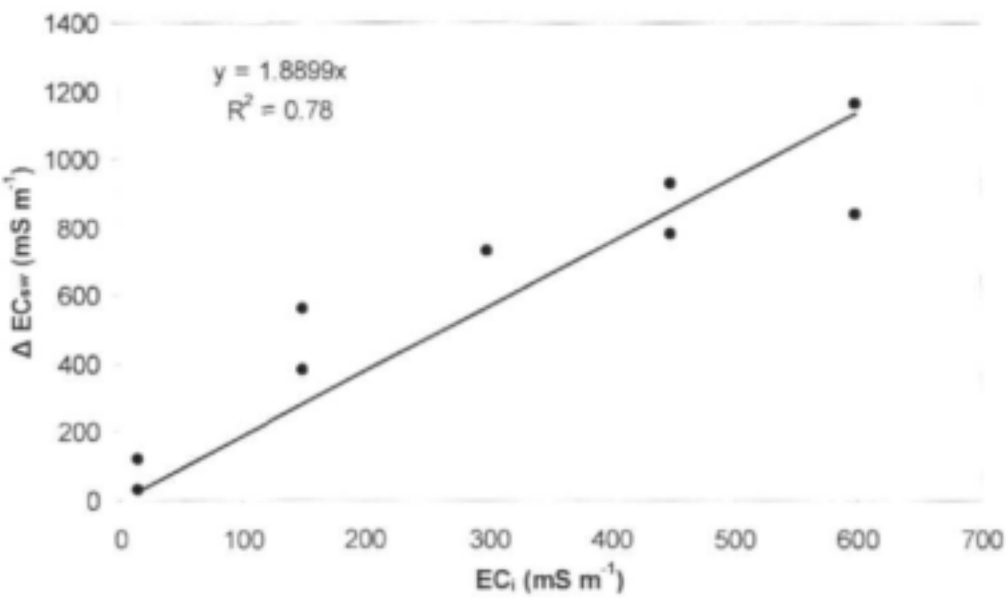

Figure 6.2 Influence of irrigation water salinity (EC_i) on the increase of soil water salinity (ΔEC_{sw}) after 612 mm irrigation.

The importance of this observation can be illustrated with Soil B. For example, irrigating a water table soil with water of which the EC is 200 mS m^{-1} will convert a non-saline soil (EC_{sw} = 225 mS m^{-1}) to saline within only one season, with an estimated EC_{sw} = 426 mS m^{-1}.

6.3.1.2 Effect of deteriorating soil water salinity on drainage

Results from the previous section indirectly illustrate the importance of drainage as the soil water salinity deteriorates linearly with an increase in the electrical conductivity of the irrigation water under restricted salt leaching. This section focuses on the effect of soil salinity on free drainage from a saturated soil. The volume of collected drainage water was used to construct cumulative drainage versus time curves for each lysimeter (Appendix 6.1). From these drainage curves three periods were selected to represent fast, moderate and slow periods of drainage, viz. 0-2 days, 2-5 days and 5-27 days. The average drainage rates were 112, 9.5 and 1.6 mm day^{-1} for Soil A and 69, 5.8 and 1.6 mm day^{-1} for Soil B, respectively. The computed drainage rates were also regressed against the measured EC_{sw} at the start of experiment 1, for each drainage period of both soils (Figure 6.3). In general the graphs demonstrate a small improvement in drainage rates associated with deteriorating soil water conditions, except for the moderate drainage period of Soil A where a negative response can be observed.

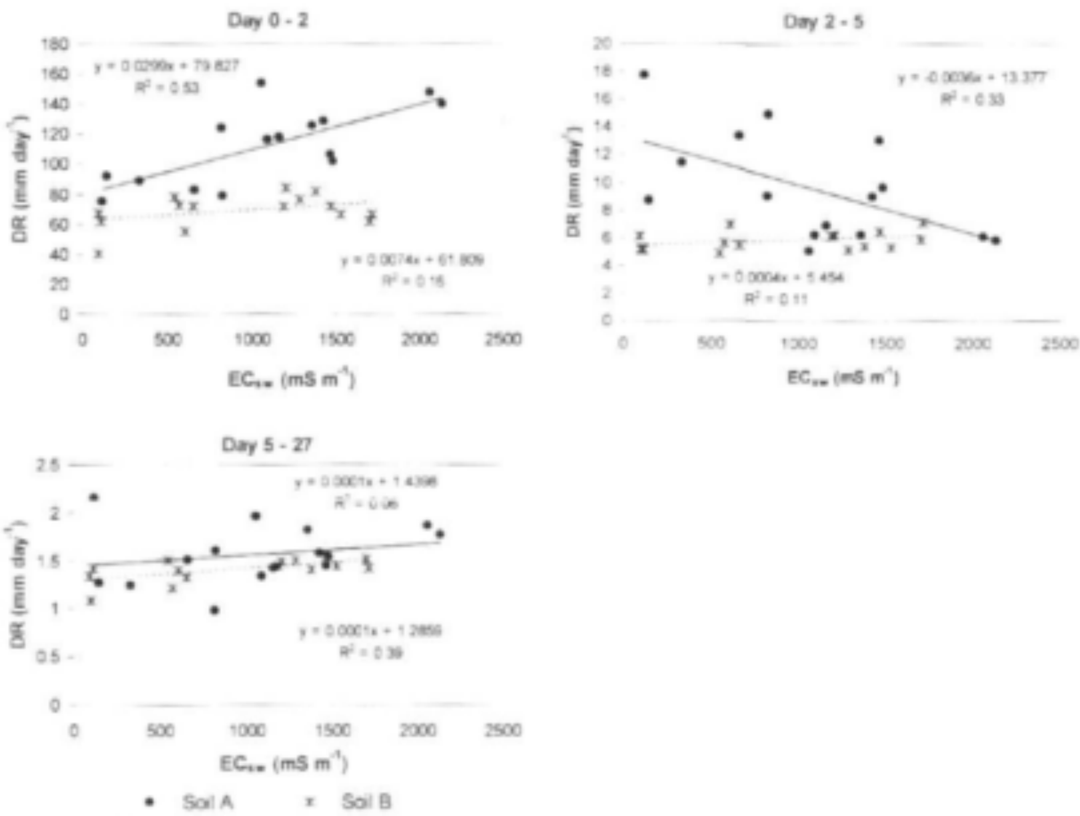

Figure 6.3 Influence of electrical conductivity of the soil water (EC_{sw}) on drainage rates (DR) for both soils.

The positive trend could be attributed to a thinner electrical double layer associated with higher electrolyte concentrations of the bulk soil solution (Bohn *et al.*, 1985). The negative slope of the moderate drainage period for Soil A indicates a reduction in drainage, which is closely related to sodic soils where swelling and clay dispersion normally blocks the soil pores. This phenomenon normally leads to a reduction of the hydraulic conductivity of the soil (Tedeschi & Dell'Aquila, 2005). It is highly unlikely that clay dispersion occurred because no traces of clay-sediment could be found in the drainage water.

The small improvement, however, was never significantly correlated with an increase in deteriorating water salinity, except between treatments T1 and T5 of Soil A. Bohn *et al.* (1985) also demonstrated that the changes in the thickness of the electrical double layer normally occur over small distances (nm). Following this theory the results indicate that the magnitude of compression of the double layer was probably not enough to improve the drainage of both soils. For practical reasons this improvement is assumed to be insignificant, the conclusion being that soil water salinity will not affect the drainage rates of apedal soils as long as the SAR values of the irrigation water are below 5 in the absence of clay dispersion.

6.3.1.3 Soil water content versus time relationships

Drainage curves derived from *in situ* measured soil water content-time functions (Appendix 6.2), as described by Ratliff *et al.* (1983), is commonly used to estimate the drainage component of the field water balance (Hensley *et al.*, 1993; Bennie *et al.*, 1994; Van Rensburg, 1996; Bennie *et al.*, 1998; Hensley *et al.*, 2000; Van Staden, 2000 and Botha *et al.*, 2003). Similar curves were computed for each soil lysimeter and the calculated drainage compared well with the corresponding measured drainage (Section 6.2.1.2). Due to the fact that soil water salinity did not apparently affect the slope of the curve, all data was combined and a single drainage curve was compiled for each soil type (Figure 6.4). The regression coefficients (R^2) in Figure 6.4 revealed that the drainage is well described for both soils. These curves also show prominent differences between the two soils, especially after the first two days following saturation (DAS). Despite the fact that both soils are apedal, the total drainage was almost twice as large for the more sandy Soil A (212 mm) in comparison with the more clayey Soil B (135 mm) at 2 DAS. This is probably due to a larger proportion of macro pores in Soil A, compared to Soil B. Soil B retained 523 mm water compared to the 456 mm of Soil A.

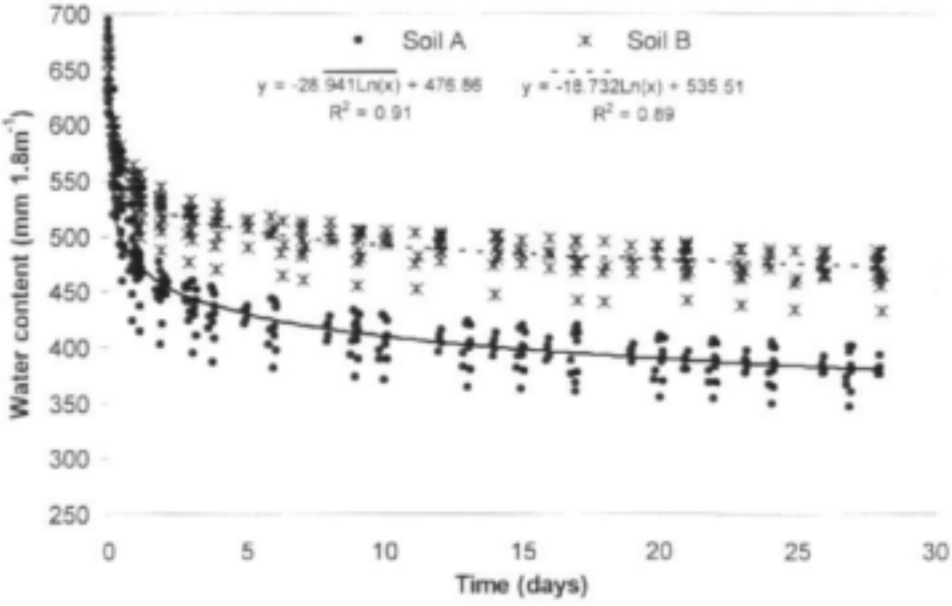

Figure 6.4 Water content versus time, for the 1.8 m profiles of both soils, for all the lysimeters.

The drained upper limit (DUL) was selected according to the guidelines of Ratliff *et al.* (1983), viz. the water content corresponding with a slow drainage. During day 27 the drainage rates were 1.1 and 0.7 mm day^{-1} for Soil A and Soil B, respectively. These rates correspond to mean DUL-values of 381 and 474 mm 1800 mm^{-1} for Soil A and B, respectively. Field saturation was measured to be 668 and 658 mm 1800 mm^{-1}, for Soil A and B respectively, which suggest that the bulk densities are also similar or closely related. Unfortunately this theory could not be tested as it was not possible to measure the bulk densities because it was decided not to disturb the soil profile in the lysimeters at this stage. An attempt was made to calculate an average bulk density for the profile from the measured field saturated water content values, assuming that 5% of the pores contain air. The estimated values seem to be realistic and amounts to 1617 and 1633 kg m^{-3} for Soil A and Soil B, respectively. Zeleke (2003) measured the bulk densities of the Bainsvlei soil in its cultivated state, using 200 mm depth intervals over the 1.6 m profile. The average value amounted to 1658 kg m^{-3} and appears to be slightly higher than the estimated values of the Bainsvlei soil in the lysimeters. Zeleke (2003) also calculated the drainage of the profile to be 0.84 mm day^{-1} on 26 DAS, using the internal drainage method of Hillel *et al.* (1978). The corresponding drainage estimated with the drainage curve obtained from the lysimeters amounted to 0.7 mm day^{-1} on the same day.

6.3.1.4 Quantifying salt removed during a complete drainage cycle

The average total drainage measured per treatment during the experiment is summarized in Table 6.1 for both soils. On average the drainage for Soil A was 54% more than that of Soil B. The total drainage for T1 to T5 varied between 242 and 334 mm for Soil A and between 158 and 199 mm for Soil B. As the electrical conductivity of the drainage water (EC_d) was regularly measured during the drainage period an attempt was made to determine a relationship between EC_d and time after saturation. Extremely poor relationships were obtained (data not shown), which indicated that salt concentration had little effect on the drainage rate.

Consequently the average EC of the drainage water, total volume of drained water and the area of the lysimeters per treatment over the entire drainage period was used as constants for computing the total amount of salts removed in kg ha^{-1} (Table 6.1). The total dissolved salts of the drainage water (TDS_d, mg L^{-1}) were calculated by multiplying EC_d (mS m^{-1}) with a factor of 7.568 (Section 5.3.3). The full data set is given in Appendix 6.3.

Table 6.1 Average electrical conductivity of drainage water (EC_d), cumulative drainage ($\sum D$) and cumulative salt removal ($\sum SR$) for both soils

Soil type	Soil A			Soil B		
Treatments	**EC_d (mS m^{-1})**	**$\sum$ D (mm)**	**$\sum$ SR (kg ha^{-1})**	**EC_d (mS m^{-1})**	**$\sum$ D (mm)**	**$\sum$ SR (kg ha^{-1})**
T1	108	242	1975	67	158	808
T2	428	258	8435	275	195	4066
T3	777	312	18171	544	192	8004
T4	1094	289	23993	738	199	11147
T5	1381	334	34901	954	186	13448

Depending on the treatment a single drainage cycle of Soil A removed between 1 975 and 34 901 kg salts ha^{-1}, while Soil B discharged between 808 and 13 448 kg salts ha^{-1}. The results indicate clearly that there is a relationship between salt discharged or removed and the initial salt concentration of the soil and that more salts were discharged from the more sandy Soil A than from the more clayey Soil B.

The rate of salt removed (kg salt ha^{-1} mm^{-1} drainage at 1800 mm depth) was calculated and regressed against measured EC_{sw} at the start of experiment 1 by forcing the regressions through the zero co-ordinates. As shown in Figure 6.5 the relationships illustrate that the salt removal rate is a function of the texture and salt content of the soils. The constant amount of salts that were discharged per ha per mm water drained per EC_{sw} (mS m^{-1}) as indicated by the slope of the linear relationship (Figure 6.5), is an indication that the volume of drained water is very similar among the salinity treatments.

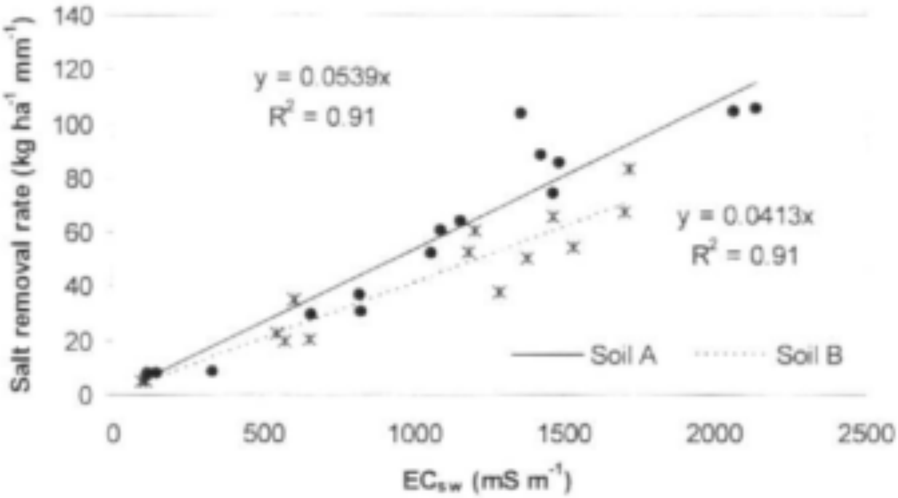

Figure 6.5 Salt removal rate (kg salts ha^{-1} mm^{-1} drainage below 1800 mm depth) of all the lysimeters for both soils as a function of the electrical conductivity of the soil water (EC_{sw}).

6.3.2 Salt removal through leaching with good quality water

As described in Section 6.2.2 experiment 2 simulates conditions where a saline soil is reclaimed by leaching with good quality water.

6.3.2.1 Water balance

Salts that accumulated in the lysimeters during the different treatments of the maize trial were removed through leaching by periodically applying 50 mm good quality water with an EC of 75 mS m^{-1}. In Figure 6.6 the irrigation frequency intervals can be followed for the 50-day leaching period. The actual measured soil water content of the profiles (Appendix 6.4), expressed as the average of 15 lysimeters, is also displayed in Figure 6.6.

In the case of Soil B, the water content varied in a narrow band between 520 and 570 mm, after the initial irrigations were completed, which was higher than the DUL of 474 mm 1800 mm^{-1}. The water content of Soil A varied from 445 to 510 mm between irrigations which is higher than the DUL of 381 mm 1800 mm^{-1}. Soil A which is more sandy than Soil B also showed a slightly higher decrease in water content between irrigation intervals due to more rapid movement of drainage water. However at the end of the 50 day measuring period, the measured cumulative drainage was approximately similar, viz. 588 and 590 mm for Soil B and Soil A respectively. Using the water balance equation to calculate evaporation ($E = \Delta W + I - D$) gives a total E value of respectively 93 and 76 mm for Soil B and Soil A over the measuring period.

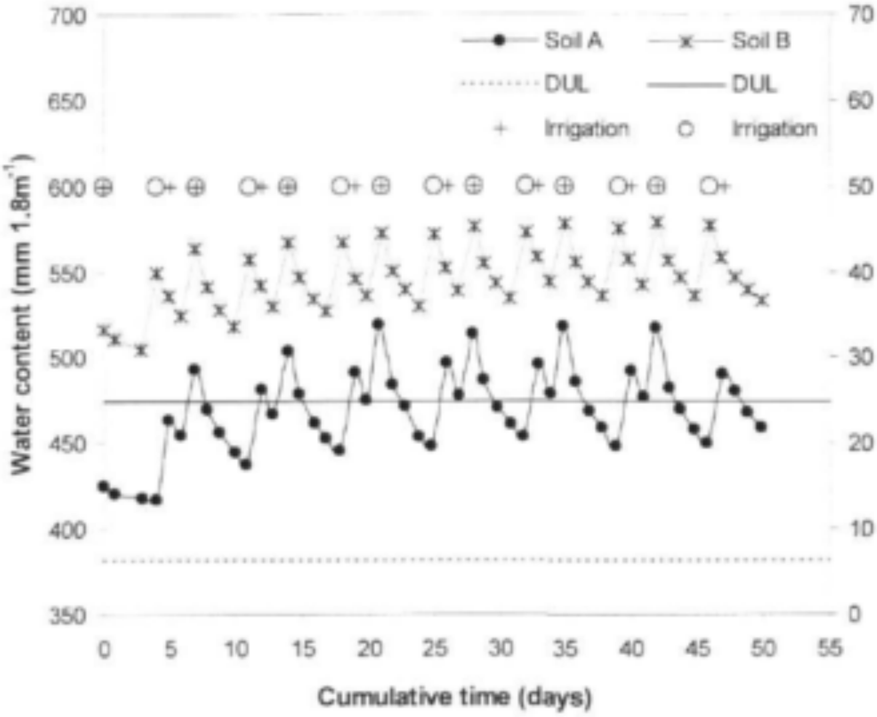

Figure 6.6 Average water content and time of irrigation during the leaching period for both soils.

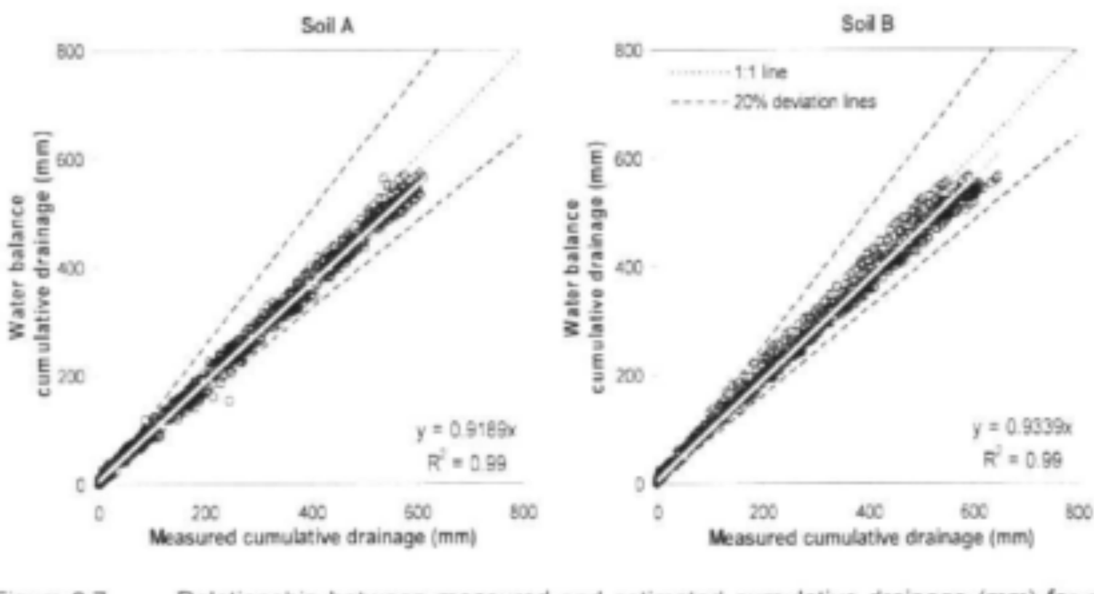

Figure 6.7 Relationship between measured and estimated cumulative drainage (mm) for all the lysimeters of both soils.

To illustrate an alternative method, the daily drainage was also computed using the water balance equation ($D = \Delta W + I - E$), with daily values of ΔW and E as inputs. Daily E was taken as the total E divided by the number of measuring days, resulting in 1.9 and 1.5 mm day^{-1} for Soil B and Soil A, respectively. The cumulative drainage calculated in this manner was compared with the actual measured data in Figure 6.7. An excellent correlation ($R^2 > 0.95$) was found between measured and estimated values. The slope of the linear regression lines was close to one, which confirmed the accuracy between the measured and estimated values. The average daily drainage rate of the two soils, under these conditions, was 11.8 mm day^{-1}.

6.3.2.2 Salt removal

It was assumed that the water extracted through the suction cups represents the salt concentration of a wet profile. Therefore the average EC_{sw} of the six soil layers was used to give the mean salt concentration of the soil water in the profile. The decline in the mean EC_{sw} of both soils as affected by cumulative drainage is displayed in Figure 6.8 while the full data set is presented in Appendix 6.5.

In general the control (T1) showed no significant change in salt concentration with an increase in drainage for both soils, indicating that the EC_{sw} was in equilibrium with the applied irrigation water (± 75 mS m^{-1}). The decrease in salt concentration is best described by a semi-logarithmic function ($y = a \ln x + b$), indicating that salt removal is very efficient over the first 100 mm of drainage, where after the efficiency declines as more water is needed for reducing a unit EC_{sw}.

It seems that Soil B will require more water to remove the salts, as the EC_{sw} of treatment T5 was still at 142 mS m^{-1}, after 550 mm of drainage water passed through the profile, while all the treatments of Soil A were in equilibrium with the irrigation water. The R^2 values of the regressed semi-logarithmic functions for treatments T2 to T5, varied between 0.94 and 0.95 for Soil A and 0.82 and 0.91 for Soil B respectively.

Salt removal was also expressed on a relative basis, in other words, as a fraction of the maximum actual salt removed (kg ha^{-1}) for a specific treatment. Appendix 6.6 provides a data set of the measured drainage (mm) as well as EC_d over the leaching period of 50 days. The total amount of salts removed (kg ha^{-1}) were calculated by multiplying EC_d with a constant factor of 7.568 in order to obtain TDS_d which is then multiplied by the volume of drainage water for that specific day. Then the actual measured maximum quantity of salt removed is obtained by subtracting the salts added with irrigation water from the total salts leached.

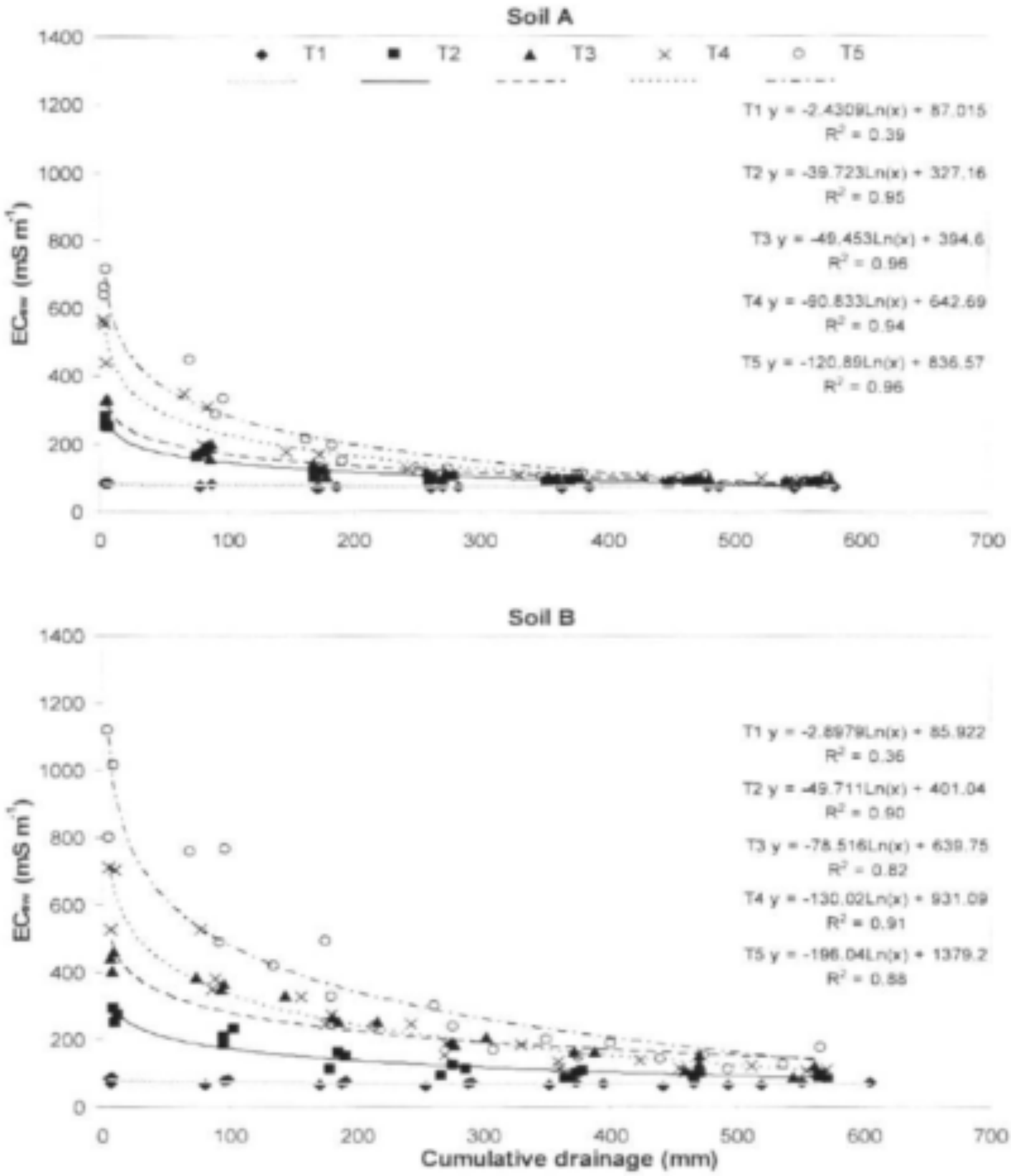

Figure 6.8 The average electrical conductivity of the soil water (EC_{sw}) over a depth of 1800 mm, for the entire leaching period for both soils.

This approach gave a single mathematical function for describing salt removal as a function of drainage per soil type, irrespective of the salt concentration of the profile (Figure 6.9). Treatment T1 is not included here because no salts were actually removed as only the salts applied leached from the soils. The combined data of relative salt removal correlated well with the cumulative drainage (R^2 = > 0.98) for both soils. From the shape of the two curves it is clear that the economic use of water will play an important role in salt removal through leaching. For example in order to remove the first 50% of the salts in the profiles, 126 mm of drainage water was required for Soil A and 180 mm for Soil B. Removing the remaining 50% salts required approximately 3 and 2 times more drainage water.

Several studies used 80% removal levels as a guideline for determining the optimum amount of water required to manage salinity effectively.

Applying this approach to the soils revealed that Soil A will require 274 mm and Soil B 349 mm or 0.5 pore volume of drainage water per 1800 mm soil depth to remove 80% of the salts. It should be kept in mind that the amount of water required to wet the soil to DUL should be added to the above mentioned values. Other factors that will influence the amount of irrigation water needed is evapotranspiration, application efficiency of the irrigation systems, runoff etc.

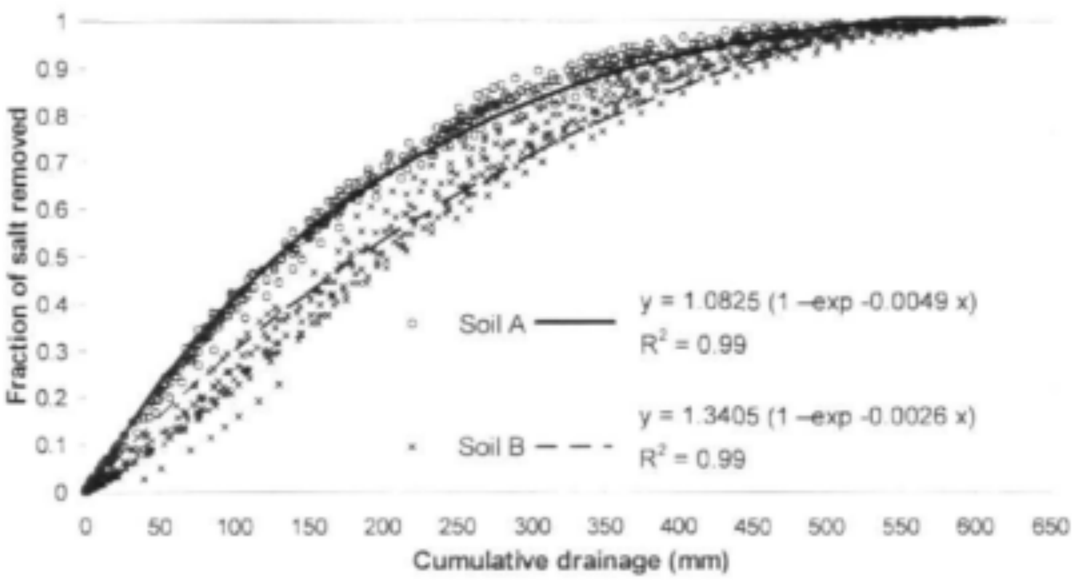

Figure 6.9 Cumulative drainage plotted as a function of the fraction of actual salt removed over a depth of 1800 mm for the two soils leached with good quality water (EC_i = 75 mS m^{-1}).

6.3.2.3 Change in salt distribution of profiles

Figure 6.10 illustrates the changing salt distribution patterns in the profiles after 2, 4, 6, 8, 10, 12 and 14 irrigations of 50 mm each with water of constant quality, namely 75 mS m^{-1}. The salt content for the various treatments and depths was expressed in EC_{sw} (mS m^{-1}) as measured in the water extracted with the suction cups. The 0 mm salt distribution line gives the EC_{sw}-values before the start of experiment 1 when the soil was saturated. All the other salt distribution lines correspond with the successive cumulative irrigation intervals.

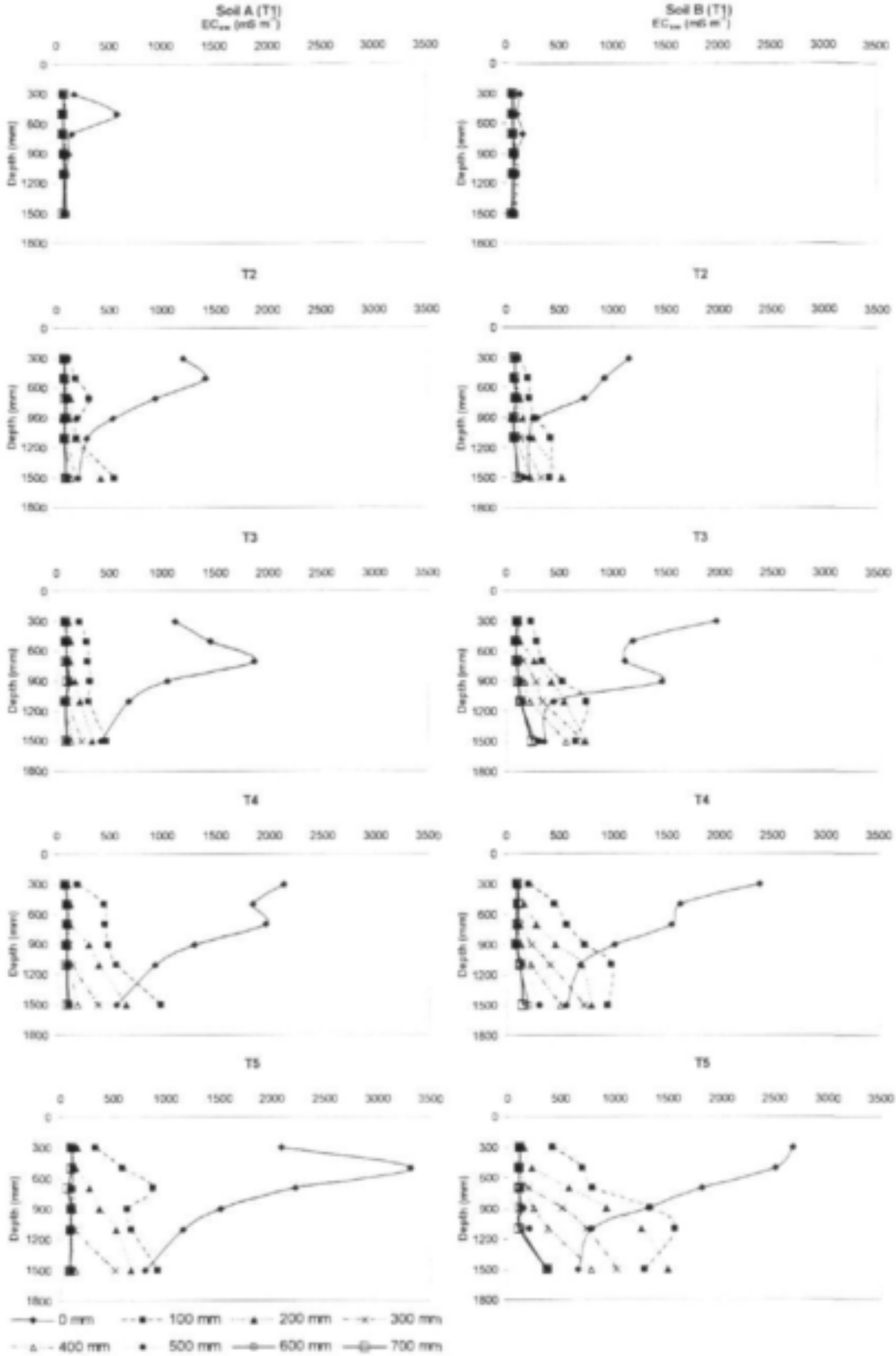

Figure 6.10 Change in salt distribution profiles of both soils, for the various treatments, during the entire leaching period of experiment 2.

After 100 mm of irrigation the salt distribution changed in comparison to the 0 mm line. The salt accumulation peak at 700 mm depth was largely removed as the salts were pushed downwards in the profile. This was induced by a complementary effect of internal drainage, as described in experiment 1, and leaching by the 100 mm irrigation applied during the first few days of experiment 2. Small amounts of water drained after the first two irrigations which total 100 mm as most of this water was stored in the profiles of both soils. The 100 mm irrigation line therefore represents the start of effective leaching of both soils.

From the third irrigation the salts in the profiles were removed and simultaneously pushed downwards. In Soil A the EC_{sw} of the top meter of the profiles were close to EC_i after 200 mm of irrigation was applied. For Soil B this stage was only reached after 300 mm of irrigation water was applied. The lag in response of Soil B can be ascribed to the lower drainage rates compared to Soil A.

6.3.3 Salt removal by leaching with different irrigation water salinities

As described in Section 6.2.3, experiment 3 simulates conditions where saline soils are reclaimed by using water with different salinities for leaching.

6.3.3.1 Salinity profiles and its leaching fraction

This experiment differed from the other two because the profiles were leached with different irrigation water salinities that varied from 30 to 300 mS m^{-1}. Leaching was done until the EC_{sw} equilibrated with EC_i. The average EC_{sw} for the soil profiles of the various treatments at the start of the leaching procedure were those measured at the end of the growing season for beans, and at the end of the leaching procedure were the target EC_{sw} values for peas. In Table 6.2 the amount of water irrigated and drained together with the drainage to irrigation ratios are presented. The full data set is given in Appendix 6.7.

The challenge was to develop a single equation for calculating the amount of leaching required at a specific irrigation water salinity to manage soil salinity. This seems simple, but involves simultaneous processes, like water drainage and solute movement. The problem is complicated as the EC_{sw} continuously change over time and depth during irrigation, as can be seen in the salinity profiles of Soils A and B presented in Figure 6.11. After each irrigation cycle the accumulated salts were pushed downward and out of the profile. The final EC_{sw} ended very close to the target EC_{sw} levels set for the pea experiment (Table 6.2).

Table 6.2 Mean EC_{sw}-values of the various salinity treatments at the end of the beans growing season, and the target values set for peas at planting

Parameter	Units	Soil type	Treatments				
			T1	T2	T3	T4	T5
End of beans	EC_{sw} (mS m^{-1})	A	158	544	835	1491	1888
		B	160	636	1372	1520	1698
Actual and (target) for peas	EC_{sw} (mS m^{-1})	A	53 (30)	117 (75)	124 (150)	251 (225)	397 (300)
		B	53 (30)	109 (75)	155 (150)	221 (225)	382 (300)
Irrigation	(mm)	A	848	848	848	848	848
		B	911	911	911	911	911
Drainage	(mm)	A	777	757	764	781	723
		B	799	850	803	855	814
Drainage : irrigation ratios		A	0.92	0.89	0.9	0.92	0.85
		B	0.88	0.93	0.88	0.93	0.89

A total of 848 mm was irrigated at Soil A, which resulted in drainage that varied from 723 to 781 mm among the treatments. Soil B required 63 mm more leaching than Soil A to reach the desired targets, while the drainage varied from 799 to 855 mm over the treatments. The ratios between the drainage and irrigation depth of water are listed in Table 6.2 and varied between 0.89 and 0.92 for Soil A and between 0.88 and 0.93 for Soil B. In fact the values should be close to one if water storage in the profile was zero and evaporation negligibly low. The application of so much extra water during the crop growing season, when ET dominates the water balance, is not practical. However, it provides sound information on salt removal in the absence of a crop as will be discussed in the next section.

6.3.3.2 Leaching curves

According to Hoffman (1980), *in situ* determined leaching curves provide reliable estimates of the quantity of water required to accomplish salt leaching. One of the various approaches that was developed is demonstrated in Figure 6.9. This type of leaching curve gives accurate information on the economical use of water for salt removal, as influenced by the soil and irrigation water salinity characteristics. The main disadvantages are that (i) its application is restricted to the quality of irrigation water to be used; (ii) it can only be applied to the same soil depth for which it was developed; and (iii) it is also only valid for a specific quality of irrigation water. Most of these disadvantages can be overcome by relating the ratio between the actual EC_{sw} to the initial EC_{sw} that is $EC_{sw\ actual}$ / $EC_{sw\ initial}$, with the depth of drainage (Dw) per unit depth of soil (Ds), that is Dw / Ds (Hoffman, 1980).

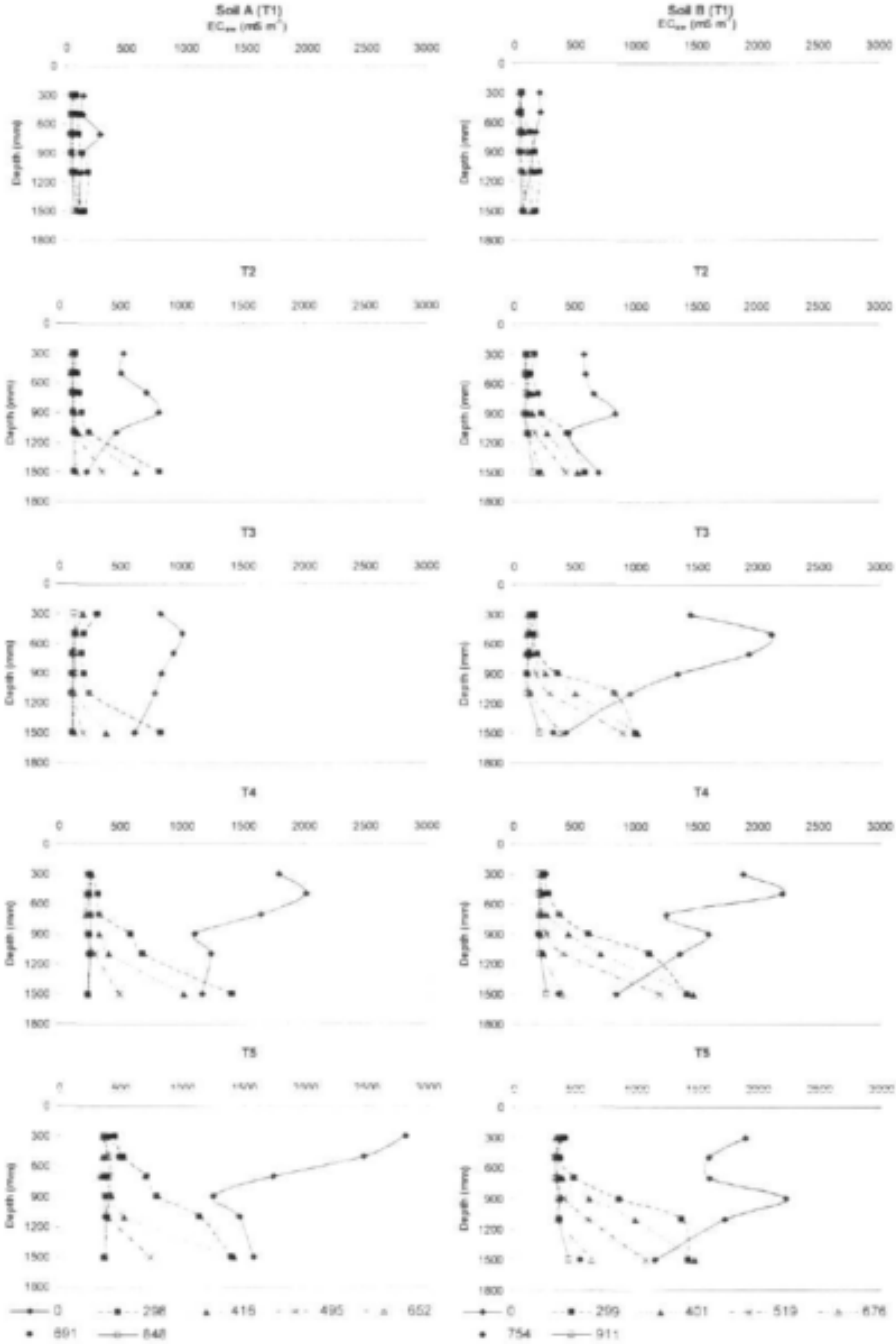

Figure 6.11 Change in salt distributions profiles of both soils, as affected by cumulative irrigation (mm) over the entire leaching period for experiment 3.

The data presented in Appendix 6.7 was used to calculate these ratios for different depth intervals of the profiles. Only the data that is not marked in bold, presents active salt removed and was used. Once equilibrium was reached the data was excluded. The ratios for the different treatments and soils are presented in Appendix 6.8. Graphical presentations of the relationship between [1 – ($EC_{sw\ actual}$ / $EC_{sw\ initial}$)] and Dw / Ds for the different treatments and soils are given in Figure 6.12. It is evident from these graphs that the optimal Dw / Ds ratio for all the salinity treatments (T2 – T5) was approximately 0.2. This value represents 200 mm drainage per meter soil depth to remove 65% or more of the salts.

Similar graphical solutions are presented by Dieleman (1963), demonstrating the non-linear relationship for a silty clay, clay and silty loam soil. These relationships are unique for soil types and irrigation water quality, as shown by Rao *et al.* (1986).

The different relationships for every treatment in Figure 6.12 could be combined, as proposed by Rhoades & Loveday (1990), by subtracting EC_i from the $EC_{sw\ actual}$ and $EC_{sw\ initial}$ values to give a dependent variable 1 – [($EC_{sw\ actual}$ – EC_i) / ($EC_{sw\ initial}$ – EC_i)]. Its relationship with Dw / Ds is presented in Figure 6.13 for the two soils. The general equation describing the relationship is y = a (1- exp –cx) where the parameter a should theoretically be one, and the parameter b should be a function of the drainage characteristics of the soil. The two equations for Soil A and B are:

Soil A: $y = 0.9468\ 1 - e^{-10.1543x}$ $\qquad R^2 = 0.91$ (6.3)

Soil B: $y = 0.9732\ 1 - e^{-7.3476x}$ $\qquad R^2 = 0.90$ (6.4)

It can be concluded from Equations 6.3 and 6.4 that the absolute value of parameter b increases with more rapid drainage of more sandy soils and *vice versa*.

Equations 6.3 and 6.4 must be rearranged to calculate Dw:

$$Dw = [(\ln(-y/a + 1)) / c]\ Ds \qquad (6.5)$$

where y = 1 – ($EC_{sw\ actual}$ – EC_i) / ($EC_{sw\ initial}$ – EC_i)

a = 1 for Soils A and B

c = -10.1543 for Soil A and -7.3476 for Soil B

Ds = depth of soil (mm)

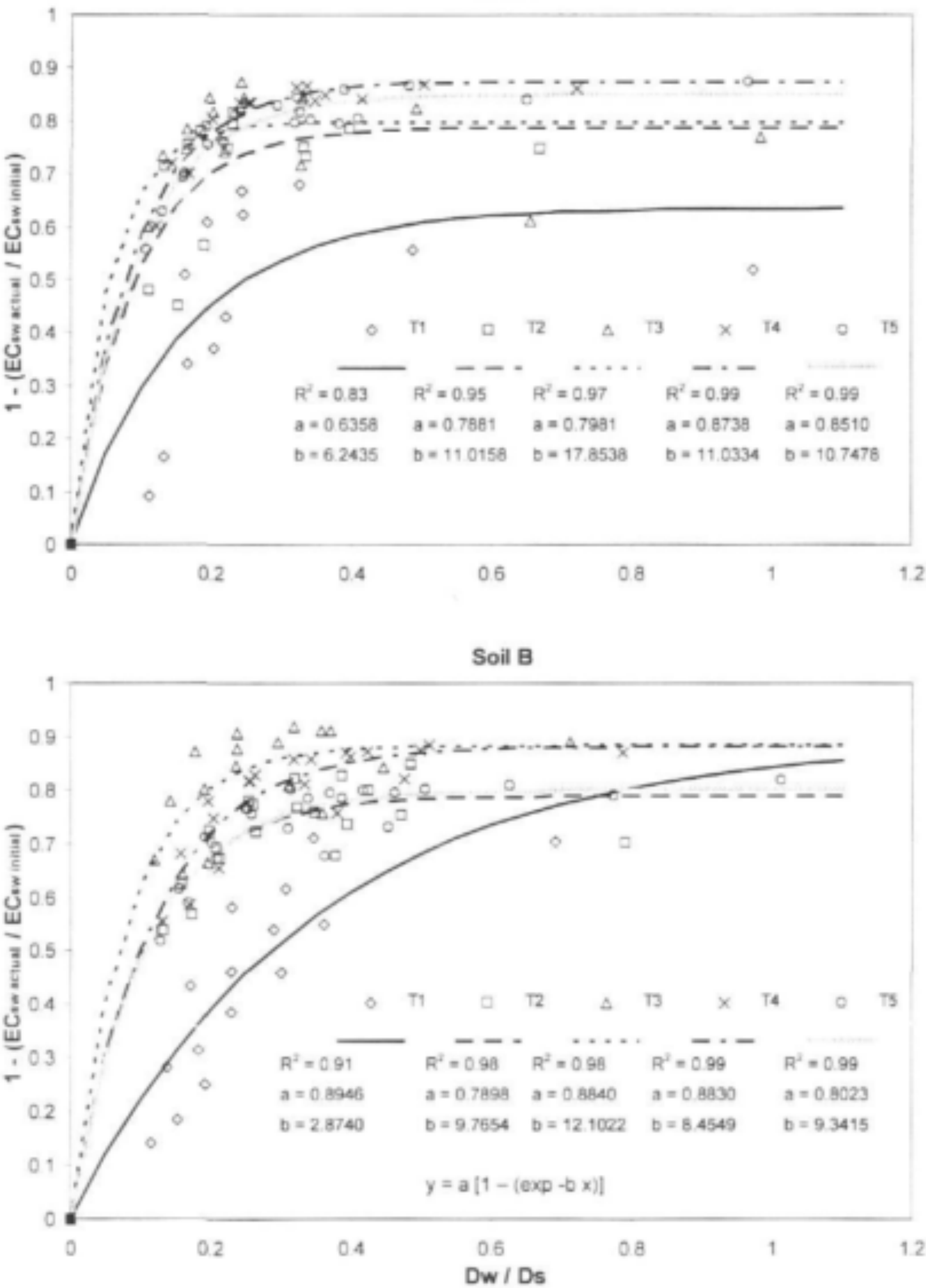

Figure 6.12 Fraction of salts removed plotted as a function of drainage per unit soil depth for the different soils and treatments.

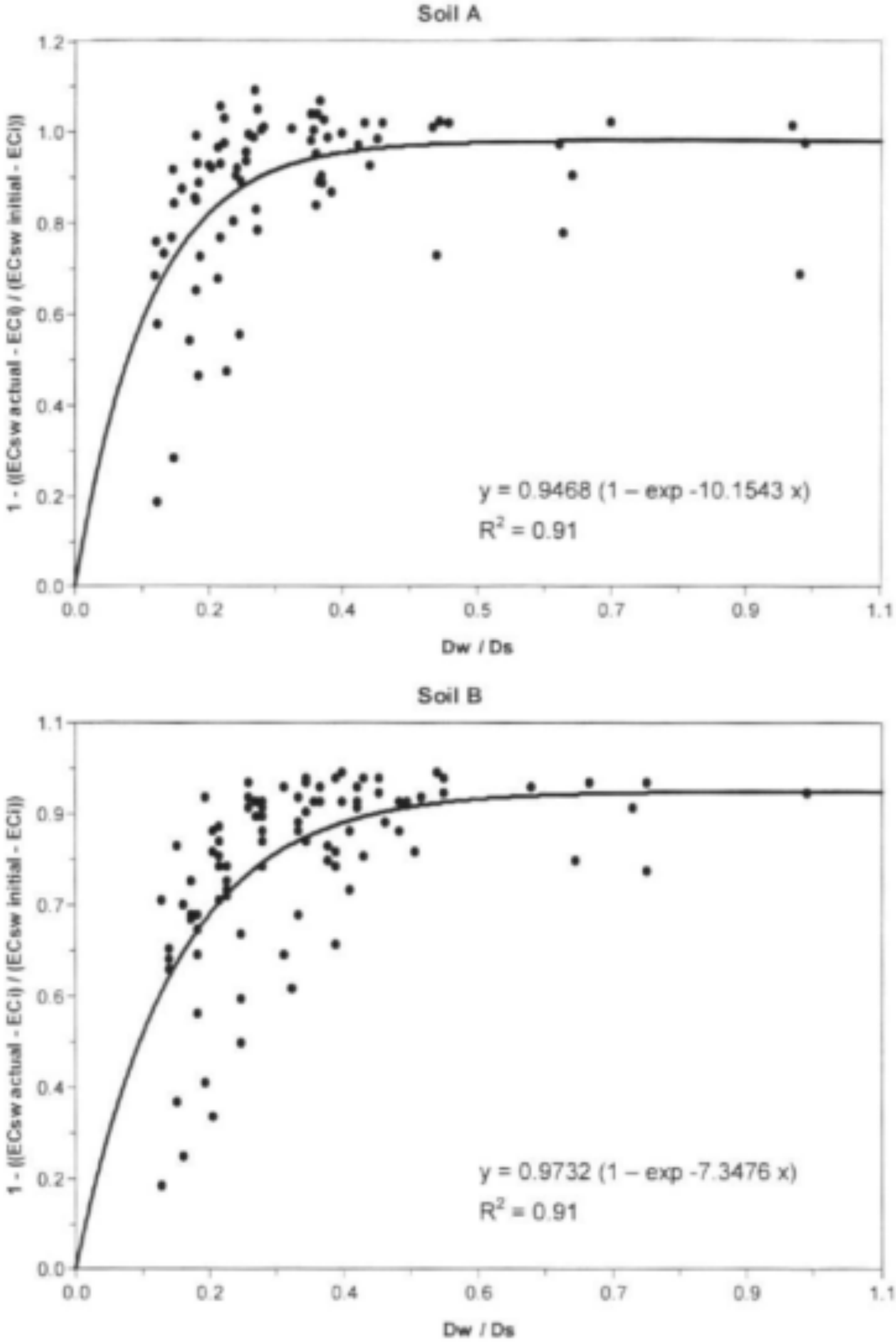

Figure 6.13 Relationship between the fraction of salts removed by leaching with different qualities irrigation water and the drainage per unit soil depth (mm).

The practical use of leaching equations is illustrated in Table 6.3. Equation 6.5 was used to calculate for Soil A and B the amounts of drainage (Dw) required to decrease the $EC_{sw\ initial}$ with 80% to different depths when irrigated with 50 and 150 mS m^{-1} water. The two soils under discussion represent approximately 60% of the total irrigated land in the Free State, Northern Cape and North West provinces.

Table 6.3 illustrates that the clayey Soil B generally requires more drainage than the sandy Soil A in order to leach 80% of the salts. The drainage required also decreased with an increase in $EC_{sw\ initial}$ levels when only 80% of the salts are leached. This indicates that although leaching will always be effective (real ability to remove salts below the root zone) its efficiency (low water volume to be employed to such purposes) will increase from a low to high soil salinity content (Monteleone *et al*, 2004). Consideration will have to be given to the fact that soil salinity will be close to that of the irrigation water.

Table 6.3 Guidelines for approximate amount of drainage required to leach 80% of the salts from different depths with two irrigation water salinities for Soil A and B.

Soil type	EC_i (mS m^{-1})	$EC_{sw\ initial}$ (mS m^{-1})	$EC_{sw\ actual}$ (mS m^{-1})	Soil depth (mm) 0-300	0-600	0-900	0-1200	0-1500	0-1800
		400	**80**	73	145	218	290	363	435
		800	**160**	57	113	170	227	284	340
	50	**1600**	**320**	52	103	155	207	258	310
		800	**160**	123	247	370	493	617	740
Soil A	**150**	**1600**	**320**	63	127	190	253	317	380
		400	**80**	100	201	301	401	502	602
		800	**160**	78	157	235	314	392	470
	50	**1600**	**320**	71	143	214	285	357	428
		800	**160**	170	341	511	682	852	1023
Soil B	**150**	**1600**	**320**	88	175	263	350	438	525

6.3.3.3 Verification of the leaching curves

The leaching equation given in Section 6.3.3.2 was verified against the independent data set from Experiment 2, where good quality irrigation water of 75 mS m^{-1} was used. Soil depths of 0-300 mm, 0-600 mm, 0-900 mm, 0-1200 mm, 0-1500 mm and 0-1800 mm were used in the analysis. The actual EC_{sw}-values were calculated with Equation 6.5 for the specific soils using the measured drainage at various measured initial EC_{sw} values and for the mentioned depths. Then the calculated actual EC_{sw}-values were statistically compared with the measured values. Both functions exhibited a very good correlation as the slopes were close to one with R^2 values of 0.76 and 0.91 for Soil A and B, respectively (Figure 6.14). Most of the calculated values were within the ± 20% variation lines.

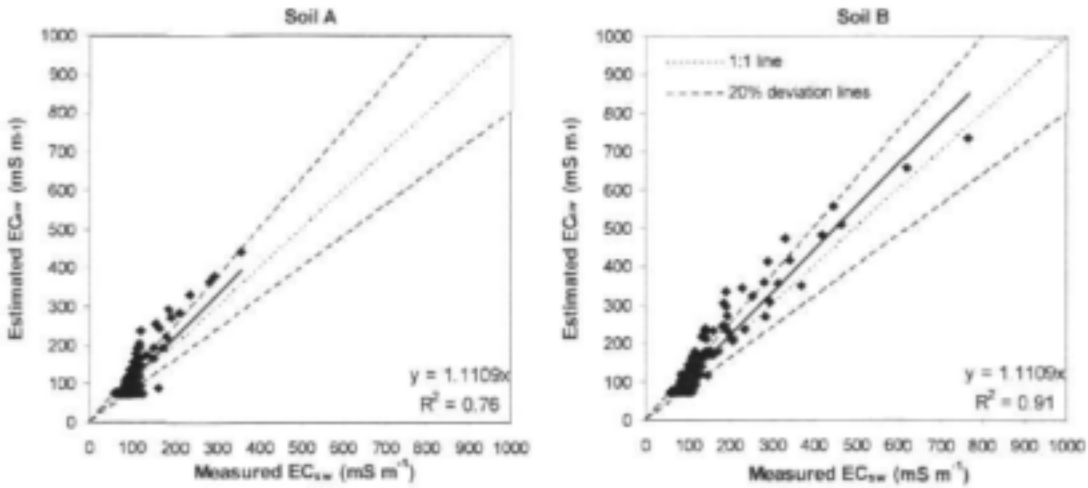

Figure 6.14 Statistical comparisons to the actual EC_{sw}, calculated with leaching equations, against the actual measured EC_{sw} values, of both soils using the independent data set of experiment 2.

Estimations of the leaching requirement for Soil A (loamy sand) and Soil B (sandy loam) were made by computing Dw for good quality water (EC_i = 50 mS m^{-1}) at various EC_{sw} levels and a Ds of 1200 mm with Equation 6.5. The EC_{sw} actual value was taken as 80 mS m^{-1}. The results were compared with values recommended by Van der Merwe (1975) in Table 6.4. These guideline values and the values estimated with Equation 6.5 are almost similar. It is apparent that both soil depth and initial EC_{sw} are important and can influence leaching considerably.

Table 6.4 Comparison of guidelines generated with the leaching equations (LE) of both soils against the recommended leaching requirement (mm 1200 mm^{-1} soil depth) of Van der Merwe (1975)

$EC_{sw\ initial}$ (mS m^{-1})	$EC_{sw\ actual}$ (mS m^{-1})	Soil type: Loamy sand		Soil type: Sandy loam	
		Van der Merwe, 1975	LE	Van der Merwe, 1975	LE
400	80	160	290	260	401
600	80	240	344	390	475
800	80	320	380	520	526
1000	80	400	408	650	564
1600	80	560	466	910	644

Unfortunately, the leaching equations are unique for a specific soil type and can only be extrapolated to different soil types, if it is possible to relate the variable b to soil properties associated with drainage rate. The drainage rate of soils is a function of the pore size distribution. For apedal soils, the percentage silt-plus-clay (< 0.05 mm) is well correlated with the hydraulic and water holding characteristics of soils (Bennie *et al.*, 1998). The relationship between the mean silt-plus-clay percentages of the two soils and the corresponding b-values is presented in Figure 6.15. Unfortunately two data pairs are insufficient to obtain a valid relationship. If it is not possible to determine leaching curves in the field the aid of models such as SWB (Annandale *et al.*, 1999) and SALTMED (Ragab, 2004) can be consulted.

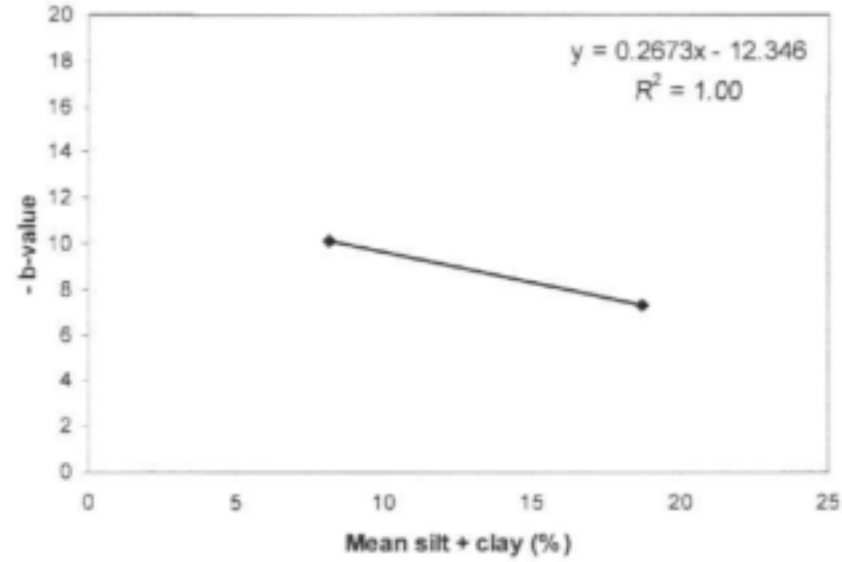

Figure 6.15 Relationship between the mean silt-plus-clay percentage of the soils and the corresponding b-values for the salt leaching equations.

6.4 Conclusions

The first experiment simulated conditions where saturated soils, containing different amounts of salts, were drained artificially. The salinity status of the two apedal soils, as affected by irrigation water salinity under water table conditions, were characterised and a strong relationship between the electrical conductivity of the irrigation water (EC_i) and soil water (EC_{sw}) was obtained. A total of 612 mm irrigation doubled the EC_{sw} during the maize growing season. This illustrates the importance of free drainage because EC_{sw} increases linearly with an increase in the EC_i. The results also revealed that EC_{sw} did not significantly affect drainage rates over a soil depth of 1800 mm. Consequently all the data was combined and a single drainage curve per soil type was derived. The single drainage cycle of Soil A removed between 1975 and 34 901 kg salts ha^{-1}, and that of Soil B between 808 and 13 448 kg salts ha^{-1} depending on the initial salinity. It can be concluded that the salt removal rate (expressed as kg salts ha^{-1} mm^{-1} drainage) is a function of the texture and salt content of a soil.

Experiment two simulated conditions where a saline soil is reclaimed by leaching with good quality water. From the water balance it was calculated that the average drainage rate between the two soils, under these conditions, was 11.8 mm day^{-1}, which amounted to 590 mm drainage over the leaching period of 50 days. The salt concentration of a wet profile was represented by the EC_{sw} which declined with an increase in cumulative drainage. This decrease is best described by a semi-logarithmic function, indicating that leaching is very efficient over the first 100 mm of drainage. Salt removal was also expressed on a relative basis, as a fraction of the maximum amount of salts removed (kg ha^{-1})

per treatment, indicating that the efficiency of salt removal decreases rapidly where the depletion level rose above 80% of the total salts actually removed.

The third experiment differed from experiment two because various saline profiles were leached with different irrigation water salinities. Almost all of the applied water drained from the soils with a drainage: irrigation ratio > 0.85. The actual or target EC_{sw} ended close to the electrical conductivity of the irrigation water, as the accumulated salts were pushed downward and out of the profiles. Leaching curves and equations, which can accommodate variables such as actual soil salinity, irrigation water salinity, amount of leaching and soil depth, were developed for both soils. The leaching curves showed that the actual EC_{sw} decreased linearly with an increase in drainage per unit soil depth, where after it declines sharply with a further increase in drainage per soil depth. Estimations made with the leaching equation (Equation 6.5) revealed that both soil depth and initial EC_{sw} are important and can influence leaching considerably. A decrease in the amount of drainage required to remove 80% of the salts, can be observed with an increase in the initial EC_{sw} of soils (Table 6.3). When almost all the salts are removed, bringing the EC_{sw} close to that of the EC_i, the required drainage will increase with an increase in the initial EC_{sw} levels (Table 6.4). Unfortunately leaching equations are unique for a specific soil type and can only be extrapolated to different soil types when sufficient data is available. For a relationship between mean silt-plus-clay content of the two soils and the corresponding b values of the leaching equations, the two data pairs were insufficient to obtain a valid relationship. Future research on leaching curves, as influenced by soil properties, is therefore required.

CHAPTER 7

PROCEDURES FOR MANAGING ROOT ZONE SALINITY

7.1 Introduction

Long-term sustainable crop production under irrigation, requires periodic information on soil salinity and distribution within the root zone. The soil salinity of the root zone should be managed in such a way that the salinity is kept below levels that are harmful to the cultivated crops. It is also important to select crops, or cultivars of the same crop, 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 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 the 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 threshold values 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 in Chapter 2. Without digressing into detail or the reasons behind this tendency, 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.

It will be the objective of this chapter to formulate procedures, based on the results discussed in Chapters 3 to 6, that can be used to manage the salinity of root zones under different conditions.

7.2 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.

i) 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 5.3), and the amount of drainage required to leach a specified quantity of salts from the root zone (Equation 6.5). In Table 7.1 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.

ii) 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 and resulting in waterlogging and the formation of a shallow water table, restricted drainage conditions will prevail.

iii) Initial root zone salinity

The salinity of the soil, averaged over the potential rooting depth, is required for comparison with the crop tolerance in order to calculate the expected decline in yield (Equation 4.2) and for calculating the expected soil salinity for the next cropping season (Equation 6.5). 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 (Rhodes & Loveday, 1990).

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.

Table 7.1 Salt tolerance of different crops (after Rhoades & Loveday, 1990 and this report) and other relevant information

Crop	Botanical name	Threshold-value for Eq 4.2 (EC_{se}, mS m^{-1})	b-value for Eq 4.2	Maximum rooting depth (mm)	Maximum biomass (kg ha^{-1})	Harvest index	β-value for Eq 4.3	Maximum crop water demand (mm)	Water table contribution with Eq 7.2 & 7.3		
									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

iv) 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 5.1. 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.

v) 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 value of a crop, biomass production will decline proportionally to the excess salinity (Equation 4.2). The parameters used in Equation 4.2 for calculating the expected decline in yield, are given in Table 7.1. The ideal situation is to keep the mean electrical conductivity of the root zone (EC_{sw}) below the threshold electrical conductivity of the crop ($EC_{threshold}$).

vi) Crop water demand (CWD, mm)

This is the amount of irrigation that is needed over the growing season of a crop to meet the required crop plus soil evaporation (evapotranspiration ET, mm) 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. Provision should also be made for the amount of water needed to wet the root zone to the upper limit of plant available water. 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 7.1.

vii) 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. 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 6.5. The b-coefficient in Equation 6.5 was determined for only two soils. As a first approximation the value of the b-coefficient can be estimated from the mean coarse silt-plus-clay percentage (% S+C) of the root zone, with Equation 7.1 (Figure 6.15):

$$b = 0.2673\,(\%\ S{+}C) - 12.346 \qquad (7.1)$$

viii 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 4.3). The parameters required in Equation 4.3 are presented in Table 7.1. The actual ET for non-saline conditions, multiplied by the relative biomass yield (Y_r) calculated with Equation 4.2, gives the actual ET at a specific mean EC_{sw} for the root zone.

ix) 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 deduced 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 4.3.3.3, 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 these models were verified by Bennie *et al.* (1998). An empirical estimation can be made with Equation 7.2.

$$MWT = 0.1 + CF\,(2000 - WTD) + 0.004\,(\%\ S{+}C) \qquad (7.2)$$

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 7.1.

WTD = depth to the top of the water table (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, the water table contribution under non-saline conditions is decreased, using Equation 7.3.

$$WTC = MWT \times [1 - ((EC_{sw} - TWT) \times SWT)] \qquad (7.3)$$

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 7.1).

SWT = crop type dependent reduction factor for the salinity above the threshold value (Table 7.1).

MWT = fractional water table uptake under non-saline conditions, simulated with SWB or SWAMP, or estimated with Equation 7.2.

7.3 Root zone salinity management options

The proposed stepwise procedure, for managing the salinity level of a root zone, is determined by the internal drainage and intrinsic salinity status of the root zone. The diagram in Figure 7.1 can be used to select a relevant root zone salinity management procedure.

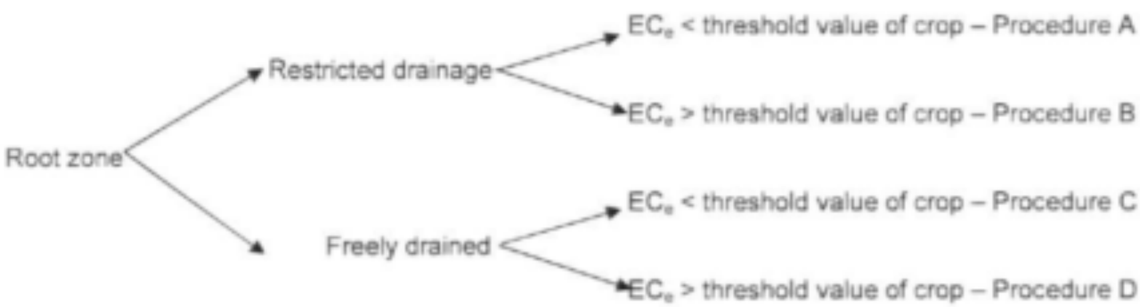

Figure 7.1 Diagram for selecting the appropriate salinity management procedure for a root zone (EC_{sw} = mean EC_{sw} of the root zone).

7.4 Description of the different root zone salinity management procedures

The appropriate procedure can be selected from Figure 7.1.

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 7.2.

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

Step 4 - Calculate the increase in root zone salinity (ΔEC_{sw}), over the growing season, with Equation 5.1.

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 - 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 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 yield (Y_r) with Equation 4.2 (Data from Table 7.1)

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

Step 3 - Calculate the water table contribution (WTC, mm) with Equation 7.3.

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.

Step 5 - Calculate the increase in root zone salinity (ΔEC_{sw}) over the growing season, using Equation 5.1.

Step 6 - Calculate the initial salinity for the next season: Initial EC_e next season = Initial EC_e this season + ΔEC_{sw} this season.

Step 7 - 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. 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, 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.

Step 3 - Take representative soil samples of the root zone, at least every 5 years, for determination of EC_e.

Step 4 - If $EC_e < EC_e$ threshold of the most salinity sensitive cultivated crop, continue with Procedure C. If $EC_e \geq EC_e$ threshold of the most salinity sensitive cultivated crop, 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 the 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. 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 6.5 and 7.1. In Equation 6.5 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 + irrigation are required to wet the root zone.

Step 5 - Calculate the salinity added during the growing season (ΔEC_{sw}) with Equation 5.1.

Step 6 - For the following seasons, repeat the procedure from Step 1, but in Step 2 in Equation 6.5, set EC_e actual = EC_e of crop to be irrigated and EC_e initial = EC_i + ΔEC_{sw}, calculated in Step 5.

7.5 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 salinisation 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.

CHAPTER 8

RESEARCH OUTCOMES AND RECOMMENDATIONS

8.1 Introduction

In this chapter the outcomes of the research are addressed in relation to each of the project objectives. This is followed by general conclusions and the practical implications of the research results. Gaps in current knowledge that were identified are then presented. Some requirements for future research are also given.

8.2 Outcomes in relation to the project objectives

8.2.1 Objective 1

Objective 1 was the quantification of the effect of increasing the salt content of irrigation water on the growth and yield of selected crops. Different experiments were conducted to attain the objective. Firstly, laboratory seed germination studies were conducted to measure the impact of salinity on the germination of wheat, maize, beans and peas. It was concluded that the percentage seed germination of maize, wheat and beans was not affected by salinity levels up to 600, 600 and 300 mS m^{-1}, respectively. A reduction in the seed germination of peas was measured at 300 mS m^{-1}. A significant reduction in the coleoptile or hypocotile length and root length with an increase in the salinity levels of the treatments were measured for maize, beans and peas. For wheat the decreases were not significant. Seedlings affected in this way would probably lead to poor emergence in the field. This might explain the observations made by farmers who were concerned about poor seedling emergence in their fields, which they ascribed to salinity (Du Preez, 2000).

The response of the mentioned crops to different levels of irrigation water salinity during the growing season, was studied in glasshouse pot experiments. Plants were sampled at three growth stages and various plant parameters such as leaf area, root mass, biomass and seed yield were measured. All these measured parameters were negatively affected by a deterioration in irrigation water salinity with peas found to be the most sensitive crop, followed by beans, maize and then wheat. All the crops in the pots used considerably more water (mm per unit soil surface) than when grown in the field. This was ascribed to a larger plant canopy area in relation to the soil area, because plant competition was absent between pots. This phenomenon required more water to be applied which accelerated the salinisation of the pots, measured as electrical conductivity of the soil extract (EC_e, mS m^{-1}). The salinity of the pots increased with a factor that varied between 1.9 and 3.2 times higher than the irrigation water salinity, measured in mS m^{-1}. Osmotic induced plant water stress was best described for all crops by a relationship between EC_e and the relative decline in biomass yields. The linear decline in biomass yield to the maximum measured EC_e level, compared to the control, was 33% for beans at 600 mS m^{-1}, 60% for peas at 1250 mS m^{-1}, 80% for wheat at 2600 mS m^{-1} and 98% for maize at 1150 mS m^{-1}.

A series of field experiments were conducted in large 5 000 L lysimeters that were designed to accurately measure both the water and salt balances in the presence of shallow water tables. 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, it was done in the wheat glasshouse trial, which was reported. The soil water salinity of the lysimeters were 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 4.11. It can be concluded that this part of the study confirmed the findings reported in literature by several researchers.

8.2.2 Objective 2

Objective 2 was 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 increases the energy required by the crop to extract 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 4.21). 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 4.3. The relative decrease in growth of all the crops was directly proportional to the relative decrease in ET (Figure 4.26, 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.

8.2.3 Objective 3

Objective 3 was the 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 top soil 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 top soil that received weekly irrigations. The salts that accumulated in the top soil, were also pushed downwards into the capillary zone with every 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.

8.2.4 Objective 4

Objective 4 was the determination and modelling of the salt balance for a range of irrigation water salinity and soil type combinations over a three year period. This objective was not fully met in terms of modelling the salt balance 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. The problem was discussed with the Steering Committee for the project and it was decided to remove the access 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 5) and the removal thereof (Chapter 6). Both these processes are strongly linked to the water and salt balance. A great effort was made to recalibrate the CPN-neutron water meter for the two soils in the lysimeters. An indirect method was used, based on the amount of water that drained from the profiles, i.e. change in soil water content versus drainage collected from the outlet of the lysimeters. The slope of the calibration equation in the instrument was adjusted until the measured change in soil water content matched the amount of measured drainage. This procedure improved the water balance calculations considerably.

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 5). The samples were analyzed for electrical conductivity of the soil water (EC_{sw}, mS m^{-1}) and total dissolve salts (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 5.1 - 5.4) 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 5.9) 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 5.11). Lastly, Equation 5.3 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.

The removal of salts was investigated through three studies conducted in the lysimeter unit. The first two studies, as described in Chapter 6, were conducted after the crop experiments were completed. For the third study the data for the leaching period between harvesting of the beans and planting of peas was used. The aim of the first study was to determine the effect of EC_{sw} on the drainage rate of both soils, from the salt profiles after the harvesting of maize. The results showed that EC_{sw} did not significantly affect drainage rates over a soil depth of 1800 mm. All the data was combined and a single drainage curve for each soil type was compiled. A single drainage cycle removed between 1 975 and 34 901 kg salts ha^{-1} from Soil A and between 808 and 13 448 kg salts ha^{-1} from Soil B, depending on the initial salinity. An equation was developed for each soil type that can be used for estimating salt removal (express as kg salts ha^{-1} mm^{-1} drainage) under saturated or water table conditions (Figure 6.5).

The second study represented conditions where saline soils are reclaimed by leaching with good quality water. It was conducted on the same lysimeters following the drainage experiment. The soils were leached with 50 mm irrigation applications twice a week for a period of 7 weeks, giving a total of 700 mm irrigation or 1.2 pore volumes. The mean drainage rates of the soils under these conditions were 11.8 mm day^{-1}, giving a total drainage of 590 mm or approximately 1 pore volume. The salt concentration of a wet profile was represented by the mean EC_{sw} of the root zone, which declined with an increase in cumulative drainage. The decrease in the root zone salinity was best described by a semi-logarithmic function, showing that leaching was very efficient for the first 100 mm of drainage (Figure 6.8). Salt removal was also expressed on a relative basis, as a fraction of the maximum amount of salts removed (kg ha^{-1}) per treatment. These curves demonstrated that the efficiency of salt removal decreases rapidly after 0.5 pore volumes of water have drained from the root zone and the depletion level rose above 80% of the total initial salts removed (Figure 6.9).

During the third study the soils were leached with water salinities ranging from 15 to 300 mS m^{-1} which corresponded with the EC_i treatments of the follow-up crop, peas. Of the 752 and 848 mm applied water for soils A and B respectively, 85% drained from the soils. The salt distribution profiles showed that at the end of the leaching period, the actual or target EC_{sw} were close to the EC_i. The leaching results were characterised for each EC_i treatment by plotting (1- (EC_{sw} actual/EC_{sw} initial)) as a function of drainage (D_w) per unit soil depth (Ds) for each soil type, as have been suggested by several researchers in literature. A single leaching curve was constructed for each soil type by plotting the relative salt removal per EC_i treatment, expressed as (1 – ((EC_{sw} actual – EC_i)/ (EC_{sw} initial – EC_i)), versus D_w Ds^{-1} (Equations 6.3 and 6.4). These leaching curves (Figure 6.13) showed that the actual EC_{sw} decreased linearly with an increase in drainage per unit soil depth to a value of 0.3 where after it declines sharply with a further increase in drainage per soil depth. Estimations made with the leaching equation (Equation 6.5) showed the amount of drainage required to reclaim saline soils increase with both soil depth and initial EC_{sw} (Tables 6.3 and 6.4).

8.2.5 Objective 5

Objective 5 was the quantification of the leaching requirements of the two soils at five salinity levels. This objective was achieved by the development of a procedure whereby the salinity level of root zones could be managed. As mentioned in Chapter 7, long-term sustainable crop production under irrigation, requires periodic information on soil salinity and its distribution within the root zone. The essential information required for managing root zone salinity was discussed. The results obtained from the laboratory, glasshouse and lysimeter experiments were used to develop step-by-step procedures that can be followed to manage root zone salinity. The procedures also make use of other local and international information sources.

The most essential information required to apply the procedures is listed in Table 7.1 according to crop type. The information include, for example, the EC_{sw} threshold value (Table 4.11) above which salinity will affect the maximum yield negatively (± 5%); the b-value listed in Table 4.11 which describes the relative decline in yield with increasing EC_{sw} by using Equation 4.2; maximum rooting depth (mm), maximum biomass and its harvest index obtained from various other sources (Bennie *et al.*, 1988; Bennie *et al.*, 1994); The b-value of Stewart *et al.* (1977), which is the slope of relative biomass yield versus relative evapotranspiration; the maximum crop water demand, which can be estimated with BEWAB, SAPWAT, SWB and other models; specialized information on water table uptake, with regard to the following components required in Equations 7.2 and 7.5, namely the crop dependent correction factor (CF), the threshold salinity of the crop (TWT) and the crop type dependent reduction factor for the salinity above the threshold value (SWT).

A procedure or theoretical framework is proposed for managing the salinity of the root zone. The procedure is based on prevailing drainage conditions grouped into restricted or freely drained categories. These categories are further subdivided into two sub-categories, depending if the actual EC_{sw} are smaller or greater than the threshold value of the crop (Figure 7.1). Unfortunately the procedures were not tested and hence needed to be verified in the near future. However, it was concluded that effective management of salt accumulation in soils with restricted drainage can only be done when good quality irrigation water with an EC_i of less than 50 mS m^{-1} is used. With more saline irrigation water the rapid salinisation of the root zone is difficult to manage without artificial drainage. On freely drained soils it is possible to manage effectively the salinity level of the root zone, through controlled over-irrigation, when necessary. When good quality irrigation water with an EC_i of more than 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.

8.3 General conclusions and practical implications

The results from this research project 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 germination, 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 which varies between 1500 and 2000 mm for the crops mentioned, were measured.

3. The amount and rate of salt removal were measured under conditions which simulated the installation of artificial drainage.

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

The percentage seed germination of the dicotyledonous bean and pea crops are not affected by irrigation water salinity levels below 300 mS m^{-1} and those of monocotyledonous maize and wheat crops at levels below 600 mS m^{-1}, respectively. Although seeds of particularly peas and maize will germinate, the growth of the seedlings in terms of hypocotile or coleoptile and root length will be impeded at even much lower salinity levels. 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 4.21 and 4.26.

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 5.5. The salt concentration in this bulge, within the capillary zone, is several fold 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 4.3.4.2 to 4.3.4.4). There are four management options:

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 salinisation 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 less 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 4.3.3). 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 salinisation 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 salinisation 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.

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. The second part of this study investigated the different aspects of salt removal from the root zone under conditions simulating both the installation and presence of artificial drains below the root zone. It can be concluded from these results that the water draining from the saturated soil towards the drainage tubes, following installation, will remove a significant amount of the salts. For example on a sandy soil with a water table at 1200 mm with a soil water EC of 777 mS m^{-1}, approximately 18 000 kg ha^{-1} salt will be removed from the root zone with the first drainage cycle. To remove 80% of the remaining salts over a depth of 1800 mm by leaching with good quality water, approximately 300 mm or 0.5 pore volume of drainage is required. More clayey soils will require more drainage to a maximum of 1 pore volume or 600 mm (Figure 6.9). When leaching salts from soils it should be kept in mind that the salinity of the irrigation water determines the equilibrium salinity of the root zone.

These conclusions were all included in a step-by-step procedure in Chapter 7 that can be followed to formulate the best management practices for controlling root zone salinity under different conditions.

8.4 Gaps in current knowledge

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

1. The procedure needs to be verified under controlled and on-farm field conditions

2. For managing the soil salinity levels within soil layers, the effect of rhizosphere salinity on water uptake needs to be quantified.

3. The soil specific leaching coefficiency of the general leaching Equation 6.5 needs to be expanded to include more soils with different textural properties.

4. The effect of soil surface salinity and its effect on seedling emergence in the field need to be quantified for more crop and soil combinations.

5. The evaluation and testing of instrumentation for on-farm monitoring of EC_e are essential.

6. Developed procedures should be included in at least the BEWAB and SWAMP models for efficient transfer and exchange of information to technicians, extension officers and farmers.

8.5 Requirements of future research

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

REFERENCES

ABID, M., QAYYUM, A., DASTI, A.A. & WAJID, R.A., 2001. Effect of salinity and SAR of irrigation water on yield physiological growth parameters of maize (*Zea maize*) and properties of the soil. *J. of Res. Sci. (Pakistan) 12*, 26 – 33.

ABROL, I.P., YADAV, J.S. & MASSOUD, F.I., 1988. Salt-affected soils and their management. FAO Soils Bulletin 39, Rome.

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.

ANDREU, L., MORENO, N.J., JARVIS, N.J. & VACHAUD, G., 1994. Application of the model MACRO to water movement and salt leaching in drained and irrigated marsh soils, Marismas, Spain. *Agric. Water Manage. 25, 71-88.*

ANNANDALE, J.G., BENADE, N., JOVANOVIC., N.Z. & DU SATOY, N., 1998. A user friendly irrigation scheduling model. Soils and Crops towards 2000 Congress, South African Society of Crop Production, Alphine Heath, KwaZulu-Natal.

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.

ARAGüES, R.M., 1996. Conceptual irrigation return flow hydrosalinity model. In K.K. Tanji (ed.). Agricultural salinity assessment and management. Am. Soc. of Civ. Eng., New York.

ARMSTRONG, A.S.B., TANTON, T.W. & RYCROFT, D.W., 1998. The effect of ped size, simulated rainfall duration and frequency on leaching of salts from clay topsoils. *Agric. Water Manage. 37, 133-143.*

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.

AYERS, R.S. & WESTCOT, D.W., 1985. Water quality for agriculture. FAO Irrigation and Drainage Paper. Rome.

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.

BAYUELO-JIMENEZ, J., CRAIG, R. & LYNCH, J., 2002. Salinity tolerance of *Phaseolus* species during germination and early seedling growth. *Crop Sci.* 42, 1584 – 1594.

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., HOFFMAN, J.E., COETZEE, M.J. & VREY, H.S., 1994. Opgaring en benutting van reënwater in grond vir die stabilisering van plantproduksie in halfdroë gebiede. Water Research Commission Report 227/1/94, 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.

BOHN, H. L., McNEAL, B. L. & O'CONNOR, G. A., 1985. Soil chemistry. Wiley, New York.

BOTHA, J.J., VAN RENSBURG, L.D., ANDERSON, J.J., HENSLEY, M., MACHELI, M.S., VAN STADEN, P.P., KUNDHLANDE, G., GROENEWALD, D.G. & BAIPHETHI, M.N., 2003. Water conservation techniques on small plots in semi-arid areas to enhance rainfall use efficiency, food security, and sustainable crop production. Water Research Commission Report 1176/1/03, Pretoria.

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.

CHABBRA, R., 1996. Soil salinity and water quality. Balkema Publishers, Brookfield, Missouri.

CORDOVILLA, M.D.P., LIGERO, F., & LLUNCH, C., 1999. Effect of salinity on growth, nodulation and N assimilation in nodules of faba bean (*Vicia faba* L.). *Appl. Soil Eco.* 11, 1 – 7.

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.

CRAMER, G.R., SCHMIDT, C.L. & BIDART, C., 2001. Analysis of cell wall hardening and cell wall enzymes of salt-stressed maize (*Zea mays*) leaves. *Aust. J. Plant Physiol.* 28, 101 – 109.

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.

EL-HENDAWY, S.E., HU, M., YAKOUT, G.M., AWAD, A.M., HAFIZ, S.E. & SCHMIDHALTER, U., 2005. Evaluating salt tolerance of wheat genotypes using multiple parameters. *Eur. J. Agron.* 22, 243 –253.

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

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

FSSA, 2003. Fertilizer handbook. Fertilizer Society of South Africa, Pretoria.

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

GOMEZ, K.A. & GOMEZ, A.A., 1984. Statistical procedures for agricultural research. Wiley Press, New York.

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.*

GUPTA, R.K. & ABROL, I.P., 1990. Salt-affected soils: their reclamation and management for crop production. *Adv. Soil Sci. 11, 223-288.*

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

HENSLEY, M., BOTHA, J.J., ANDERSON, J.J., VAN STADEN, P.P. & DU TOIT, A., 2000. Optimizing rainfall use efficiency for developing farmers with limited access to irrigation water. Water Research Commission Report 878/1/00, Pretoria.

HENSLEY, M., HATTINGH, H.W. & BENNIE, A.T.P., 1993. A water balance modelling problem and a proposed solution. Proceedings of the 4th Annual Scientific Conference of the SADC-Land and Water Management Research Program, Gaborone Botswana.

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.

HILLEL, D., KRENTOS, V.D. & STEYLIANOU, Y., 1972. Procedure and test of an internal drainage method for measuring soil hydraulic characteristics *in situ*. *Soil Sci. 114, 395-400.*

HINTZE, J.L., 1998. Number cruncher statistical system – NCSS 2000. NCSS, Kaysville, Utah.

HOFFMAN, G.J., 1980. Irrigation management - salinity control. Irrigation challenges of the 80's, Proceedings of the ASAE Second National Irrigation Symposium. ASAE, St. Joseph, Michigan.

HYAMS, D., 1995. Curve Expert, a comprehensive curve fitting system for Windows. http://www.ebicom.net/-dhyams/cvxpt.htm

JORENUSH, M.H. & SEPASKHAH, A.R., 2003. Modelling capillary rise and soil salinity for shallow saline water table under irrigated and non-irrigated conditions. *Agric. Water Manage. 61, 125-141.*

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.

JURY, W.A. & HORTON, R., 2004. Soil physics, 6^{th} edn. John Wiley & Sons, New Jersey.

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., KARAM, F. & MASTROLLI, M., 1996. Effect of water stress, growth, and yield of maize and sunflower. *Agric. Water Manage.* 30, 237 – 249.

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.

LANTZKE, N., & CALDER, T., 2000. Water salinity and crop irrigation. Farm note 46/99, Western Australia. http://agspsrv38.agric.wa.gov.au/pls

LÄUCHLI, A. & EPSTEIN, E., 1990. Plant response to saline sodic conditions. In K.K. Tanji (ed). Agricultural salinity assessment management. Am. Soc. of Civil Eng., New York.

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., 1977a. Crop salt tolerance – current assessment. *J. Irrig. Drain. Div. Am. Soc. Civ. Eng.* 103, 115-134.

MAAS, E.V. & HOFFMAN, G.J., 1977b. Crop salt tolerance: Evaluation of existing data. In E.H. Dregne (ed). Managing saline water for irrigation. Proceedings of the International Salinity Conference, Texas.

MARSHALL, T.J., HOLMES, J.W. & ROSE, C.W., 1996. Soil physics, 3rd edn. Cambridge University Press, Cambridge.

McNEAL, B.L. & COLEMAN, R.J., 1966. Effect of solution composition on soil hydraulic conductivity. *Soil. Sci. Soc. Am. Proc.* 30,308-312.

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.

MONTELEONE, M., GATTA, G., GIUZIO, L., LA ROTONDA, P. & DE CARO, A., 2004. Effect of leaching on salt accumulation in soil under brackish water irrigation. The *55th IEC meeting, international workshop on management of poor quality water for irrigation: institutional, health and environmental aspects, 102-112.*

MOOLMAN, J.H., 1993. An evaluation of a range of computer models simulating the transport of solutes and water in the root zone of irrigated soils. Water Research Commission Report 196/1/93, Pretoria.

MUNNS, R., 2002a. The impact of salinity stress. CSIRO Division of Plant Industry. Australia.

MUNNS, R., 2002b. Comparative physiology salt and water stress. *Plant, Cell Environ.* 25, 239 – 250.

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.

MUNNS , R. & RAWSON, H.M., 1999. Effect of salinity on salt accumulation and reproductive development in the apical meristem of wheat and barley. *Aust. J. Plant Physiol.* 26, 459 – 464.

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.*

PASSIOURA, J.B. & MUNNS, R., 2000. Rapid environmental changes that effect leaf water status induce transient surges or pauses in leaf area expansion rate. *Aust. J. Plant Physiol.* 27, 941 – 948.

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

RAMOLIYA,. P.J. & PANDEY, A., 2001. Effect of salinisation of soil on emergence, growth and survival of seedling of *Cordia rothii*. *For. Ecol. Manag.* 176, 185 – 194.

RAO, K.V.G.K., SINGH., O.P., GUPTA, R.K., KAMRA, S.K., PANDEY, R.S., KUMBHARE, P.S. & ABROL, I.P., 1986. Drainage investigations for salinity control in Haryana. Technical Bulletin 10, Central Soil Salinity Research Institute, Karnal, India.

RATLIFF, L.F., RITCHIE, J.T. & CASSEL, D.K., 1983. Field measured limits of soil water availability as related to laboratory measured properties. *Soil Sci. Soc. Am. J. 47, 770-775.*

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

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.

RICHARDS, L.A., 1954. Diagnosis and improvement of saline and alkali soils. Government Printing Office, Washington.

RUSSELL, E.W., 1973. Soil conditions and plant growth, 10^{th} edn. Longman, London.

SAQIB, M., AKHTAR, J. & QURESHI, R.H., 2004a. Pot study on wheat growth in saline and waterlogged compacted soil. I. Grain yield and yield components. *Soil Tillage Res.* 77, 169 – 177.

SAQIB, M., AKHTAR, J. & QURESHI, R.H., 2004b. Pot study on wheat growth in saline and waterlogged compacted soil. II. Root growth and leaf ionic relations. *Soil Tillage Res. 77*, 169 – 177.

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.*

SHAINBERG, I. & OSTER, D., 1978. Quality of irrigation water. International Irrigation Information Centre Publication 2, Israel.

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

SINGH, R., 2004. Simulations on direct and cyclic use of saline waters for sustaining cotton-wheat in a semi-arid area of north-west India. *Agric. Water Manage. 66, 153-162.*

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.

STEPPUHN, H., VOLKMAR, K.V. & MILLER, P.R., 2001. Comparing canola, field pea, dry bean and durum wheat crops grown in a saline medium. *Crop Sci.* 41, 1821 – 1833.

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., 1986. Agronomical and ecological impact of irrigation on soil and water salinity. *Adv. Soil Sci.* 4, 189-218.

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

TEDESCHI, A. & DELL'AQUILA, R., 2005. Effects of irrigation with saline waters, at different concentrations, on soil physical and chemical characteristics. *Agric Water Manage. 77, 308-322.*

THEIVEYANATHAN, S., BENYON, R.G., MARCAR, N.E., MYERS, B.J., POLGLASE, P.J. & FALKINER, R.A., 2004. An irrigation-scheduling model for application of saline water to tree plantations. *Forest Ecology and Management 193, 97-112.*

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 DER MERWE, A.J., 1975. Physico-chemical relationships of selected O.F.S soils – A statistical approach based on taxonomic criteria. Ph.D. thesis, University of the Free State, Bloemfontein.

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.,1996. Interaksie tussen stikstof-en wateropname deur koring en mielies. Ph.D. thesis, University of the Free State, Bloemfontein.

VAN STADEN, P.P., 2000. Effek van afloop-opgaarverwantskappe op reënvalbenutting deur mielies op kleigronde met hoë droogterisiko. M.Sc. Agric. dissertation, University of the Free State, Bloemfontein.

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 salinisation. 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.

XU, P. & SHAO, Y., 2002. A salt-transport model within a land-surface scheme for studies of salinisation in irrigated areas. *Environmental Modelling and Software 17, 39-49.*

ZELEKE, K.T., 2003. Tracing water and nitrate movement through soils with bromide. Ph.D. thesis, University of the Free State, Bloemfontein.

ZHANG, 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.*

APPENDICES

Appendix 4.1 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	29	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	396	1005	246	626	306	780	306	776	286	726	273	696

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 4.1 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	406	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 4.2 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
	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
A	600	1.35	1.18	1.23	2.20	1.95	1.73
	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
B	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
	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
A	600	0.00	0.00	0.00	0.00	0.00	0.00
	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
B	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
	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
A	300	0.67	0.77	0.53	1.05	0.92	0.92
	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
B	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
	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
A	600	1.10	1.10	1.06	1.83	2.48	2.79
	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
B	600	1.08	1.28	1.11	2.84	2.67	2.29

Appendix 4.3 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, 11
TREATMENT : SOIL A - CONTROL

DATE			29-Dec-04									
DAYS AFTER PLANTING			12									
REPLICATION			Rep 1			Rep 2			Rep 3			
			Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	AVE
0-300	(mm)	θv	0.069	0.067	0.065	0.065	0.083	0.076	0.049	0.061	0.055	0.065
300-600	(mm)	θv	0.151	0.142	0.146	0.155	0.150	0.152	0.153	0.153	0.153	0.152
600-900	(mm)	θv	0.172	0.172	0.174	0.175	0.196	0.185	0.180	0.153	0.174	0.176
900-1200	(mm)	θv	0.282	0.279	0.281	0.255	0.290	0.290	0.301	0.290	0.295	0.289
1200-1500	(mm)	θv	0.303	0.302	0.303	0.305	0.296	0.301	0.308	0.315	0.311	0.306
1500-1800	(mm)	θv	0.287	0.286	0.286	0.292	0.289	0.290	0.292	0.278	0.285	0.287
MEAN	0-1800mm	(mm/mm)			0.210			0.215			0.212	0.212
TOTAL W	0-1800mm	(mm)			372.43			387.12			382.31	382.285
CHANGE W	0-1800mm	(mm)			0			0			0	0
PAW upper	0-1800mm	(mm)			391			391			391	391
PAW lower	0-1800mm	(mm)			212			212			212	212
WATER DEFICIT	0-1800mm	(mm)			13.17			3.88			8.695	8.715
PAW	0-1800mm	(mm)			165.43			175.12			172.31	170.29
IRRIGATION		(mm)			0			0			0	0
RAINFALL		(mm)			0			0			0	0
IRRIGATION + RAINFALL		(mm)			0			0			0	0
WT DEPLETION		(mm)			0			0			0	0
		(mm/day)			0			0			0	0
PERCOLATION	1800mm	(mm)			0			0			0	0
EVAPOTRANSPIRATION		(mm)			0			0			0	0
		(mm/day)			0			0			0	0
Eo		(mm/day)			7.16			7.16			7.16	7.16
CUM EVAPOTRANSPIRATION		(mm)			0			0			0	0
CUM IRRIGATION + RAINFALL		(mm)										0
CUM WT DEPLETION		(mm)										0
CUM PERCOLATION	1800mm	(mm)										0

DATE			05-Jan-05									
DAYS AFTER PLANTING			19									
REPLICATION			Rep 1			Rep 2			Rep 3			
			Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	AVE
0-300	(mm)	θv	0.054	0.046	0.050	0.053	0.072	0.062	0.039	0.049	0.044	0.052
300-600	(mm)	θv	0.142	0.138	0.140	0.144	0.141	0.143	0.141	0.145	0.143	0.142
600-900	(mm)	θv	0.161	0.164	0.163	0.167	0.175	0.171	0.164	0.158	0.161	0.165
900-1200	(mm)	θv	0.282	0.279	0.281	0.291	0.290	0.290	0.301	0.290	0.295	0.289
1200-1500	(mm)	θv	0.303	0.302	0.303	0.305	0.296	0.303	0.308	0.315	0.311	0.306
1500-1800	(mm)	θv	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)			0.204			0.210			0.207	0.207
TOTAL W	0-1800mm	(mm)			366.59			377.85			371.91	372.1
CHANGE W	0-1800mm	(mm)			-10.045			-9.3			-10.395	-10.2
PAW upper	0-1800mm	(mm)			391			391			391	391
PAW lower	0-1800mm	(mm)			212			212			212	212
WATER DEFICIT	0-1800mm	(mm)			24.415			13.15			19.09	18.9
PAW	0-1800mm	(mm)			154.59			165.85			159.91	160.1
IRRIGATION		(mm)			15.7			15.7			15.7	15.7
RAINFALL		(mm)			0			0			0	0.0
IRRIGATION + RAINFALL		(mm)			15.7			15.7			15.7	15.7
WT DEPLETION		(mm)			0			0			0	0.0
		(mm/day)			0			0			0	0.0
PERCOLATION	1800mm	(mm)			0			0			0	0.0
EVAPOTRANSPIRATION		(mm)			26.145			24.97			26.095	25.9
		(mm/day)			3.7921			3.5671			3.7279	3.7
Eo		(mm/day)			8.54			8.54			8.54	8.54
CUM EVAPOTRANSPIRATION		(mm)			26.15			24.97			26.10	21.87
CUM IRRIGATION + RAINFALL		(mm)			15.70			15.70			15.70	15.70
CUM WT DEPLETION		(mm)			0.00			0.00			0.00	0.00
CUM PERCOLATION	1800mm	(mm)			0.00			0.00			0.00	0.00

DATE			12-Jan-05									
DAYS AFTER PLANTING			26									
REPLICATION			Rep 1			Rep 2			Rep 3			
			Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	Tube 1	Tube 2	Ave	AVE
0-300	(mm)	θv	0.048	0.048	0.048	0.049	0.068	0.059	0.036	0.046	0.041	0.049
300-600	(mm)	θv	0.139	0.137	0.138	0.142	0.138	0.140	0.144	0.145	0.144	0.141
600-900	(mm)	θv	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
1200-1500	(mm)	θv	0.303	0.302	0.303	0.305	0.296	0.303	0.308	0.315	0.311	0.306
1500-1800	(mm)	θv	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)			0.205			0.210			0.208	0.208
TOTAL W	0-1800mm	(mm)			368.22			378.75			325.18	324.05
CHANGE W	0-1800mm	(mm)			1.615			0.9			3.27	1.935
PAW upper	0-1800mm	(mm)			391			391			391	391
PAW lower	0-1800mm	(mm)			212			212			212	212
WATER DEFICIT	0-1800mm	(mm)			22.78			12.25			15.82	17.0
PAW	0-1800mm	(mm)			156.22			166.75			163.18	162.1
IRRIGATION		(mm)			23.6			23.6			23.6	23.6
RAINFALL		(mm)			0			0			0	0.0
IRRIGATION + RAINFALL		(mm)			23.6			23.6			23.6	23.6
WT DEPLETION		(mm)			0			0			0	0.0
		(mm/day)			0			0			0	0.0
PERCOLATION	1800mm	(mm)			0			0			0	0.0
EVAPOTRANSPIRATION		(mm)			21.965			22.7			20.33	21.7
		(mm/day)			3.1379			3.2429			2.9043	3.1
Eo		(mm/day)			6.6			6.6			6.6	6.6
CUM EVAPOTRANSPIRATION		(mm)			48.11			47.67			45.43	47.54
CUM IRRIGATION + RAINFALL		(mm)			39.30			39.30			39.30	39.30
CUM WT DEPLETION		(mm)			0.00			0.00			0.00	0.00
CUM PERCOLATION	1800mm	(mm)			0.00			0.00			0.00	0.00

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

Appendix 5.1 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 6.1 Statistical results of the rational function for measured cumulative drainage per lysimeter regressed with time, for both soils and all EC_i treatments

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

Appendix 6.2 Water content of the lysimeters during the entire drainage period, for both soils and all EC_i treatments

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

Soil B															
EC_i (mS m^{-1})	15			150			300			450			600		
Rep	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Water content (mm 1.8m^{-1})	640	678	668	676	673	663	658	666	636	665	630	666	656	647	647
	595	598	613	603	585	584	603	574	553	596	552	578	597	587	594
	578	585	595	574	580	566	582	558	540	571	533	562	573	565	577
	563	556	577	546	555	547	564	533	522	547	506	541	554	537	555
	558	548	571	542	547	539	557	525	516	540	499	533	542	526	547
	550	538	558	530	535	530	544	516	505	527	487	522	534	510	533
	539	527	551	519	524	523	533	506	497	515	477	518	522	502	522
	534	523	544	513	520	516	529	501	490	513	470	507	519	492	513
	529	511	537	504	514	509	519	493	487	502	465	497	507	484	507
	523	512	532	498	512	506	513	492	481	495	461	502	505	483	498
	510	505	529	496	505	501	504	487	479	492	456	487	500	478	495
	514	503	524	492	504	497	504	482	475	487	453	484	499	475	488
	513	497	522	490	501	498	501	480	471	484	448	483	494	474	487
	509	497	518	485	497	492	497	476	468	476	442	476	496	470	481
	509	495	517	485	496	495	492	473	468	474	441	476	491	467	481
	504	490	514	483	493	490	492	469	465	475	442	472	489	464	477
	502	488	495	477	489	487	488	469	464	472	430	467	485	462	474
	499	487	507	475	488	487	488	463	462	467	434	469	484	459	474
	500	486		475	485		488	465		467	433		482	456	
Time (days)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.3	0.3	0.2	0.2	0.3	0.2	0.2	0.2
	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.4	0.5	0.4	0.4	0.4
	0.9	1.0	0.9	0.9	1.0	0.9	0.9	1.1	1.0	0.9	1.0	0.9	0.9	1.0	0.9
	1.2	1.2	1.2	1.1	1.2	1.2	1.2	1.3	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	1.9	1.9	1.9	1.9	1.9	1.9	2.0	2.0	1.9	2.0	1.9	1.9	1.9	1.9	1.9
	3.0	3.0	3.0	3.0	2.9	3.0	3.0	3.0	3.1	3.0	3.0	3.1	3.0	2.9	3.0
	3.9	3.9	5.0	3.9	3.9	5.0	4.0	4.0	5.1	4.0	4.0	5.1	4.0	3.9	5.0
	5.9	6.3	7.0	5.9	6.3	7.0	5.9	6.4	7.0	5.9	6.3	7.0	5.9	6.3	7.0
	8.0	7.1	9.1	8.0	7.1	9.1	8.1	7.1	9.1	8.1	7.1	9.1	8.0	7.0	9.1
	10.0	9.0	12.0	10.0	9.0	12.0	10.0	9.1	12.0	10.0	9.0	12.0	10.0	9.0	11.9
	12.0	11.1	15.0	11.9	11.1	15.0	12.0	11.2	15.0	12.0	11.1	15.0	12.0	11.1	14.9
	14.1	14.0	16.0	14.0	14.0	16.0	14.1	14.1	16.0	14.1	14.0	16.0	14.1	14.0	15.9
	16.9	17.0	19.0	16.9	17.0	19.0	17.0	17.1	19.0	17.0	17.0	19.0	17.0	17.0	18.9
	19.9	18.0	21.0	19.9	18.0	21.0	20.0	18.1	21.0	20.0	18.0	21.0	20.0	18.0	20.9
	20.9	21.0	22.9	20.9	21.0	22.9	21.0	21.1	22.9	21.0	21.0	22.9	21.0	21.0	22.9
	23.9	23.0	26.0	23.9	23.0	26.0	24.0	23.1	26.0	24.0	23.0	26.0	24.0	23.0	26.0
	25.9	24.9	27.9	25.9	24.9	27.9	26.0	25.0	28.0	26.0	24.9	28.0	26.0	24.9	27.9
	27.9	28.0		27.8	28.0		27.9	28.1		27.9	28.0		27.9	28.0	

Appendix 6.3 The electrical conductivity of the drainage water (EC_d), cumulative measured drainage ($\sum$ D) and the cumulative salt removed ($\sum$ SR) during the entire drainage period of all the lysimeters on both soils.

Soil		A			B		
EC_i (mS m^{-1})	Rep	EC_d (mS m^{-1})	$\sum$ D (mm)	$\sum$ SR (kg ha^{-1})	EC_d (mS m^{-1})	$\sum$ D (mm)	$\sum$ SR (kg ha^{-1})
	1	107	237	1922	64	121	588
	2	113	239	2049	68	183	941
	3	103	251	1953	69	171	894
15	**Average**	**108**	**242**	**1975**	**67**	**158**	**808**
	1	487	296	10929	296	204	4577
	2	407	238	7318	263	190	3778
	3	390	239	7057	267	190	3842
150	**Average**	**428**	**258**	**8435**	**275**	**195**	**4066**
	1	799	282	17038	467	161	5706
	2	687	367	19076	664	212	10639
	3	843	288	18398	501	202	7665
300	**Average**	**777**	**312**	**18171**	**544**	**192**	**8004**
	1	1131	266	22778	696	194	10218
	2	979	283	20996	803	220	13368
	3	1171	318	28206	716	182	9856
450	**Average**	**1094**	**289**	**23993**	**738**	**199**	**11147**
	1	1371	310	32169	872	198	13081
	2	1391	337	35417	1100	186	15519
	3	1381	355	37116	889	175	11744
600	**Average**	**1381**	**334**	**34901**	**954**	**186**	**13448**

Appendix 6.4 Water content of the lysimeters during the entire leaching period for the EC_i treatments on both soils

Soil	A														
EC_i (mS m^{-1})	15			150			300			450			600		
	Rep														
Time (days)	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
0	409	419	427	389	401	423	453	435	436	444	438	421	428	418	434
1	408	413	425	384	399	422	449	429	433	440	437	416	425	411	425
3	402	411	422	382	393	417	443	424	431	434	430	414	420	411	430
4	402	410	421	379	393	414	440	424	431	437	431	412	418	412	426
5	444	455	469	422	438	455	491	473	478	481	481	461	468	467	475
6	432	443	461	414	433	449	479	461	470	462	474	453	463	455	471
7	462	478	493	444	472	485	518	501	509	518	513	498	494	495	514
8	443	461	474	425	452	466	489	474	482	492	495	468	475	466	483
9	427	450	458	411	440	454	478	462	471	481	482	456	465	450	465
10	421	437	443	402	431	445	466	449	456	469	470	441	454	435	451
11	417	431	434	395	422	434	459	440	456	461	464	435	446	419	451
12	451	469	474	436	466	474	511	489	497	511	506	482	490	477	493
13	442	457	460	423	449	439	491	473	483	493	493	468	481	472	482
14	475	480	495	447	482	503	515	511	524	525	529	509	523	517	529
15	455	463	480	433	460	475	496	482	492	504	506	475	491	478	495
16	434	450	461	410	444	457	482	464	473	486	487	462	482	456	479
17	425	439	452	406	438	448	471	456	464	480	478	452	467	450	467
18	416	430	442	403	429	439	466	449	459	469	472	445	459	443	461
19	456	469	479	437	472	480	516	497	515	516	524	498	506	496	516
20	439	456	461	425	454	468	497	483	494	498	502	479	493	480	498
21	479	495	494	470	500	500	545	524	540	546	561	533	539	534	533
22	449	465	471	442	469	476	500	485	496	514	519	489	495	489	500
23	431	451	454	504	452	464	484	463	479	490	512	467	510	444	473
24	423	436	442	408	442	450	474	457	469	478	489	453	471	451	465
25	412	430	433	403	435	443	469	451	467	480	480	450	463	443	464
26	461	474	474	442	469	482	520	508	524	526	534	507	520	494	513
27	441	456	457	425	462	468	499	487	497	506	509	481	503	481	498
28	477	492	490	458	488	496	545	525	530	546	550	515	539	519	533
29	452	466	471	442	471	480	507	489	502	519	525	491	505	487	504
30	439	454	457	423	457	467	496	471	484	501	506	469	487	464	484
31	426	444	447	411	447	461	485	461	474	492	496	459	477	454	475
32	422	437	439	407	443	447	476	453	470	483	491	453	469	449	467
33	461	473	475	442	477	484	527	503	516	527	536	489	513	499	512
34	436	453	460	429	463	471	503	485	496	506	514	480	500	481	501
35	478	495	491	464	500	499	548	527	540	546	559	523	550	525	536
36	447	467	473	437	457	482	503	492	501	523	525	492	507	483	500
37	433	453	456	418	454	465	489	476	483	505	503	474	492	460	482
38	422	444	445	410	449	455	482	465	473	494	495	459	480	452	469
39	411	430	433	401	436	447	475	448	458	481	481	446	468	443	469
40	451	465	472	444	474	481	520	499	507	525	528	497	514	491	511
41	439	448	459	426	457	463	504	484	491	507	510	481	501	485	500
42	470	486	488	472	499	499	549	525	538	548	565	527	545	520	536
43	445	455	461	442	463	472	510	486	496	514	521	485	509	478	501
44	429	447	449	426	452	463	492	478	483	503	510	475	494	462	484
45	418	435	437	406	445	456	485	463	476	492	495	460	483	453	472
46	412	428	402	406	439	448	479	459	466	483	489	447	481	444	466
47	443	462	458	444	471	480	524	488	515	531	528	498	510	493	515
48	430	451	459	431	461	471	504	489	499	515	515	489	503	487	504
49	422	442	445	421	448	461	493	476	488	501	502	477	492	469	489
50	414	431	436	414	437	453	483	465	478	493	495	466	481	458	479

Appendix 6.4 continued

Soil	B														
EC_i (mS m^{-1})	15			150			300			450			600		
	Rep														
Time (days)	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
0	525	500	527	519	526	533	518	504	528	509	502	513	532	500	515
1	519	496	521	513	521	525	513	501	520	501	500	509	526	492	511
3	514	490	518	509	513	519	510	495	515	494	492	500	516	485	504
4	556	534	555	555	560	565	552	539	555	536	537	548	566	531	552
5	548	519	540	540	545	542	547	527	542	534	525	536	546	518	536
6	539	509	528	529	535	531	536	512	531	522	511	524	533	504	529
7	573	549	565	567	572	574	576	549	571	565	555	562	579	530	568
8	551	522	543	542	552	545	555	531	550	543	528	541	546	527	547
9	539	509	529	526	535	534	540	517	535	528	515	528	537	509	535
10	532	497	519	519	527	526	533	507	528	517	506	518	525	500	523
11	565	537	559	556	566	570	566	545	567	557	546	560	573	539	561
12	548	522	539	546	550	546	557	534	552	544	533	543	553	525	550
13	540	507	530	528	534	534	542	520	544	531	517	528	542	511	534
14	573	543	561	566	576	574	580	563	579	578	562	573	580	550	562
15	553	520	540	546	553	552	563	541	558	554	537	546	559	530	552
16	534	505	530	532	545	538	551	522	547	540	523	533	542	527	542
17	533	501	521	527	532	536	544	517	539	534	514	526	539	508	534
18	569	544	561	565	574	576	586	558	577	572	557	570	583	552	565
19	556	519	540	543	552	549	563	538	559	551	535	548	558	530	551
20	539	506	529	527	541	556	556	525	544	541	525	536	550	519	543
21	570	551	567	568	576	588	586	560	584	574	561	579	586	564	581
22	552	522	539	549	553	556	569	544	562	561	546	553	565	535	557
23	547	515	527	546	542	540	561	530	548	546	527	541	554	523	544
24	536	497	522	528	530	540	547	519	543	537	518	532	544	516	538
25	570	542	560	575	575	576	586	564	592	578	563	578	586	557	575
26	552	522	544	552	557	554	568	544	564	558	545	551	566	539	561
27	542	506	531	536	543	545	567	530	542	547	530	537	555	525	551
28	573	555	559	574	581	584	594	567	583	586	572	585	589	562	586
29	558	526	542	552	554	558	577	546	561	566	547	555	568	540	582
30	547	514	532	541	543	547	562	539	551	553	534	543	557	529	555
31	539	501	525	532	535	536	559	526	544	546	526	535	549	520	548
32	568	547	564	569	571	580	593	562	584	583	563	575	591	562	585
33	550	530	550	557	560	563	575	546	568	571	558	562	572	547	569
34	543	509	535	542	548	550	562	532	557	555	536	545	561	532	557
35	559	546	569	573	582	590	593	567	588	592	572	581	597	576	590
36	550	524	545	556	561	557	575	550	564	571	551	560	569	545	565
37	541	509	535	542	547	548	565	536	557	558	537	546	561	530	556
38	535	499	525	533	540	543	557	527	548	548	529	538	551	525	547
39	555	552	562	573	579	590	591	569	591	587	570	583	593	567	573
40	549	525	545	555	561	559	575	551	563	578	554	562	575	545	567
41	540	506	532	542	531	550	562	534	555	557	535	550	556	532	559
42	561	547	566	583	574	586	597	569	592	587	575	588	597	572	592
43	547	522	543	557	558	554	575	552	566	573	551	566	574	545	572
44	547	514	530	544	548	551	563	538	558	562	538	551	566	535	559
45	533	504	525	534	535	541	556	530	549	551	527	539	551	522	551
46	562	547	562	576	572	589	596	567	588	592	575	577	594	569	593
47	550	522	545	558	561	559	579	552	572	573	552	563	576	549	573
48	539	509	534	542	547	554	567	537	560	559	538	550	564	536	563
49	535	500	526	537	538	544	559	530	554	554	531	542	557	528	557
50	530	494	521	531	534	539	553	525	546	549	527	534	549	521	551

Appendix 6.5 The electrical conductivity of the soil water (EC_{sw}, mS m^{-1}) measured at specific times (days) during the leaching period for all the lysimters of the EC_i treatments on both soils

Soil A																
Time (days)	EC_i (mS m^{-1})	15			150			300			450			600		
		Rep														
	Depth (mm)	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
	300	73.4	72.5	71.6	118	131	96.9	310	145	211	232	177	173	323	235	438
	500	83.3	85.1	85.2	202	168	173	287	295	286	465	477	406	617	600	541
	700	75.5	78.2	69.7	188	554	201	298	296	286	452	455	463	666	1344	638
5	900	100	92.1	89.2	207	199	203	303	355	287	496	516	440	670	605	610
	1100	89.9	87.8	92.4	212	188	191	309	289	309	596	599	474	702	597	723
	1500	91.1	87.6	99	593	444	628	476	320	613	1094	1177	687	984	907	878
	Ave	**86**	**84**	**85**	**253**	**281**	**249**	**331**	**283**	**332**	**556**	**567**	**441**	**660**	**715**	**638**
	300	71.3	54.4	57.5	75.7	86.5	58.8	106	92.4	92.2	124	79.7	113	102	160	224
	500	62.9	57.5	66.6	104	88.7	81	158	118	144	120	142	116	121	185	119
	700	66.5	67.3	72.6	114	187	102	139	113	136	114	136	117	486	176	161
12	900	86.8	78.6	75.8	156	108	114	164	168	181	338	456	117	610	317	160
	1100	98.3	102	80.4	204	180	174	271	159	234	490	486	209	621	526	436
	1500	92.9	92.2	86.7	465	380	428	305	281	412	674	782	493	737	633	633
	Ave	**80**	**75**	**73**	**187**	**172**	**160**	**191**	**155**	**200**	**310**	**347**	**194**	**446**	**333**	**289**
	300	82.1	57.3	68.3	69.2	71.1	65.6		78.3	73.7	101	80.4	81.3	90.7	94.3	190
	500	63.7	58.4	68.4	93.1	80.4	68	103	83.8	96.7	97.8	111	117	83.5	145	120
	700	63.4	65.2	58.6	104	111	87.1	100	95.5	106	110	102	103	142	115	92.3
19	900	77	68.2	66.4	99.1	86.9	87.1	102	145	101	103	121	119	137	102	92.7
	1100	80.8	74.2	70.8	113	93.4	93.3	119	97.7	96.4	140	184	108	208	116	90.5
	1500	80.4	89.6	74.7	232	173	192	286	120	292	462	462	242	630	332	582
	Ave	**75**	**69**	**68**	**118**	**103**	**99**	**142**	**103**	**128**	**169**	**177**	**128**	**215**	**151**	**195**
	300	79.3	54.9	72	70.5	84.3	70.1	173	84.6	78	96.7	78.8	83	92.7	90.7	186
	500	65.9	57.4	73.7	92.8	79.6	68.9	102	82.2	133	94.8	103	91.8	88.8	143	99.7
	700	66.1	73.8		96.9	103	88.7	89.3	91.5	101	86.7	107	101	124	103	113
26	900	76.1	70.2	68.5	93.7	85.1	83.1	93.4	138	108	90.1	114	85	102	99	153
	1100	72.9	72.8	71.3	103	90.2	89.3	108	91.9	89.2	104	123	86.9	109	110	88.8
	1500	76.6	84.4	71.6	153	138	138	138	96.7	171	195	239	124	205	104	114
	Ave	**73**	**69**	**71**	**102**	**97**	**90**	**117**	**97**	**113**	**111**	**127**	**95**	**120**	**108**	**126**
	300	79.3	61.5	72.9	76.9	88.8	81.9	123	84.4	85.8	93.9	81.3	91.8	91.8	106	144
	500	65.9	62	77.9	76.1	77.6	70.6	95.9	82.7	95.3	94.6	104	110	87.4	163	110
	700	67	67.9	86.8	95.6	102	85.3	85.2	86.1	115	91.5	103	100	129	102	111
33	900	73.4	69.6	69.4	92	83.3	79.4	90.8	168	97.4	83.4	111	81.5	101	99.9	97.8
	1100	72.1	71.4	74.5	97.6	87.6	84.2	98.6	86.7	85.9	95.7	122	85.7	101	102	90.2
	1500	75.8	83.5	62.1	117	112	122	118	89.5	112	128	131	105	120	97.2	92.2
	Ave	**72**	**69**	**74**	**93**	**92**	**87**	**102**	**100**	**98**	**98**	**109**	**96**	**105**	**112**	**108**
	300	83.9	67.4	65.4	75.6	77.7	73.6	94.1	80.3	83.6	87.5	75.9	88.7	110	100	103
	500	64	66.2	71.4	86.5	77.4	72.4	94.5	84.6	97	92.1	101	99.3	92	161	104
	700	71.2	71.8	71.9	94.2	95.1	85.2	82.1	84.4	120	84.9	102	104	87.5	95.2	112
40	900	74.4	72.1	67.4	90.4	84.6	81.1	84.6	167	103	81.7	110	83.2	99.2	98.8	88.3
	1100	73	71.8	74.4	92	83.3	78.7	96.4	81.1	83.3	89.5	118	83.8	102	103	98.4
	1500	72.7	76.5	162	102	97.8	98.4	101	85.6	99.9	109	112	92.9	103	92.9	85.2
	Ave	**73**	**71**	**89**	**90**	**86**	**82**	**92**	**97**	**98**	**91**	**103**	**92**	**99**	**109**	**99**
	300	85.2	67.1	68.4	71.2	78.5	78.1	125	83	75.6	84.8	73.5	86.4	87.2	109	117
	500	65.9	69.1	70.9	85.6	75.6	72.4	91.9	84.7	102	89.9	98.8	99.6	88	120	105
	700	69.4	71.9	73	91.2	86.1	84.6	78.7	82.6	113	87.1	101	105	11.7	103	99.1
47	900	75	73.7	70.4	89.1	85.1	83.4	83.7	147	95.7	83.5	109	83.4	104	97.8	92.4
	1100	73.6	72.1	74	88.8	83.4	78.6	88.8	77.5	84.1	84.6	118	80.2	104	102	85.8
	1500	72.4	77	62.7	98.2	93.2	95.5	84	81.2	100	101	107	96.3	102	90.3	84.5
	Ave	**74**	**72**	**70**	**87**	**84**	**82**	**92**	**93**	**95**	**88**	**101**	**92**	**83**	**104**	**97**

Appendix 6.5 continued

Soil B																
Time (days)	EC_i (mS m^{-1})	15			150			300			450			600		
		Rep														
	Depth (mm)	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
4	300	57.7	67.2	71.9	101	117	114	272	156	275	177	161	287	204	339	727
	500	49.7	55.1	80.6	145	177	284	294	289	285	472	419	468	560	866	676
	700	64.5	83.1	79.1	177	306	169	378	346	305	711	458	539	802	672	899
	900	93.2	105	106	242	322	225	577		477	937	535	713	1485	910	1569
	1100		104	103	402	466	400	689	820	769	1094	706	1135	1762	1213	1727
	1500	79.5		99.3	425	361	454			651	888	875	1074	1280		
	Ave	**69**	**83**	**90**	**249**	**291**	**274**	**442**	**403**	**460**	**713**	**526**	**703**	**1016**	**800**	**1120**
11	300	53.8	64.9	69.4	78.5	81.4	86.5	118	97	146	125	106	94.3	108	139	200
	500	52.8	56.6	66.2	83.4	85.4	100	164	109	119	118	254	117	140	175	366
	700	59.9	69.7	71.8	98.6	201	96.3	388	208	201	425	193	220	468	625	618
	900	79.9	94.9	87.4	126	185	165	466		383	668	358	364	874	697	1177
	1100		103	85.4	209	282	289	565	509	552	930	523	660	1507	814	1420
	1500	85.4	76.9	94.3	522	419	646	616	902	710	885	658	833	1501		
	Ave	**66**	**78**	**79**	**186**	**209**	**231**	**386**	**365**	**352**	**525**	**349**	**381**	**766**	**490**	**756**
18	300	52.8	66.3	62.1	71.1	80.1	79.4	102	83.3	144	104	95.3	94.6	97.9	108	131
	500	51.6	57.1	77.4	72.1	77.7	83.5	104	96.4	92.3	94.4	101	99.4	95.1	114	144
	700	57.5	65.4	61.8	76.7	206	73.2	276	103	98.7	176	105	111	188	173	206
	900	76.1	78.1	74.8	81.8	96.6	93.6	355		200	390	188	113	447	327	733
	1100	65.8	88.4	73.7	112	161	166	427	238	346	670	281	271	783	537	883
	1500	83.7	97.4	77.1	255	341	415	710	748	711	534	858	783	1337	694	
	Ave	**65**	**75**	**71**	**111**	**160**	**152**	**329**	**254**	**265**	**328**	**271**	**245**	**491**	**325**	**420**
25	300	54	67.2	63.5	70.7	82.3	97.8	96.1	78.9	113	101	94.6	97.5	94.2	106	116
	500	51.2	58.2	68.9	70	79.3	86.3	103	87.4	86.7	97.5	96.9	102	92.6	105	132
	700	57.2	64.7	61.6	83.9	104	69.1	171	84.7	85.1	143	87.8	97.3	84.5	148	118
	900	72.5	74.5	70.4	72.9	78.6	77.1	236		119	205	111	85.2	214	154	346
	1100		78.1	76.8	83.3	111	107	301	157	193	403	153	124	409	269	477
	1500	74.8	98.3	75.5	173	288	242	612	507	562	525	582	408	912	648	
	Ave	**62**	**74**	**69**	**92**	**124**	**113**	**253**	**183**	**193**	**246**	**187**	**152**	**301**	**238**	**238**
32	300	56.6	67	65.8	74.4	83.9	95.5	99.7	83.9	144	106	102	101	99.4	104	127
	500	53.5	61	89.5	67.2	78.7	85.9	105		94.2	95.5	105	104	97.9	109	141
	700	69	67.4	68.8	87.5	101	77.1	129	86.6	95.7	129	93.9	102	115	135	145
	900	72.3	76.6	69.6	72.1	74.9	76.7	181	87.9	133	127	93	84.1	139	116	203
	1100		73.1	73.2	74.8	99.6	94.6	239	106	140	252	93.4	99.9	226	168	232
	1500	73.9		78.2	141	200	176	485	59.7	386	387	331	207	515	270	
	Ave	**65**	**69**	**74**	**86**	**106**	**101**	**207**	**85**	**166**	**183**	**136**	**116**	**199**	**150**	**170**
39	300	56.4	70.4	64	76.5	90.3	98.8	89.8	80.4	144	108	95.8	98.2	103	122	112
	500	54	62.3	74.6	70.4	78.0	76.3	101	78	86.0	100	99.6	105	99.1	100	121
	700	69	65.2	67.5	83	114	73	98.4	85.2	91.9	77.2	92.6	106	94.8	118	111
	900	68.2	72.7	66.7	68.8	70.7	74.4	135		103	102	86.1	84.2	109		133
	1100	60.5	68.2	72.3	71.8	91.1	88.5	203	90	106	188	77.1	90.4	154	121	133
	1500	62.8	59.7	69.1	110	150	135	356	204	250	258	231	132	302	311	526
	Ave	**62**	**66**	**69**	**80**	**99**	**91**	**164**	**108**	**130**	**139**	**114**	**102**	**144**	**154**	**189**
46	300	62.2	77.6	69.1	77.3	87.1	96.4	97.4	85.7	140	114	101	94.8	106	118	114
	500	59.7	64.8	73.3	74.1	89.9	84	102	84.2	92.1	104	108	121	106	98.9	115
	700	65.4	68.1	69.6	87.1	108	71.3	103	89.1	98.8	116	98.4	105	97.9	98	113
	900	69.8	79.2	77.4	73	71.5	74.5	121		106	99.4	93.1	86.4	104	110	115
	1100	68.6	69.5	77	74.5	92.9	86.9	201	92	107	148	77.5	161	131	104	106
	1500	59.9		66	103	127	116	290		189	159	174	109	210	542	
	Ave	**64**	**72**	**72**	**81**	**96**	**88**	**152**	**88**	**122**	**123**	**109**	**113**	**126**	**179**	**112**

Appendix 6.6 The full data set of the electrical conductivity of the drainage water (EC_e, mS m^{-1}) as well as the measured drainage (mm) for all the lysimeters of the EC_i treatments on both soils

Soil A															
EC_i (mS m^{-1})	15			150			300			450			600		
Rep	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Time (days)	Drainage (mm)														
1	0.4	0.4	0.5	0.4	0.5	0.5	0.3	0.4	0.5	0.5	0.4	0.4	0.3	0.4	0.5
3	2.1	0.7	1.3	1.2	1.2	2.2	1.1	1.2	1.5	0.9	0.6	1.1	0.7	0.7	0.5
4	2.0	0.8	1.4	1.1	1.2	2.1	1.6	1.3	1.5	1.0	0.7	1.1	0.8	1.2	1.2
5	2.3	1.4	1.4	1.5	1.6	2.1	2.0	2.2	2.1	1.6	1.1	1.7	1.4	2.2	1.1
6	10.1	5.6	4.8	5.1	11.8	4.6	9.7	10.2	9.0	5.1	2.0	4.6	5.6	8.5	6.3
7	10.2	8.7	11.8	9.8	8.6	8.6	12.3	7.9	11.0	10.0	6.5	11.8	11.2	19.6	8.3
8	18.7	20.1	19.9	24.2	18.5	20.0	22.5	20.5	24.1	20.2	16.0	24.0	14.6	26.1	34.3
9	9.7	9.7	10.8	10.6	8.8	9.6	10.8	10.9	10.9	9.9	8.5	9.1	9.8	14.5	16.3
10	12.7	13.0	16.0	12.8	11.0	8.9	10.3	12.8	11.8	12.9	11.8	13.0	12.0	11.8	10.2
11	10.0	7.9	6.0	8.7	10.3	11.8	7.9	9.1	8.6	10.0	10.2	8.3	7.9	6.2	6.4
12	8.2	9.4	3.9	10.6	8.3	5.4	5.6	9.0	6.5	11.8	8.2	5.7	6.1	5.6	5.0
13	14.1	13.3	13.3	12.5	12.7	14.1	10.6	12.6	11.8	11.8	10.2	10.4	8.4	7.9	9.4
14	12.1	13.8	15.7	12.0	12.1	11.8	12.9	13.7	13.4	13.5	10.4	12.9	13.0	14.1	14.3
15	27.5	20.5	15.7	24.5	20.4	20.4	28.2	24.3	27.5	23.8	20.4	27.5	35.4	33.8	35.7
16	18.1	16.6	16.8	16.4	15.1	17.3	14.0	16.5	15.2	16.4	15.0	14.4	14.3	16.8	16.3
17	10.3	9.0	2.1	8.1	10.0	10.6	7.1	8.2	8.1	8.2	8.9	10.1	8.1	8.0	7.2
18	8.7	10.6	18.1	7.9	10.3	10.5	6.0	8.7	7.9	8.5	8.7	6.5	7.0	5.4	5.4
19	8.0	8.2	12.5	5.2	8.1	8.1	4.6	8.4	5.6	5.1	6.6	4.5	4.9	8.0	4.1
20	14.6	12.1	11.8	13.5	13.7	12.0	12.0	12.1	14.2	12.0	12.1	12.4	10.0	14.0	9.9
21	12.0	15.7	15.7	15.7	12.2	13.3	13.3	14.4	14.1	13.5	12.4	14.1	14.4	12.9	14.5
22	25.1	20.9	11.8	33.4	20.9	19.6	28.7	28.7	31.4	25.2	25.2	26.0	29.0	34.1	33.8
23	17.2	11.8	19.6	14.2	15.7	15.7	13.7	14.2	15.7	17.2	17.4	23.6	17.8	12.4	14.2
24	14.6	11.8	20.3	16.4	12.8	12.7	10.2	8.8	8.5	10.6	13.0	8.8	8.6	5.2	8.7
25	8.1	9.5	6.5	6.5	8.1	9.5	5.1	4.2	5.9	6.9	8.2	9.8	5.7	5.2	5.5
26	5.0	9.0	11.9	5.7	8.0	8.0	6.8	9.8	5.6	5.6	8.9	5.0	4.1	5.3	4.6
27	16.7	16.8	11.8	12.5	14.7	13.6	9.0	16.8	19.6	13.2	11.8	15.7	14.8	6.3	10.8
28	13.9	15.7	14.2	12.1	16.1	11.8	13.2	17.7	17.4	12.1	11.8	14.2	15.7	15.7	14.2
29	28.0	24.1	16.1	29.3	23.6	20.0	31.9	31.9	31.9	26.1	24.0	27.5	32.0	31.7	35.5
30	16.0	15.7	9.7	15.7	13.2	13.2	15.7	13.2	15.9	15.7	13.3	16.8	13.1	17.1	16.8
31	8.2	8.2	9.6	8.1	8.8	8.8	7.9	6.1	8.6	8.1	8.1	9.6	6.9	8.5	9.1
32	11.8	11.8	19.6	8.8	11.8	11.8	8.5	10.0	7.9	9.4	9.6	9.4	8.7	7.9	6.7
33	9.2	10.6	12.0	7.1	9.6	13.3	9.6	9.6	4.7	8.2	9.3	5.6	6.7	9.5	9.1
34	12.0	17.5	14.2	15.7	17.4	12.0	14.4	13.3	17.1	15.7	13.3	11.8	17.5	10.1	11.9
35	15.7	15.7	12.9	13.3	14.2	13.9	13.2	15.7	13.2	11.8	13.6	15.7	13.4	13.1	14.1
36	27.5	29.9	12.2	28.4	23.6	16.3	31.4	28.1	32.2	25.8	25.7	27.5	34.2	35.8	35.7
37	15.7	15.7	14.2	16.7	14.2	19.6	14.2	12.5	15.7	15.7	14.2	16.1	17.1	13.7	14.2
38	13.5	15.7	17.2	10.8	14.2	14.2	10.2	10.8	12.4	13.9	12.7	14.1	11.8	13.7	9.1
39	8.8	11.8	12.4	7.9	11.8	10.3	6.1	9.0	4.1	8.9	9.0	7.9	7.9	6.0	5.8
40	7.9	9.2	16.2	6.1	9.8	9.2	5.0	9.0	6.0	7.9	8.3	5.6	5.9	5.3	4.7
41	13.8	14.4	13.7	10.9	14.5	14.2	13.6	15.7	11.8	11.0	11.8	10.7	7.9	8.9	6.8
42	13.1	12.2	13.5	12.1	13.6	12.0	12.0	13.6	13.9	12.1	12.1	12.6	12.1	14.2	12.5
43	27.5	27.5	20.6	32.6	23.6	23.6	35.4	29.6	32.3	28.3	27.5	26.4	31.4	35.9	39.3
44	14.7	19.6	11.8	19.6	15.7	15.7	11.8	14.2	15.7	15.7	15.7	11.8	14.2	16.7	17.6
45	8.3	9.0	10.3	8.5	10.2	8.8	8.4	8.9	9.6	8.9	9.0	12.4	8.5	9.7	9.1
46	7.9	9.8	9.3	7.9	9.8	9.8	6.2	7.9	7.9	9.6	9.8	8.6	7.2	5.8	9.5
47	6.7	8.0	6.3	6.3	9.3	9.6	5.1	8.9	6.2	8.0	8.9	9.7	5.8	5.4	4.8
48	10.1	12.2	10.0	11.8	12.2	12.1	14.5	10.1	10.2	12.1	12.1	10.6	8.2	9.5	11.8
49	11.8	13.5	12.5	11.8	11.8	11.8	12.9	11.8	13.1	11.8	11.8	12.6	11.0	12.6	12.3
50	7.9	8.0	10.6	8.6	8.9	8.9	8.4	9.1	8.6	8.8	8.9	8.3	7.9	8.2	8.2

Soil A															
EC_i (mS m^{-1})	15			150			300			450			600		
Rep	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Time (days)	EC_e (mS m^{-1})														
1	87	98	93	595	438	399	839	646	854	1168	1028	1179	1422	1347	1258
3	93	87	87	491	426	404	841	643	838	1158	999	1141	1387	1320	1273
4	93	89	89	503	437	411	836	643	843	1188	1035	1168	1375	1356	1277
5	91	89	87	500	431	410	838	627	831	1168	1018	1143	1369	1325	1254
6	87	89	81	468	421	696	824	630	785	1165	1012	1085	1362	1295	995
7	81	83	82	466	417	408	822	628	750	1111	959	1013	1298	1231	1175
8	76	76	80	453	397	437	800	609	699	1087	944	935	1195	1119	1156
9	72	73	82	434	714	412	757	626	718	1116	943	891	1199	1022	1087
10	74	77	82	442	425	465	758	644	726	1141	980	943	1197	1066	1018
11	76	78	82	574	416	431	759	611	730	1108	925	893	1149	1024	951
12	76	75	80	431	413	435	740	579	718	1097	993	877	1134	1024	911
13	72	76	78	396	390	412	686	469	640	1053	957	819	1074	962	854
14	69	71	74	368	357	382	628	424	587	964	885	736	964	890	843
15	74	75	74	356	355	372	566	376	551	927	889	719	916	862	846
16	76	75	74	327	340	369	554	381	516	837	877	682	842	769	811
17	83	77	73	318	328	377	552	380	519	819	884	677	838	765	751
18	80	76	76	312	310	365	540	369	496	773	866	649	802	739	706
19	79	75	76	314	308	358	534	367	478	758	857	638	794	734	671
20	83	81	78	279	288	339	527	346	416	742	800	589	807	708	673
21	84	79	77	264	277	317	492	325	402	704	773	587	771	699	691
22	84	77	71	231	246	288	415	270	349	640	697	596	709	620	669
23	83	77	75	292	243	276	403	394	331	595	675	619	677	603	554
24	84	78	76	208	224	253	388	272	315	563	639	483	659	503	435
25	83	77	75	198	212	250	370	265	298	541	618	454	644	474	377
26	82	75	75	190	206	237	368	273	285	527	601	437	637	472	350
27	82	75	72	181	194	210	350	209	254	512	524	372	603	406	308
28	81	75	70	170	189	204	333	212	244	487	492	358	573	371	350
29	80	75	69	162	174	183	279	212	221	434	428	332	504	301	359
30	80	76	68	153	176	178	265	292	210	386	426	277	442	265	319
31	83	78	70	150	183	179	263	207	209	360	430	254	415	250	255
32	79	74	71	143	173	173	248	201	182	334	405	252	387	254	272
33	80	76	72	142	164	160	242	76	182	311	394	226	320	256	209
34	80	75	69	133	150	146	220	171	168	281	343	201	310	209	187
35	77	73	69	129	148	142	173	153	159	243	331	200	170	189	219
36	77	72	65	122	139	132	174	127	142	220	291	166	209	159	242
37	78	73	67	118	142	129	202	147	131	198	290	189	273	148	167
38	77	73	68	116	143	123	175	145	124	189	289	117	135	142	205
39	77	73	69	116	139	124	171	144	121	175	268	153	147	133	147
40	78	73	71	118	137	120	174	142	119	171	267	148	145	134	141
41	77	72	69	111	121	112	147	121	113	160	230	134	135	120	127
42	77	71	68	106	124	109	139	113	111	153	218	132	127	112	143
43	75	71	67	100	113	103	121	100	105	139	187	125	116	107	165
44	76	71	69	99	116	103	126	106	103	133	184	122	111	105	141
45	77	71	68	99	116	101	123	106	102	130	181	118	110	102	118
46	77	71	68	98	117	100	123	105	101	127	173	115	110	100	110
47	78	72	68	99	115	100	123	108	109	127	167	111	109	101	107
48	77	71	67	95	107	96	110	100	99	123	152	107	109	96	105
49	76	71	67	92	102	95	106	94	99	120	145	107	106	95	108
50	77	71	67	92	103	94	109	98	98	120	140	107	105	95	108

Appendix 6.6 continued

Soil B															
EC_i (mS m^{-1})	15			150			300			450			600		
Rep	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Time (days)	Drainage (mm)														
1	0.6	1.0	1.0	2.6	1.2	1.1	1.6	0.6	1.0	0.6	0.8	0.4	0.0	0.5	0.9
3	0.7	2.6	2.5	3.1	3.9	5.7	0.6	2.1	3.9	0.7	1.6	2.8	3.1	2.6	0.5
4	5.3	2.1	4.3	4.8	4.0	6.2	4.7	5.2	4.4	4.2	4.6	6.8	5.7	2.2	2.7
5	2.2	12.6	11.8	10.4	10.2	9.5	0.1	9.7	9.3	1.9	5.2	5.2	5.8	8.7	1.1
6	10.0	16.6	14.6	14.2	13.6	17.2	9.1	14.0	14.0	10.1	13.9	12.4	16.0	16.9	9.5
7	10.2	9.6	8.6	10.0	9.4	12.6	12.1	10.1	9.7	10.1	10.3	13.6	13.0	8.9	8.2
8	22.0	21.9	25.7	21.6	21.2	19.6	14.5	19.7	19.6	17.1	18.5	11.9	19.6	21.3	19.6
9	11.8	13.3	12.5	10.1	14.0	12.8	10.2	12.5	13.0	12.7	12.8	13.5	13.9	12.7	12.7
10	8.7	9.9	10.1	9.7	9.6	10.1	10.2	9.4	9.5	9.7	10.2	9.4	10.2	11.8	5.9
11	9.1	6.0	7.9	8.6	8.0	9.4	10.3	12.1	8.6	9.1	8.3	11.9	8.5	6.3	8.2
12	14.6	17.3	17.2	10.9	14.6	13.1	6.1	7.9	13.4	5.7	10.7	10.3	13.2	16.1	9.0
13	11.8	14.2	13.7	14.5	13.7	13.6	10.7	13.1	13.7	11.8	13.3	12.6	13.2	13.7	12.7
14	13.3	8.5	9.8	9.6	11.9	12.1	12.4	10.5	9.5	9.8	11.8	14.0	4.1	8.1	9.1
15	21.4	22.1	20.9	18.9	19.6	18.3	12.7	26.6	21.3	25.9	19.6	17.9	18.2	21.4	7.9
16	12.3	15.9	12.8	14.0	14.4	14.0	12.5	16.2	14.1	14.4	16.7	13.7	14.2	14.2	12.7
17	6.3	11.8	7.9	7.9	7.9	7.4	6.1	7.0	7.9	8.5	8.0	6.8	8.3	7.9	6.9
18	10.4	6.7	7.9	8.0	7.9	9.6	10.3	8.8	8.6	3.9	13.0	12.1	8.4	6.3	7.0
19	16.5	17.3	18.2	16.7	15.9	14.6	11.0	17.0	15.9	13.2	13.1	13.9	14.0	17.0	10.5
20	15.8	15.8	13.2	13.6	14.0	14.5	7.9	13.9	14.0	13.8	14.5	13.2	13.3	13.8	12.6
21	12.3	9.5	8.3	9.5	10.2	12.2	13.6	10.6	9.3	13.0	11.8	13.3	10.0	9.1	8.1
22	13.1	28.3	29.9	20.9	20.1	21.5	13.2	18.1	21.2	17.0	18.1	16.9	20.1	25.0	19.6
23	12.2	13.2	13.3	9.6	12.7	13.1	12.0	14.7	14.1	14.0	14.1	17.0	9.3	11.8	13.5
24	4.7	9.0	8.6	10.2	9.4	8.9	4.7	8.5	10.1	8.9	9.8	8.3	10.7	13.7	8.9
25	9.0	6.0	7.9	7.9	8.1	9.5	10.4	8.8	8.4	6.7	9.6	12.1	8.3	6.3	5.8
26	13.4	18.0	17.6	15.8	24.9	8.5	4.8	13.8	23.7	13.4	11.9	12.7	14.1	17.1	15.8
27	11.1	13.3	13.8	16.5	13.5	13.7	14.2	13.6	13.7	12.5	13.5	12.5	13.3	13.6	12.6
28	12.1	9.8	8.2	10.6	11.8	11.8	10.1	10.7	11.8	9.4	12.6	12.2	12.0	8.0	12.4
29	23.6	29.2	20.6	23.6	23.6	21.7	23.6	22.2	17.3	21.8	18.9	19.6	19.6	23.7	24.6
30	13.5	16.3	12.1	13.1	15.7	13.2	11.8	13.5	13.0	13.1	14.2	13.2	13.0	17.0	12.9
31	7.9	8.5	3.9	8.3	8.0	7.5	6.1	7.9	7.9	7.9	7.9	7.9	7.9	10.6	6.6
32	15.7	8.4	8.4	8.9	4.9	9.6	15.7	9.6	9.2	9.1	9.3	11.8	8.3	7.9	9.2
33	13.3	18.3	15.7	22.3	13.7	12.2	16.0	13.6	17.5	13.3	10.6	13.6	7.1	16.3	12.8
34	11.8	16.6	12.8	14.2	14.0	13.0	10.6	14.2	14.2	12.9	13.7	14.0	14.2	14.1	13.1
35	12.8	9.8	8.6	10.0	12.4	13.2	12.5	12.3	12.1	9.3	14.1	14.1	12.8	9.3	8.9
36	17.1	24.5	26.0	25.5	25.4	21.9	19.8	17.7	24.8	28.5	21.6	23.6	23.6	29.0	26.6
37	9.8	14.2	13.0	13.4	13.8	13.0	9.8	13.8	13.1	13.2	14.1	13.4	14.2	13.7	13.0
38	6.3	9.0	8.7	8.9	9.2	8.8	6.3	8.8	8.4	9.2	8.9	9.4	8.8	9.2	8.5
39	18.1	8.3	8.2	8.2	4.9	9.9	10.3	9.8	8.5	8.0	11.8	10.3	8.6	7.9	8.1
40	13.8	24.2	18.0	15.7	16.2	21.2	14.8	11.8	17.6	17.4	13.3	19.6	16.2	19.6	17.5
41	8.9	16.6	14.3	15.7	15.0	13.6	10.2	13.7	14.2	13.7	14.5	15.1	14.8	14.2	13.1
42	12.6	9.5	8.7	9.9	12.1	11.8	12.9	12.0	10.0	8.8	16.3	14.1	9.9	8.5	9.1
43	13.9	27.9	21.1	27.7	20.7	22.5	18.7	16.0	19.9	21.5	23.8	23.6	21.2	25.6	25.6
44	8.3	18.1	13.2	17.2	14.1	12.6	9.6	13.7	13.4	12.4	14.2	18.1	14.2	11.8	13.2
45	5.7	8.8	6.3	5.6	8.3	7.9	5.5	8.4	8.0	8.3	8.7	9.2	8.9	6.3	7.9
46	14.9	7.0	4.2	13.2	9.4	10.1	10.1	10.1	8.9	6.3	10.0	12.3	12.1	6.3	6.7
47	12.7	17.6	18.7	19.6	15.7	15.7	17.1	12.9	17.9	17.7	13.5	14.2	15.7	19.6	15.7
48	9.6	14.7	13.8	13.6	14.9	11.9	9.9	14.0	13.5	13.5	15.7	13.7	13.7	12.8	13.2
49	6.1	8.5	8.2	8.2	8.9	7.9	5.6	7.9	7.9	8.1	8.3	8.3	8.3	6.8	8.3
50	5.0	6.0	5.1	5.3	6.1	5.0	4.0	4.9	5.3	5.7	5.7	5.5	5.4	5.0	5.5

Soil B															
EC_i (mS m^{-1})	15			150			300			450			600		
Rep	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Time (days)	EC_e (mS m^{-1})														
1	68	79	79	335	284	271	528	733	533	741	841	745	899	1161	911
3	67	74	67	327	293	286	514	440	533	733	820	753	904	1168	895
4	65	75	72	336	287	285	486	712	531	722	827	748	894	1164	902
5	62	73	64	344	302	320	528	730	558	726	822	778	923	1185	889
6	64	73	67	367	322	33	549	760	586	761	885	806	995	1193	805
7	66	79	69	389	326	330	588	763	621	779	906	803	1012	1171	983
8	68	80	73	392	349	371	633	797	631	826	765	721	1047	1192	1026
9	69	81	74	416	382	397	603	781	678	852	953	881	1115	1230	1073
10	76	90	79	442	409	410	660	810	727	923	979	927	1190	1252	1021
11	75	89	79	449	410	408	638	795	737	932	991	926	1207	1255	1164
12	75	86	79	454	425	442	662	808	747	967	1001	1000	1216	1259	1158
13	78	83	80	449	438	443	675	801	760	996	996	1002	1253	1224	1216
14	76	95	75	425	818	1201	639	722	481	946	924	945	721	419	1178
15	73	80	73	414	400	1091	720	698	702	998	913	965	1049	425	1159
16	79	75	74	411	412	1005	727	696	731	1035	894	996	1231	425	1216
17	81	77	77	419	410	1009	685	661	731	1072	910	1019	1249	422	1238
18	79	76	75	406	403	405	670	646	711	1049	874	1026	1220	1071	1229
19	76	72	72	376	377	368	668	631	689	1029	838	974	1220	1017	1220
20	80	72	76	369	378	379	592	645	710	1065	894	996	1204	997	1209
21	79	73	75	366	664	373	629	599	673	1034	848	1008	1166	981	1192
22	76	68	72	330	324	336	631	580	651	1024	796	888	1140	897	1210
23	75		72	318	313	328	628	562	604	1002	648	704	1087	887	1153
24	76	67		320	304	316	613	521	580	967	735	894	1048	854	1122
25	74	67	71	313	296	310	584	502	556	937	723	908	1008	843	1088
26	71	67	69	282	264	282	571	482	540	909	660	760	988	769	1060
27	71	67	69	268	251	263	550	441	487	885	634	769	935	753	1034
28	71	67	69	270	249	264	530	414	467	855	623	792	909	730	987
29	68	63	67	226	212	228	500	382	439	792	556	632	863	625	940
30	75	63	65	224	209	220	484	354	400	751	534	652	809	608	885
31	71	65	65	218	200	216	486	335	385	726	570	661	789	605	866
32	69	65	66	222	210	224	464	312	369	698	512	677	761	598	820
33	69	64	64	206	192	209	446	277	351	643	464	556	748	518	801
34	69	63	64	198	189	200	426	274	325	628	443	592	705	510	776
35	68	61	64	189	180	199	385	250	298	592	419	580	671	489	726
36	64	59	61	160	153	167	366	225	279	549	355	440	542	406	667
37	66	58	61	158	151	167	355	217	246	493	345	462	547	401	627
38	68	59	62	159	149	167	342	210	229	484	336	469	513	385	592
39	64	59	61	158	150	166	311	204	222	465	332	482	507	388	589
40	62	57	59	131	128	140	309	193	215	418	283	326	481	307	524
41	64	59	60	136	131	140	292	173	251	396	276	353	389	310	520
42	65	58	60	137	131	133	263	163	191	382	269	377	414	310	494
43	62	56	59	115	113	123	259	149	179	332	227	262	378	245	432
44	64	56	58	117	146	124	243	142	161	318	223	297	344	285	418
45	65	109	59	118	117	124	239	139	155	311	216	300	335	251	418
46	63	58	59	120	116	127	223	132	150	297	216	308	325	255	403
47	60	57	57	104	101	108	217	126	147	269	185	211	296	208	353
48	62	56	59	105	104	110	208	119	138	261	189	240	286	210	348
49	63	58	59	106	105	113	208	116	134	246	182	242	271	210	344
50	65	60	57	110	102	111	209	120	129	226	184	242	266	211	350

Appendix 6.7 The full data set of cumulative irrigation, cumulative drainage as well as the change in the electrical conductivity of the soil water (EC_{sw}, mS m^{-1}) for all the EC_i treatments on both soils

Soil	A							B						
EC_i (mS m^{-1})	15													
Average irrigation	0	298	416	495	652	691	848	0	299	401	519	676	754	911
Soil depth (mm)	Average EC_{sw} (mS m^{-1})													
300	142	80	68	54	53	49	46	206	61	52	51	42	51	52
500	144	102	59	47	47	45	45	218	61	46	58	37	42	45
700	288	109	56	51	50	43	48	180	131	77	65	55	63	45
900	144	128	56	52	52	45	49	150	173	125	87	55	54	44
1100	129	188	92	64	57	52	52	140	215	165	133	80	73	61
1500	103	152	136	136	108	96	75	64	181	153	139	92	83	74
Average drainage	0	199	292	368	620	662	764	0	207	275	346	541	635	774

Soil	A							B						
EC_i (mS m^{-1})	75													
Average irrigation	0	298	416	495	652	691	848	0	299	401	519	676	754	911
Soil depth (mm)	Average EC_{sw} (mS m^{-1})													
300	528	134	99	106	126	118	120	580	173	102	111	103	107	102
500	509	144	92	92	112	107	118	592	138	108	103	99	103	95
700	715	163	108	98	118	106	110	656	200	148	122	112	117	97
900	812	187	119	110	124	114	113	837	227	155	115	101	101	88
1100	473	244	149	126	131	120	117	453	438	273	173	115	119	114
1500	227	822	630	348	140	126	122	696	587	527	425	225	206	157
Average drainage	0	200	276	345	596	639	757	0	237	312	383	582	679	850

Soil	A							B						
EC_i (mS m^{-1})	150													
Average irrigation	0	298	416	495	652	691	848	0	299	401	519	676	754	911
Soil depth (mm)	Average EC_{sw} (mS m^{-1})													
300	823	319	190	185		302	119	1446	156	161	124	116	133	175
500	1002	196	129	117	124	128	132	2115	153	124	114	107	118	179
700	936	195	121	107	113	109	131	1935	200	149	125	109	110	129
900	842	202	119	111	117	108	131	1345	363	267	187	120	118	113
1100	788	253	125	112	114	100	114	963	837	507	294	139	136	120
1500	619	833	393	195	129	118	115	428	1003	1023	898	383	331	216
Average drainage	0	197	295	363	593	650	764	0	214	286	354	555	646	803

Soil	A							B						
EC_i (mS m^{-1})	225													
Average irrigation	0	298	416	495	652	691	848	0	299	401	519	676	754	911
Soil depth (mm)	Average EC_{sw} (mS m^{-1})													
300	1785	250	272	232	269	246	255	1883	246	226	235	224	262	209
500	2011	324	249	218	243	239	248	2201	287	233	211	227	249	213
700	1640	329	232	209	260	258	260	1249	374	274	226	218	224	214
900	1110	590	332	221	243	241	250	1591	618	447	268	216	214	204
1100	1237	679	406	292	248	245	253	1355	1108	715	404	241	238	217
1500	1167	1402	1018	497	236	232	240	839	1416	1469	1193	397	367	272
Average drainage	0	216	301	382	622	665	781	0	236	307	381	597	684	855

Soil	A							B						
EC_i (mS m^{-1})	300													
Average irrigation	0	298	416	495	652	691	848	0	299	401	519	676	754	911
Soil depth (mm)	Average EC_{sw} (mS m^{-1})													
300	2815	456	355	359	390	407	367	1891	397	343	371	382	422	386
500	2474	517	357	380	506	484	410	1590	355	348	332	374	381	344
700	1736	713	377	329	397	363	415	1601	493	401	347	359	373	352
900	1255	798	432	374	412	379	420	2230	863	617	413	376	387	378
1100	1464	1145	531	401	401	383	385	1727	1369	995	607	366	385	373
1500	1580	1401	1418	746	369	368	384	1151	1426	1478	1081	636	548	457
Average drainage	0	195	290	351	572	612	723	0	232	304	376	555	652	814

Appendix 6.8 The ratios used in the leaching equations for the different treatments and soil depths of all the EC_i treatments on both soils

EC ($mS\ m^{-1}$)	Soil	A							B						
	Drainage (mm)	0	199	292	368	620	662	764	0	207	275	346	541	635	774
	Soil Depth (mm)	x													
	0-300	0		0.97					0	0.69					
	0-600	0		0.49					0	0.35					
	0-900	0	0.22	0.32					0	0.23	0.31				
	0-1200	0	0.17	0.24					0	0.17	0.23	0.29			
	0-1500	0	0.13	0.19	0.25				0	0.14	0.18	0.23	0.36		
	0-1800	0	0.11	0.16	0.2				0	0.12	0.15	0.19	0.3		
15	Soil Depth (mm)	y													
	0-300	0		0.52					0	0.7					
	0-600	0		0.56					0	0.71					
	0-900	0	0.43	0.68					0	0.58	0.62				
	0-1200	0	0.34	0.67					0	0.44	0.48	0.54			
	0-1500	0	0.17	0.61	0.62				0	0.28	0.31	0.39	0.55		
	0-1800	0	0.09	0.51	0.37				0	0.14	0.19	0.25	0.46		

EC ($mS\ m^{-1}$)	Soil	A							B						
	Drainage (mm)	0	200	276	348	596	639	757	0	227	312	383	682	679	860
	Soil Depth (mm)	x													
	0-300	0	0.67						0	0.79					
	0-600	0	0.33						0	0.4					
	0-900	0	0.22						0	0.26	0.35	0.43			
	0-1200	0	0.17	0.23					0	0.2	0.26	0.32	0.48		
	0-1500	0	0.13	0.18	0.23	0.4			0	0.16	0.21	0.26	0.39		
	0-1800	0	0.11	0.15	0.19	0.33			0	0.13	0.17	0.21	0.32	0.38	0.47
75	Soil Depth (mm)	y													
	0-300	0	0.75						0	0.7					
	0-600	0	0.73						0	0.74					
	0-900	0	0.75						0	0.72	0.76	0.8			
	0-1200	0	0.76	0.81					0	0.72	0.77	0.82	0.85		
	0-1500	0	0.71	0.78	0.79	0.78			0	0.62	0.69	0.78	0.83		
	0-1800	0	0.48	0.45	0.56	0.75			0	0.54	0.57	0.67	0.77	0.68	0.75

EC ($mS\ m^{-1}$)	Soil	A							B						
	Drainage (mm)	0	197	295	363	593	650	764	0	214	286	354	555	646	803
	Soil Depth (mm)	x													
	0-300	0	0.66	0.98					0	0.71					
	0-600	0	0.33	0.49					0	0.36					
	0-900	0	0.22	0.33					0	0.24	0.32				
	0-1200	0	0.16	0.25					0	0.18	0.24	0.29			
	0-1500	0	0.13	0.2	0.24				0	0.14	0.19	0.24	0.37		
	0-1800	0	0.11	0.16	0.2	0.33			0	0.12	0.16	0.2	0.31	0.36	0.45
150	Soil Depth (mm)	y													
	0-300	0	0.61	0.77					0	0.89					
	0-600	0	0.72	0.83					0	0.91					
	0-900	0	0.74	0.84					0	0.91	0.92				
	0-1200	0	0.75	0.84					0	0.87	0.88	0.89			
	0-1500	0	0.73	0.84	0.87				0	0.78	0.8	0.85	0.91		
	0-1800	0	0.6	0.79	0.82	0.85			0	0.67	0.65	0.66	0.81	0.76	0.84

EC ($mS\ m^{-1}$)	Soil	A							B						
	Drainage (mm)	0	216	301	382	622	665	781	0	236	307	381	597	684	855
	Soil Depth (mm)	x													
	0-300	0	0.72						0	0.79					
	0-600	0	0.36	0.5					0	0.39	0.51				
	0-900	0	0.24	0.33					0	0.28	0.34	0.42			
	0-1200	0	0.18	0.25	0.32				0	0.2	0.28	0.32	0.5		
	0-1500	0	0.14	0.2	0.25	0.41			0	0.16	0.2	0.25	0.4		
	0-1800	0	0.12	0.17	0.21	0.35			0	0.13	0.17	0.21	0.33	0.38	0.48
225	Soil Depth (mm)	y													
	0-300	0	0.86						0	0.87					
	0-600	0	0.85	0.87					0	0.87	0.89				
	0-900	0	0.83	0.87					0	0.83	0.86	0.87			
	0-1200	0	0.77	0.83	0.86				0	0.78	0.82	0.86	0.88		
	0-1500	0	0.72	0.8	0.84	0.84			0	0.68	0.75	0.82	0.86		
	0-1800	0	0.6	0.7	0.77	0.84			0	0.56	0.59	0.66	0.81	0.76	0.82

EC ($mS\ m^{-1}$)	Soil	A							B						
	Drainage (mm)	0	195	290	351	572	612	723	0	232	304	376	555	652	814
	Soil Depth (mm)	x													
	0-300	0	0.65	0.97					0	0.77	1.01				
	0-600	0	0.33	0.48					0	0.39	0.51	0.63			
	0-900	0	0.22	0.32	0.39				0	0.28	0.34	0.42			
	0-1200	0	0.16	0.24	0.29				0	0.19	0.25	0.31	0.46		
	0-1500	0	0.13	0.19	0.23	0.38	0.41		0	0.15	0.2	0.25	0.37		
	0-1800	0	0.11	0.16	0.2	0.32	0.34		0	0.13	0.17	0.21	0.31	0.36	0.45
300	Soil Depth (mm)	y													
	0-300	0	0.84	0.87					0	0.79	0.82				
	0-600	0	0.82	0.87					0	0.78	0.8	0.81			
	0-900	0	0.76	0.84	0.86				0	0.76	0.78	0.8			
	0-1200	0	0.7	0.82	0.83				0	0.71	0.77	0.8	0.79		
	0-1500	0	0.63	0.79	0.81	0.79	0.8		0	0.62	0.7	0.76	0.79		
	0-1800	0	0.56	0.69	0.75	0.8	0.8		0	0.52	0.59	0.67	0.73	0.68	0.73

$x = Dw / Ds$ and $y = [1 - (EC_{sw\ actual} / EC_{sw\ initial})]$

Other related WRC reports available:

Multi-dimensional models for the sustainable management of water quantity and quality in the Orange-Vaal-Riet convergence system.

Viljoen MF; Armour RJ; Oberholzer JL; Grosskopf M; Van der Merwe B; Pienaar P

Salinisation of various irrigation schemes has become a problem in South Africa. One such area that experiences salinisation problems is the Lower Vaal and Lower Riet irrigation areas, upstream from where these rivers converge and flow into the Orange River. From a total irrigation area of 12 556 ha in the Orange-Vaal Water Users Association, 23 % is either slightly or severely affected by salinity problems.

The overall aim of this study was to develop and integrate multi-dimensional models for sustainable management of water quantity and quality in the Orange-Vaal-Riet (OVR) convergence system.

The main results from the research are the following: Salinisation is an important problem in the study area that needs special management attention. The relative importance of the problem differs between WUAs and irrigation blocks. From various management options, drainage installation and consequent leaching is a better option financially, environmentally and socially than changing to more salt tolerant crops at farm, WUA and regional level. At regional level the direct and indirect benefits of modelled improved drainage (and subsequent investment in higher value crops) proved far greater than the costs of drainage, and produced the highest index for socio-economic welfare (ISEW), and an addition of jobs to the irrigation and linked industries over the long term. The total real cumulative cost (2005 basis) of salinisation over a period of 15 years for the whole study area was calculated at R955 million, a good benchmark to use to leverage funds for remediation action

This above mentioned finding presents an overwhelming case for the full sustainability ("green box") grant assistance of additional irrigation drainage in the interest of increased sustainable regional socio-economic welfare. The main recommendations of this research project is that drainage installation for facilitation of leaching, needs to be promoted in the Orange-Vaal WUA and especially in the Lower Riet Irrigation Blocks in the study area. Factoring in the costs of drainage into irrigators' water use charges, is less than the additional financial benefits derived from the drainage, and should therefore be acceptable to farmers. This should however be re-evaluated with a detailed survey and feasibility study.

Report Number: 1352/1/06 **ISBN No: 1 77005 486 3**

9781770054769

TO ORDER: Contact **Publications** - Telephone No. 012 330 0340
Fax Number: 012 331 2565
E-mail: publications@wrc.org.za

Water Research Commission
Private Bag X03, Gezina, 0031, South Africa
Tel: +27 12 330 0340, Fax: +27 12 331 2565
Web: http://www.wrc.org.za