MANAGING SALINITY ASSOCIATED WITH IRRIGATION AT ORANGE-RIET AND VAALHARTS IRRIGATION SCHEMES

Report to the

WATER RESEARCH COMMISSION

on the project "Managing salinity associated with irrigation in selected areas of South Africa"

by

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EXECUTIVE SUMMARY

1. Introduction

Salinity associated with irrigation has in the past, and continues to be arguably the most important factor threatening agricultural production under irrigation. Unfortunately the problem extends beyond the confines of irrigated fields, degrading water resources and resulting in extensive areas of land becoming waterlogged and saline. Poor planning and ineffective water and salt management practices by farmers and managers of irrigation schemes therefore strongly affect the sustainability of irrigation.

Researchers are in agreement about the fact that sustainable irrigation is technically possible with the proper design and operation of irrigation and drainage systems, together with the implementation of suitable crop and soil management practices, provided that acceptable political and social structures are in place. The general opinion is that irrigated agriculture will not only survive, but will indeed thrive under realistic circumstances and appropriate management practices. With regard to political and social structures, management practices should however be scientifically sound.

South Africa is therefore divided into 19 Catchment-based Water Management Areas (CWMAs). Each of these areas has an agency which manages water resources, co-ordinates water-related activities of water users and other water management institutions within demarcated areas of jurisdiction. Within these CWMAs the water required for irrigation is managed by Water User Associations (WUAs). The WUAs manage the day-to-day supply of irrigation water to the farms and are therefore responsible for the maintenance of water conveyance infrastructure, which includes the removal of drainage water. The next level for water management is on-farm where the farmer has the sole authority over the fate of irrigation water. If the farm is large enough, it may comprise more than one irrigation field, which is the smallest unit where irrigation management decisions are made. The area covered by the irrigation system together with the depth of the potential root zone, defines the physical dimensions of this management unit. The potential root zone of field crops can be up to 2000 mm. Thus an in-field drainage system will be part of the smallest management unit if installed within this depth, which is often the case.

The estimated fraction of salt-affected irrigated land in South Africa is only 9%, which is much lower compared to the 34, 33, 30, 26 and 23% of Argentina, Egypt, Iran, Pakistan and the United States of America, respectively. Between 1% and 12% of the total irrigated area in South Africa is severely waterlogged or salt-affected, and 5% to 20% moderately affected. Salinity problems were reported occasionally in the Breede, Berg, Great Fish and Sundays Rivers. Ten irrigation schemes showed high increases in mean river water salinity from upstream to downstream over the length of the scheme, *viz*. Breede River, Great Fish River, Groot River, Hluhluwe River, Lower Vaal River, Modder River, Pongola River, Riet River, Tarka River and Vaalharts.

Despite the fact that salt-related problems are not at present a significant factor threatening production under irrigation in South Africa, increasing evidence of deterioration of physical resources suggests that the problem cannot be ignored. A solicited research project on managing salinity associated with irrigation in selected areas of South Africa was therefore introduced by the Water Research Commission (WRC).

2. Objectives

A general objective and seven specific objectives were stipulated for the above-mentioned project. The general objective was to develop best practices and guidelines for managing the salt load associated with irrigation at farm and scheme level, and the specific objectives were to:

i) Conduct a desktop study to synthesise current knowledge (at a generic level, but from a technical perspective) regarding the management of the salt load associated with irrigation, with reference to problems being experienced in South Africa.
ii) Formulate generic best practices and identify harmful practices to be avoided.
iii) Select at least two case study areas from existing salinity problem areas such as the Breede, Olifants and Orange-Vaal-Riet rivers. Assess selected best management practices on a case study basis (with formal stakeholder participation) with the aim to develop specific guidelines for the selected case study areas.
iv) Identify incentives that could be applied to changed behaviour of water managers at farm and irrigation scheme level.
v) Provide feedback on outcomes of the research to stakeholders and formulate recommendations for the implementation of sustainable solutions in consultation with them.
vi) Formulate generalized recommendations about best practices and guidelines for managing the salt load associated with irrigation at farm and irrigation scheme level.
vii) Identify further research needs and gaps.

3. Selected irrigation schemes

The study was conducted at the Orange-Riet and Vaalharts Irrigation Schemes in semi-arid South Africa. Water in this region is managed by the CWMAs, Upper Orange or Lower Vaal, with several WUAs contributing to each one. Only the WUAs, Orange-Riet and Vaalharts Water, are of interest to this project as they manage the water allocated to the two irrigation schemes. The two irrigation schemes were selected, *inter alia*, for the following reasons.

i) Irrigation has been practised for more than 70 years on both schemes, which is important for salt to reach equilibrium at this level.
ii) The two schemes have a range of crops, soils and irrigation methods, with and without artificial drainage to study water and salt balances.
iii) Water of different quality is used for irrigation since water is transferred between some sources in this region.
iv) Both schemes are managed by well-organised WUAs which have reliable data essential for the project.
v) On each of the two schemes there is a large knowledge-base concerning water and salt-related problems and their management.
vi) Logistically, the location of the two schemes suited the project team best for detailed measurements.
vii) Several farmers at both schemes have a sincere interest in the project and their collaboration should prove to be valuable.
viii) Water and salt-related problems were experienced occasionally at the two schemes.

4. Research approach

In addressing the stipulated objectives of this solicited project, literature was studied to formulate eventual best management strategies for salinity associated with irrigation at farm and scheme level (Chapter 2). Next, sites and measuring points were identified at the Orange-Riet and Vaalharts Irrigation Schemes where data were collected over four cropping seasons to study the mechanism of water and salt movement under a range of crops, soils and irrigation methods, with and without artificial drainage (Chapter 3). These measurements yielded sufficient good quality data for the calculation of short-term water and salt balances covering a large range of situations. It was thus decided to use a local model known to the project team to test scenarios of salinity management in the long term. The test and validation of SWAMP using independent data sets are presented in Chapter 4. In a successive series of simulations using experimental data, crop selection under irrigation (Chapter 5), response of soils to irrigation management (Chapter 6), effect of irrigation water salinity on crop production (Chapter 7) and irrigation scheduling methods (Chapter 8) were assessed by using SWAMP-generated simulations. Based on the outcome of these simulations, best management practices and guidelines are suggested in Chapter 9 for on-farm level and WUA level.

5. Main research findings

i) ***Improvement and utilization of the SWAMP model (Chapter 4):*** The success of this project depended on obtaining an appropriate method to acquire water and salt balances at the two irrigations schemes. The fact that most of the measuring points at Orange-Riet and Vaalharts had shallow water tables was problematic. This is because crops utilize this water source and unlike irrigation applications which are measurable, water table contribution towards crop production is not measurable under fluctuating conditions. To overcome this problem, the SWAMP model was introduced, because it is known for its ability to estimate the soil water balance components under dryland and irrigation conditions, including water tables. However, the model has a major weakness as it has no salt balance subroutine. Thus, it was necessary to develop a salinity subroutine for the model that could simulate the osmotic effect of salt on crop yield as well as the up- and downward flux of salt above water tables. Hence salinity algorithms were developed programmed and validated using an independent data set from a previous WRC salinity project conducted in lysimeters. The results revealed that the model was accurate with its prediction of water uptake and yield when the field crops were subjected to a range of irrigation induced osmotic stress levels. Similarly the model performed well in simulating water and salt movement within the root zone of two soils under water table conditions. It was concluded that the model could be applied as a research tool for obtaining water and salt balances under field conditions with fluctuating water tables, provided that critical input requirements are available, *viz.* amounts of irrigation water and rainfall, initial water and salt contents of soil layers, mean evaporative demand of the atmosphere for the growing season, etc.

These prerequisites for applying the model in field conditions were met in all the case studies reported in Chapters 5, 6, 7 and 8.

ii) **Assessment of crop selection under irrigation (Chapter 5):** The focus of this study was on field crops, although perennial crops such as lucerne, grape, pecan and citrus are cultivated in the irrigation schemes. These field crops comprise of maize, wheat, barley, groundnuts and peas often combined in either single or double cropping sequences. According to local literature, double cropping is by far the most popular cropping sequence in the two irrigation schemes; about 80% of the total irrigated land is planted under double cropping. This trend was also observed in the cropping sequences employed at the farms where 29 points were measured for this project. The most popular practice at Orange-Riet and Vaalharts Irrigation Schemes is a continuous wheat-maize sequence. These farmers often replaced wheat with either barley or peas as a control measure against pest infestations. If peas is not an option, a winter fallow is introduced. Under extreme pest pressures some farmers will shift to a perennial crop like lucerne, or they will replace maize in the following summer with broadleaf crops like groundnuts and cotton. Summer-fallowing is popular amongst farmers that have sufficient land, but experience shortage in irrigation water. For example farmers along the Orange-Riet Canal are often involved in water trading at farm level which will be discussed later.

A dual cropping practice, i.e. where the irrigated land is divided into halves, was evaluated *in situ* over four growing seasons at Vaalharts. Double and single cropping practices were utilized on a sandy soil which was irrigated with a centre pivot designed to apply 12 mm per day. The hypothesis that dual cropping lowers the peak application rates was rejected by the results obtained from this case study. It was suggested that the farmer should rather shift to sole cropping. Time saved through simplifying management could be invested in sound irrigation scheduling and appropriate crop selection to achieve optimum planting dates during the summer cropping period. It was found for example that the maize yields decrease with 153 kg ha^{-1} day^{-1} if planted after the end of November in the Vaalharts Scheme.

A 20 year long predictive modelling study was undertaken with SWAMP to investigate the effect of salinity on crop yields. Four popular crop sequences were used (40 consecutive growing seasons), *viz*. continuous wheat-maize double cropping which was alternated with either a wheat-groundnut double cropping sequence, or a peas-maize sequence, or a winter fallow-cotton rotation. The results showed that the mean salinity of the sandy loam soil used in the study never rose above 350 mS m^{-1} in any of the crop sequences, posing a risk only to peas. The simulated yields confirmed that peas were affected by the prevailing salinity conditions induced by the irrigation practice. The reason why soil salinity did not increase to detrimental levels for the other crops, as would be expected by the lack of provision for leaching, can be explained by the leaching of salts by excess rain during infrequent heavier rainfall events. Thus, it seems that climate plays a significant role in protecting the crops against the harmful effect of salt accumulation in soils.

iii) **Assessment of soil response to irrigation management (Chapter 6):** Soil surveys at Vaalharts and Orange-Riet Settlement were completed in the early thirties. Irrigation commenced shortly after these surveys, which implied that the soils currently under irrigation should be near their long-term salt equilibrium. It was argued that salinity assessment at this point in time will enhance our understanding of how soils respond to long-term irrigation. As mentioned earlier, 29 measuring points were established over the two schemes: 15 in sandy soils (Hutton and Bloemdal forms), 10 in loamy soils (Hutton, Bloemdal, Plooyesburg and Bainsvlei forms) and 4 in clayey soils (Sepane and Valsrivier forms). The mean electrical conductivity (EC) and sodium adsorption ratio (SAR), determined from saturated soil paste extracts over four growing seasons, showed a generally increase from the sandy (75 mS m^{-1} and 1.5), to the loamy (143 mS m^{-1} and 2.1) and to the clayey soils (174 mS m^{-1} and 2.9). The worst salinity was observed in a Bloemdal soil at Vaalharts; EC of 266 mS m^{-1} and SAR of 4. This high salinity was expected because of the main road that impaired surface and groundwater flow to the Harts River. Nonetheless, this problem can easily be rectified with the installation of surface drains. Despite the long history of irrigation, it can be concluded that the salinity of the soils is generally low in both schemes. The mechanisms associated with how these soils maintained a low salinity was revealed through the detailed *in situ* assessment over four cropping seasons. The case studies selected were a sandy (Hutton) and a clayey (Valsrivier) soil from the Lower Riet River area. The water and salt balances showed that between 72 and 89% of the total salt additions in the Hutton soil leached from the profile, mainly due to excess rain during the fallow periods. Drainage, on the other hand, only accounted for 9% of the total salt removal in the Valsrivier soil. Despite the low salt removal by drainage the EC of the soil extract remained consistently low (< 200 mS m^{-1}) over the four seasons, which led to the hypothesis that precipitation may have removed the solutes from the water phase. However, this hypothesis was never tested and needs clarification in future research.

The extent to which soils affect hydro-salinity processes and associated crop yields under long-term irrigation was addressed later in this Chapter. Two soils from Orange-Riet (Hutton and Valsrivier forms) and two soils from Vaalharts (Bainsvlei and Bloemdal forms), were selected for the predictive modelling experiment. Simulations were conducted with the SWAMP model over 20 successive wheat-maize double crop sequences. In this simulation study it was assumed that the water tables in the Bloemdal and Bainsvlei soils were constant at a depth of 1000 and 1500 mm, respectively, while there were no water tables present in the other two soils. Contributions from water tables and rainfall were accounted for in the estimation of irrigation schedules to minimize unproductive losses. The results revealed that the soils responded uniquely. Huge differences in water and salt accumulation were found which affected the crop yields. Yield losses were severe in the Hutton soil (Class 2 irrigability) and moderate in the Bainsvlei soil (Class 2 irrigability). In the Valsrivier soil (Class 3 irrigability) no yield losses and in the Bloemdal soil (Class 2 irrigability) occasional yield losses were evident. The unique response was attributed to inherent soil properties, such as presence of impermeable layers in the deep subsoil that allows water table formation, texture and structure. These properties have a strong influence on hydraulic processes such as infiltration, water storage, drainage, evaporation and transpiration, hence the build-up or removal of salt in the root-zone. For example, the low crop productivity in the Hutton soil was attributed to poor water retention, which results in a low (<80 mm) profile available water capacity (PAWC). The results illustrate that salts tend to build up in the root-zone under tight irrigation scheduling strategies like the one employed in the simulation. These salts reduce the availability of the soil water to the crop (osmotic effect), which reduces the PAWC further, making it more unmanageable. The opposite is also true; high PAWC soils pose low cropping risk and therefore acquire lower managerial inputs as in the case of the Valsrivier soil. Lastly, the results of the Bloemdal and Bainsvlei soils illustrated that water tables can be positively utilized to reduce irrigations and hence the amount of salt deposited in the field. However, effective utilization demands additional managerial inputs from irrigators to maintain a high productivity.

iv) **Assessment of irrigation water salinity on crop production (Chapter 7):** In any catchment with economic activities such as industries and irrigation, the water quality of rivers tends to deteriorate over time. Therefore water samples need to be taken from rivers for water quality assessment on a regular basis. This task and responsibility belongs to the Department of Water Affairs and Forestry in South Africa, but water samples were also collected in rain gauges after irrigation at the 29 measuring points. These samples were grouped according to the main irrigation source, namely Orange River, Vaal River and on-farm blended water. The mean EC and SAR values for water from the Orange River were 21 mS m^{-1} and 0.38, respectively, compared to the corresponding long-term means of 19 mS m^{-1} and 0.38. The mean EC and SAR values for water from the Vaal River were 68 mS m^{-1} and SAR 1.37, respectively, compared to the corresponding long term mean of 52 mS m^{-1} and 1.17. From these results it can be concluded that the water quality of both rivers is still highly suitable for irrigation (C1S1 for Orange-Riet Irrigation Scheme and C2S1 for Vaalharts Irrigation Scheme).

Blending of water occurs naturally along rivers when drainage from subsurface and surface drains and groundwater enters the river beds and streams. However, on-farm blending is a special case where the primary irrigation water source is mixed with secondary water sources such as in-field drainage. The salinity of water tables as a potential source for blending was assessed wherever water tables were present at the measuring points. Water samples were taken from installed piezometers on a weekly basis. The salinity of this source varied considerably amongst irrigation areas; the mean EC and SAR were 135 mS m^{-1} and 1.7, respectively, at Orange-Riet, 226 mS m^{-1} and 2.9 at the Vaalharts and 414 mS m^{-1} and 7 at the Lower Riet River section of the Orange-Riet Irrigation Scheme. Thus the water table source is 2-5 times poorer compared to the irrigation water source. The worst case scenario for on-farm blending is the Lower Riet River section. Nevertheless several farmers made use of on-farm blending, but stopped during the early stage of the project when realizing how poor the water quality was. Despite the poor water quality, one farmer continued with this practice in the worst case scenario area. The resulting mean EC and SAR values after blending were 84 mS m^{-1} and 1.82 (C3S1), which are much better than those of the water table as a sole source. Very high yields were obtained constantly at this site, which could be attributed to good agronomical practices. The farmer used an irrigation scheduling service and introduced single cropping rotations on both the sandy and clay soils irrigated with the blended water. Sufficient leaching was recorded in the sandy soil during fallow periods. This was not the case with the clay soil. Despite minute leaching in the clay soil the EC of its saturated paste extract was low, which implied that the accumulated salts had precipitated in the soil. This blending practice is not recommended for clay soils until the mechanisms of salt removal are clarified.

A long-term predictive modelling study was also undertaken with the SWAMP model to obtain a better understanding of what can be expected when poor water quality is utilized for crop production in the study area. Four irrigation water qualities (EC of 21, 65, 102 and 225 mS m^{-1}) were introduced on two soils, *viz.* a freely drained sandy Hutton soil from Jacobsdal and a sandy loam Bloemdal soil with a water table from Vaalharts. A similar irrigation scheduling strategy was imposed on a wheat-maize rotation as explained earlier. Yield losses in the Hutton soil increased as the salinity of the irrigation water increased, more so for maize than wheat. The reason for this is that salts build up in the root zone due to the water conservation scheduling approach followed. This approach does not cater for leaching, and salts are mainly leached during high rainfall events that occurred about three times over the 20 year simulation period. The Bloemdal soil on the other hand showed only yield losses during a 7 year period of salt build-up when high rainfall events were absent. During this period yield losses increased with an increase in the salinity of irrigation water. The better performance of the Bloemdal soil can be attributed to the water table that increases the plant available water, which mask the osmotic effect of the salts in the profile.

v) **Assessment of irrigation scheduling methods (Chapter 8):** Sound irrigation scheduling methods hold the key to sustain irrigation practices in the long-term. Thus it is important to match the field situation with an appropriate irrigation scheduling method as there is no one method that suits all situations. Therefore four irrigation strategies for managing plant available water were assessed in a long-term predictive modelling study with the SWAMP model: (i) In strategy A, irrigations were calculated to meet the potential evapotranspiration, taking into account the contribution of water tables and rain; (ii) Strategy B is similar to strategy A, except that the contribution of water tables was ignored in the estimation of the irrigation schedule; (iii) Strategy C makes use of the bonus that actual evapotranspiration is known, but ignores the osmotic effect on the plant available water; (iv) Strategy D caters for the build-up of salts in the profile (similar as C) until a point before the osmotic effect impacts negatively on the delicate balance of water supply and demand functioning of the system. The salts are then leached by excess irrigation. The same two soils and double cropping sequences applied in assessing irrigation water salinity on crop production were used in this simulation. Strategy B was obviously not relevant in the case of the freely drained soil. Thus, applying strategies A, C and D, on freely drained soils resulted in the following conclusions: Strategy A will over the long term (> 20 years) result in occasional short term (5 years) salt accumulation in the root-zone. These salts will be leached from the root zone during high rainfall events. In the absence of high rainfall events, occasional over-irrigation, during periods of low crop water demand towards the end of a crop growing season, might be required. The same conclusion is true for Strategy D except that a somewhat larger saving in irrigation water can be expected, 6% in the simulated example. Applying Strategy C, with a weekly irrigation cycle, will result in even larger irrigation water savings (>30%), with a reduction in salt additions through irrigation. However, the occasional salt accumulation in the root zone will result in crop yield losses, which can be reduced by shorter (< 5 days) irrigation cycles. This may be considered a high risk strategy on shallow (< 1 m) soils. For the deep sandy soils with a shallow water table the conclusions were as follows: Applying Strategy B, where the potential water uptake by crops from the water table is ignored, significant salt additions through irrigation and irrigation induced leaching of salts will result. For the simulated example the mean "over-irrigation" was approximately 150 mm per season. This 150% "over-irrigation" assured that the salt content of the root zone remained constantly low during the simulated 20 years an approach presently used by most farmers which explains the low salt content of the soils. Using Strategies A, C and D results in considerable irrigation water savings, while salt additions through irrigation are reduced. Due to a lack of irrigation induced salt leaching, short term (3 years) salt accumulation in the root zone can be expected, but leaching by rain occurs frequently. These strategies, when used by some farmers will be sustainable, but when all the irrigators on the schemes convert to either of these strategies a real time salt monitoring system should be put in place.

vi) **Best management practices and guidelines (Chapter 9):** The literature review in Chapter 2 led to the development of a framework for best management practices for dealing with soil salinity on two scales, namely field and WUA.

Field scale:

i) Use of efficient irrigation systems: Farms at both schemes were initially designed for wide-bed flood irrigation systems. These systems are gravity fed and hence have the advantage of saving electricity, but from a water application efficiency viewpoint it is probably the worst system available with 50-60% efficiency only. This led to over-irrigation to compensate for the system inefficiency, which caused waterlogging in large areas of both schemes. Fortunately, these systems have gradually been replaced with centre pivot systems at a rate of 266 ha per annum since 1975. The centre pivot systems have efficiencies above 90%, which means a huge saving in water applications, hence salt deposits in crop fields.

ii) Use of irrigation scheduling practices: The literature survey showed that 82% of South African irrigators make use of a subjective or intuitive method (based mainly on experience) to decide when and how much water to irrigate. This is obviously a venue where water savings can be made by improving on (a) the way crop water requirements can be determined, (b) how rainfall can be incorporated in schedules and (c) how water tables can be utilized and incorporated in schedules. This technology does exist, but needs to be re-visited, re-thought and re-packed to render it acceptable to a larger group of irrigators who have abundant scientific-based technology. With this in mind guidelines were developed to improve the scientific basis of the farmers who make use of subjective modes of irrigation scheduling. Greater resources should also be invested into farmer friendly models like BEWAB to improve the salinity management component of on-farm irrigation scheduling.

iii) Utilization of shallow water tables: About 50% of Vaalharts area and large parts of Orange-Riet have artificial sub-surface drains and large parts of the remaining areas have water tables either in the root zone or near the root zone. Although the literature indicated that farmers blocked the outlets of the drainage pipes during water scarce periods such as in the early eighties, it was demonstrated in this project that the water table is largely ignored as a water resource. The simulation studies employed indicated that up to 50% of the irrigation requirement of crops can be supplied by the water table. Such practices can lead to huge water savings and pumping costs as well as reduction in salt additions. Again, technology is available to incorporate water tables as an important resource for irrigation scheduling.

General awareness of this resource needs to be created and water table utilization methods need to be outlined in simple guidelines and farmer friendly irrigation scheduling models.

iv) Monitoring of root-zone salinity: Literature showed that routine salt monitoring of the root-zone to prevent salinity in a pro-active way is not a regular practice in the two schemes under investigation. Salinity problems which arise from time to time are dealt with in an *ad hoc* manner. However, the long-term predictive modelling experiments showed that in certain field situations (freely drained soils and also soils with water tables below 1500 mm) where water conservation scheduling approaches (utilization of rain and water tables) are followed, salts tend to build-up in the unsaturated zone that could harm even maize and wheat production. Under these conditions it would be wise to embark on pro-active measures to obtain spatial and temporal salinity maps of the irrigated area. The proposed guidelines give an indication when irrigators should employ pro-active measures or not.

v) On-farm interception and re-use of drainage water: This is not a common practice in both schemes because water supply from the irrigation infrastructure is sufficient to meet crop water requirements. However, there were a few farmers who had made use of this practice to save water, but soon aborted the practice when realising that they were also recycling the salts from the groundwater. One farmer in the Lower Riet River continued with this practice, mainly to get rid of excess drainage from the higher lying sandy soils that flood the lower lying clay soils. This farmer makes use of a single cropping practice which allows for fallow periods that create opportunities for leaching of excess salts. However, this practice is not generally recommended as it demands additional management inputs from farmers, especially when the quality of drainage water is poor and the internal and external drainage of soils are insufficient to drain excess water and salts.

vi) Selection of crops with salt tolerance adapted to the situation: Findings suggest that soil salinity can rise occasionally to levels that can harm salt sensitive crops like peas. The predictive modelling exercise showed that maize, and more unlikely wheat, can be harmed under conditions where water conservation scheduling approaches are followed as explained earlier. Again guidelines are provided to make farmers aware of those situations.

Guidelines: The guidelines that were developed for field scale application take into account the following variables: soil type, irrigation water salinity, rainfall, water table uptake, leaching fraction, root-zone salinity of the root- zone, re-use of drainage water and selection of crops.

Water user association scale:

The literature review on water and salt management of the two irrigation schemes revealed that significant interventions were made in the past to ensure that farmers received sufficient water of a decent quality to protect soils, crops and the environment from the devastating effects of salinity and sodicity. Some of the interventions were the obtaining of subsidies for in-field subsurface drains, especially Vaalharts, the installation of a network of surface drains in both schemes to control flood water and to discharge effluent from in-field drains; the installation of telemetric devices to monitor and manage water supply at Orange-Riet scheme, the use of the WAS program to facilitate the daily supply and demand for water. The WUA Vaalharts Water is currently involved in the upgrading of the water supply canal system which will ensure sufficient water to the Taung Irrigation Scheme.

Comments on water and salinity management at WUA scale:

i) Blending of drainage water with better quality water for downstream users: Currently all water that is not being used in the Vaalharts Irrigation Scheme or in the Orange-Riet Settlement, drains, respectively, into the Harts River or Riet River, to be used by downstream irrigators. Managers use the WAS program for calculating the amount of tail-end water required to meet the water demand of the downstream irrigators. The water salinity, for example, in the Lower Riet is monitored regularly and additional tail-end water is adjusted accordingly. This type of practice, although not studied in this project, is judged to be sufficient for controlling water and salt management in both schemes.

ii) Interception, isolation and re-use of drainage water for irrigation and/or disposal: The necessity for extreme measures such as the interception and re-use of drainage water, as applied elsewhere, will not be feasible in our view. Such extreme measures demand a total new infrastructure of canals and storage facilities, which is unaffordable. Therefore it is recommended that the current methods of managing drainage, tail-end and groundwater need to be promoted and improved in the future.

iii) Provision of incentives for water users to promote savings: On most of the farms in both schemes the total farm area is irrigated, and billing for water usage is based on a specific allocation. There is currently an incentive for irrigators to use less water or to irrigate a larger area with the excess saved water which involves trading water among themselves. In some instances the WUAs also participate in this water trading process when necessary.

iv) Development of a policy to accommodate shallow groundwater use, originating from water uptake by crops: As explained earlier, crops can be forced to utilize groundwater by decreasing irrigation. This can result in water and cost savings. A problem will arise when this practice is accepted by all irrigators with shallow water table soils. This will result in a temporary surplus of irrigation water in the scheme, and a simultaneous drop in the level and quality of the water table. This might be sustainable in the short term but certainly not in the long term. A longer term solution might be to give an incentive to strategically located farmers to employ this practice during periods of restricted water supply. For example, allowing them to trade water with farmers who run short of water.

Keeping in mind the role and function of the WUAs to ensure on-demand supply of water to farms and their role in protecting natural resources, it is of utmost importance that these organizations extend their role in facilitating training to create awareness of the proposed field guidelines. It should be mentioned that the current state of the guidelines needs to be improved in a practical way to cater for the huge group of irrigators who have aborted scientifically-based technology.

6. Recommendations for future research

The following topics are proposed for further research.

i) Cost benefit analyses of suggested best management practices.
ii) An investigation into the fate of salts in sandy loam and more clayey soils.
iii) Quantification of salinity-related problems below the Douglas weir.
iv) Impact of perennial crops on proposed best management practices.
v) Mapping of water table depths at both farm and irrigation scheme level.
vi) Regular monitoring of spatial and temporal salt distribution in soils at both farm and irrigation scheme level.

It can be concluded that continuation with the *status quo* with a sufficient supply of water might be sustainable in the long term. Short term restrictions in water supply can be accommodated, and with the use of present knowledge, the impact may be minimised. A permanent reduction in the water supply will force irrigators and administrators to introduce more sophisticated management practices.

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CHAPTER 1
INTRODUCTION

1.1 Motivation

Salinity associated with irrigation has and continues to be arguably the most important factor threatening agricultural production under irrigation. Unfortunately the problem extends beyond the confines of irrigated fields degrading water resources and resulting in extensive areas of land to become waterlogged and saline. Poor planning and ineffective water, and salt management practices by farmers and managers of irrigation schemes therefore strongly affect the sustainability of irrigation.

Van Schilfgaarde (1990), Letey (1994) and Rhoades (1997) all agreed that sustainable irrigation is technically possible with the proper design and operation of irrigation and drainage systems, together with the implementation of suitable crop and soil management practices, provided that acceptable political and social structures are in place. Hillel & Vlek (2005) emphasize that irrigated agriculture will not only survive, but thrive under realistic circumstances and appropriate management practices. With regard to political and social structures, as emphasised by Van Wyk et al. (2003), management practices should however be scientifically sound.

South Africa is therefore divided into 19 Catchment-based Water Management Areas (CWMAs). Each of these areas has an agency which manages water resources, co-ordinates water-related activities of water users and other water management institutions within their demarcated areas of jurisdiction. Within these CWMAs the water required for irrigation is managed by Water Users Associations (WUAs). The WUAs manage the day-to-day supply of irrigation water to the farms and are therefore responsible for the maintenance of water conveyance infrastructure, which includes the removal of drainage water. The next level for water management is on-farm where the farmer has the sole authority over the fate of irrigation water. If the farm is large enough it may comprise more than one irrigation field, which is the smallest unit where irrigation management decisions are made. The area covered by the irrigation system together with the depth of the potential root zone, defines the physical dimensions of this management unit. The potential root zone of field crops can extend up to 2000 mm (Bennie et al., 1988). Thus an in-field drainage system will be part of the smallest management unit if installed within this depth which is often the case.

It is essential to notice that hydro-salinity processes, such as water and salt movement in the soil, vadoze zone and groundwater zone, do not always follow managerial boundaries as mentioned earlier. Therefore, it is important to understand the impact of managerial decisions and activities imposed at different scales on these processes. For example, the time to reach salt equilibrium at different spatial scales differs widely. This can be observed from Figure 1.1 compiled by Thayalakumaran et al. (2007). The figure shows clearly that the time required for an area to reach a salt equilibrium becomes generally longer at larger spatial scales. For example, the time taken to reach a salt equilibrium at root-zone scale varies between 1 and 10 years and is heavily influenced by agronomic factors, such as crop rotation, soil types, water quality, irrigation methods and scheduling. The time to reach equilibrium at farm level is more portrayed and Thayalakumaran et al. (2007) estimated that this process can vary between 10 and 100 years, depending on the size of the farm and the factors influencing the hydro-salinity processes. Thayalakumaran et al. (2007) estimated the time to reach equilibrium at catchment scale is 100-300 years.

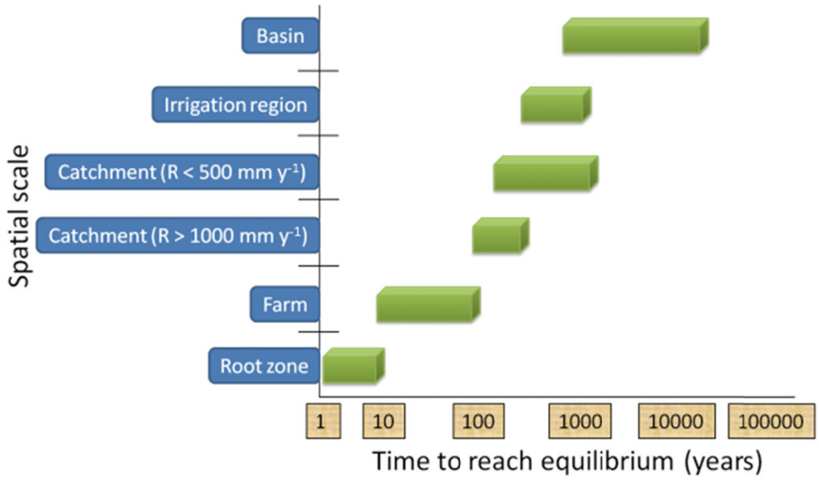


Figure 1.1 Relationship between time to reach salt equilibrium and spatial scales (reproduced from Thayalakumaran et al., 2007)

Climate plays a huge role in achieving a salt balance on the larger scales as indicated in Figure 1.1; i.e. a wetter climate will shorten the time to reach salt equilibrium. Irrigation tends to change climate since substantial amounts of water are applied in addition to rain. This implies that the hydro-salinity processes could be even faster as shown in Figure 1.1. Hydro-salinity processes at irrigation region scale are very slow and could vary between 300 and 1000 years. Therefore, it is important to have CWMAs and WUAs to regulate water and salt management that might affect downstream communities and their natural resources.

The estimated fraction of salt-affected irrigated land in South Africa is only 9%, which is much lower compared to the 34, 33, 30, 26 and 23% of Argentina, Egypt, Iran, Pakistan and the United States of America, respectively (Ghassemi et al., 1995). Between 1% and 12% of the total irrigated area in South Africa is severely waterlogged or salt-affected, and 5% to 20% moderately affected (Backeberg et al., 1996). In a comprehensive synthesis of literature Ghassemi et al. (1995) reported salinity problems in the Breede, Berg, Great Fish and Sundays Rivers. Ten irrigation schemes showed high increases in mean river water salinity from upstream to downstream over the length of the scheme, *viz*. Breede River, Great Fish River, Groot River, Hluhluwe River, Lower Vaal River, Modder River, Pongola River, Riet River, Tarka River and Vaalharts. Research by Du Preez et al. (2000) confirmed the deterioration in water quality of the lower Vaal River and its tributaries, which includes the Riet, Modder and Harts Rivers.

Despite the fact that salt-related problems are not at present a significant factor threatening production under irrigation in South Africa, increasing evidence of deterioration of physical resources does suggest that the problem cannot be ignored. A solicited research project on managing salinity associated with irrigation in selected areas of South Africa was therefore introduced by the Water Research Commission.

1.2 Objectives

A general objective and seven specific objectives were stipulated for the above-mentioned project.

General objective: Develop best practices and guidelines for managing the salt load associated with irrigation at farm and scheme level.

Specific objectives:

i) Conduct a desktop study to synthesise current knowledge (at a generic level, but from a technical perspective) regarding the management of the salt load associated with irrigation, with reference to problems being experienced in South Africa.

ii) Formulate generic best practices and identify harmful practices to be avoided.

iii) Select at least two case study areas from existing salinity problem areas such as the Breede, Olifants and Orange-Vaal-Riet rivers. Assess selected best management practices on a case study basis (with formal stakeholder participation) with the aim to develop specific guidelines for the selected case study areas.

iv) Identify incentives that could be applied to change behaviour of water managers at farm and irrigation scheme level.

v) Provide feedback on outcomes of the research to stakeholders and formulate recommendations for the implementation of sustainable solutions in consultation with them.

vi) Formulate generalized recommendations about best practices and guidelines for managing the salt load associated with irrigation at farm and irrigation scheme level.

vii) Identify further research needs and gaps.

1.3 Selected irrigation schemes

The study was conducted at the Orange-Riet and Vaalharts Irrigation Schemes in semi-arid South Africa (Figure 1.2).

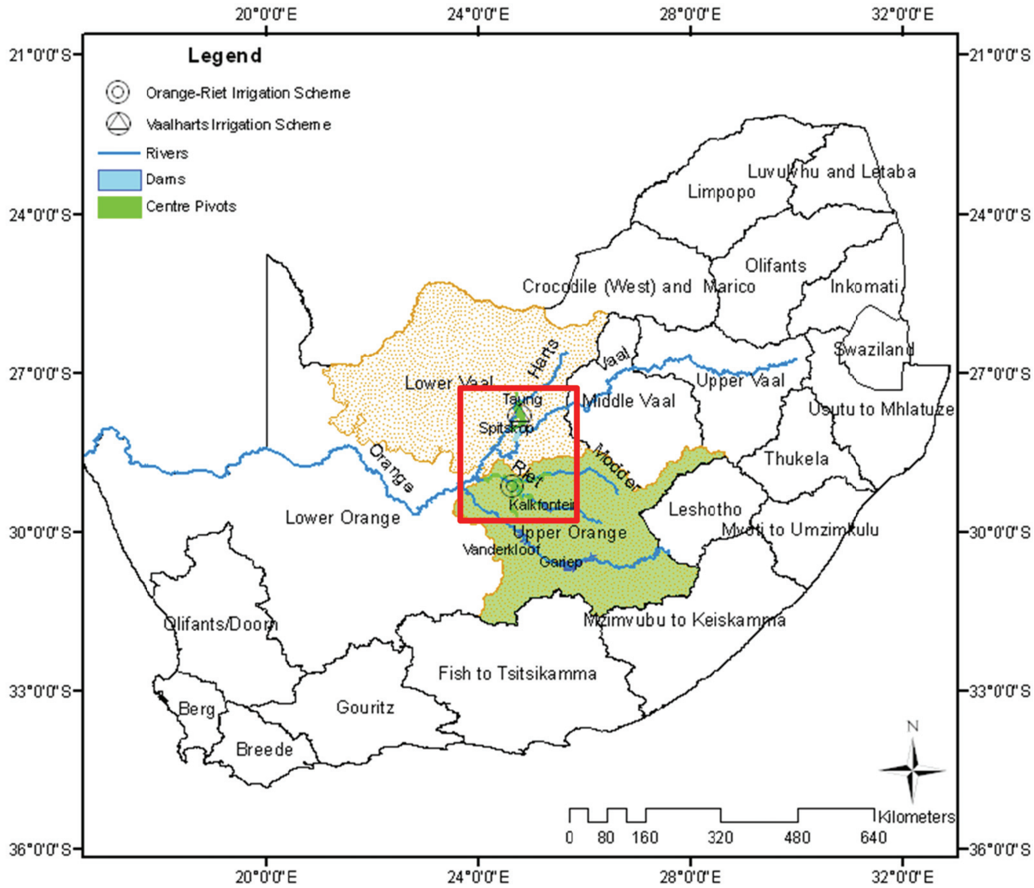


Figure 1.2 Location of the Orange-Riet and Vaalharts Irrigation Schemes and the 19 catchment water management areas (CWMAs) of South Africa.

Water in this region is managed by the CWMAs, Upper Orange or Lower Vaal, with several WUAs contributing to each one. Only the WUAs, Orange-Riet and Vaalharts Water, are of interest to this project as they manage the water allocated to the two irrigation schemes (Figure 1.3). The two irrigation schemes were selected *inter alia* for the following reasons.

i) Irrigation has been practised for more than 70 years on both schemes, which is important for salt to reach equilibrium at this level (Figure 1.1).

ii) The two schemes have a range of crops, soils and irrigation methods, with and without artificial drainage to study water and salt balances.

iii) Water of different qualities is used for irrigation since water is transferred between some sources in this region (Figure 1.3).

iv) Both schemes are managed by well organised WUAs who have reliable data essential for the project.

v) On each of the two schemes there is a large knowledge base concerning water and salt-related problems and their management.

vi) Logistically the location of the two schemes suited the project team best for detailed measurements.

vii) Several farmers at both schemes have a sincere interest in the project and their collaboration should be valuable.

viii) Water and salt-related problems were experienced occasionally at the two schemes (Section 1.4).

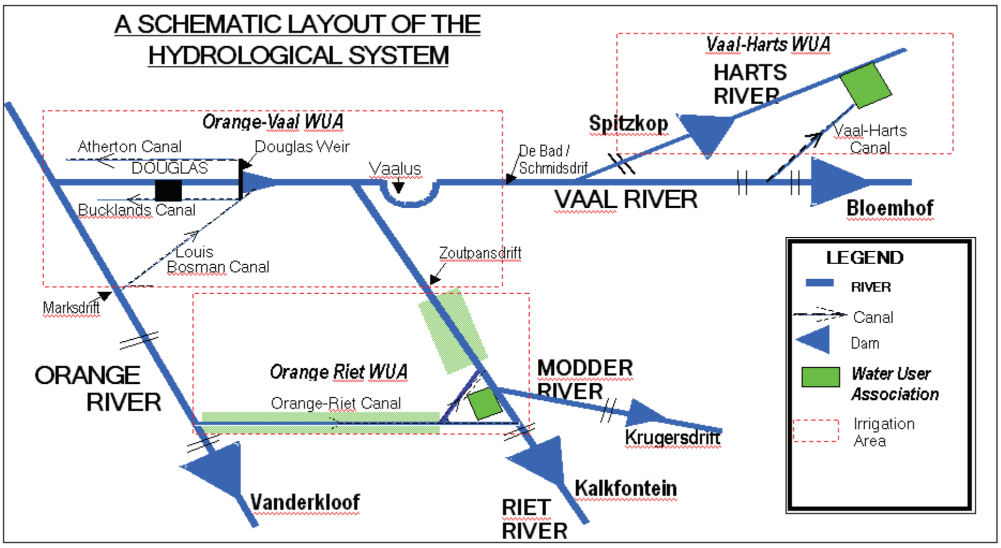


Figure 1.3 Diagram representing the Lower Vaal Irrigation Region (after Viljoen et al., 2006), with Water User Associations (WUAs) Orange-Riet and Vaalharts Water, who manage the water allocated for Orange-Riet and Vaalharts Irrigation Schemes.

1.4 Historical water management interventions in the study area

As pointed out earlier, groundwater flow at irrigation region scale is a slow process and salt equilibrium will probably be reached over thousands of years. However, once the groundwater as well as tail-end, artificial drainage and surface runoff water are discharged in a particular river the transport of the effluent from one WUA to another is a relatively rapid process compared to groundwater flow. Salts can be transported over vast areas in a relatively short time, pending on the flow rates, connectivity of the river system and the distance between WUAs. For example heavy salt release into the Harts River will be picked up in Spitskop Dam within days (Figure 1.3). Effluent released at Spitskop could reach the confluence of the Vaal River within days and within weeks the salts are at the lower end of the Vaal River. Thus, salt transport through river systems needs to be managed, because communities at the lower end of river systems have to deal with the consequences. This is especially true for the Orange-Vaal WUA, which is the recipient of effluent discharged from 85 000 ha irrigated land located along the lower Vaal River and its tributaries (Figure 1.3). The problem with poor water quality experienced by farmers along the Vaal River below Douglas Weir was resolved through pumping good quality water from the Orange River (long term EC average is 21 mS m^{-1}) to the weir via the Louis Bosman Canal. Water is redistributed to farmers via the Atherton and the Bucklands canals from the weir.

In the Orange-Riet WUA area extraordinary water management strategies can be traced back to the early 1900s. Rosenstrauch (1935) reported that farmers along the Riet River lost considerable stock since pasture could not be irrigated for long periods of continuous droughts induced by irregular rainfall patterns. The government installed therefore small pumping stations along the Riet River to supplement rainfall. Although it improved the livelihoods of the farmers it did not solve the problem fully, as water supply depended on the flow of the river. The next water management intervention was introduced with the completion of the Kalkfontein Dam in 1938. Water supply was controlled at the dam, but authorities soon realised that supply was inadequate for the irrigation farmers along the Riet River and in the Settlement area near Jacobsdal. The latest water management intervention, namely the building of the Orange-Riet Canal, checked the long history of inconsistent and inadequate water supplies to farmers. The 89 km canal was completed in 1992, stretching from Vanderkloof Dam to the Riet River Settlement.

Water supply through the Orange-Riet Canal not only benefited the farmers in the Settlement area, but also those who farmed along the lower Riet River. The Soil and Irrigation Research Institute (SIRI) has done many *ad hoc* investigations on waterlogging and salinity along this section of the river. These problems were induced by discharge of salts in groundwater flow to the Riet River from irrigated areas along the banks of the river. The main reasons for the high salinity of the groundwater are the concentration effect caused by water use of crops and the mobilization of residual salts stored in the stratum below the irrigated areas due to excess drainage (Moolman & Quibell, 1995). This conclusion is supported by the long term (1971-1997) annual salinity and sodicity of water in the river as reported by Du Preez et al. (2000). For example the electrical conductivity (51 to 136 mS m^{-1}) and sodium adsorption ratio (1.43 to 3.17) increased substantially downstream.

Several investigations in the study area on salinization of irrigated soils showed that evaluation of the suitability of soil for irrigation is a key element in sustaining long term quality of irrigated soils (Van Woerkom, 1964, 1965; Botha & Schoeman, 1986; Schoeman & Geers, 1988; Geers, 1989; Moolman & Quibell, 1995; Du Preez et al., 2000). Fortunately, the soil in the study area was properly surveyed by soil scientists before establishment of the irrigation schemes. The surveyors were very strict in their application of soil suitability guidelines for irrigation (Louw, 1967; Verster & Stofberg, 1974; MacVicar, 1976; Irrigation Planning Staff, 1980; Hensley & Laker, 1980; Schoeman, 1987; Bester & Liengwe, 1989).

In the mid-seventies managers and researchers started raising their concerns about the potential negative effect of imported salts via irrigation water on soils and crops at Vaalharts Irrigation Scheme. This was because the water quality of the Vaal River has deteriorated substantially since the commissioning of the scheme in the mid-1930s due to large scale urban, industrial and mining development upstream (Herold & Bailey, 1996). In addition to the poorer water quality, a rising water table induced by over-irrigation through flood irrigation methods and the leakage of conveying and storage facilities was also threatening (Streutker, 1977). The Dwyka shales and tillite stratum underlying the scheme were known to be highly mineralizable (Temperley, 1967), implying an additional source of salts that poses a major threat to soils and crops once the groundwater is connected to the root-zone. After several *ad hoc* investigations by SIRI, the government started to support farmers with the installation of in-field drainage systems. From 1975/76 until 1991/92, 505 farms totalling 12 476 ha were artificially drained in this manner (Herold & Bailey, 1996). Since 1994 all artificial drainage was installed without support of the government. However, the extent of it nowadays is captured in Figure 1.4. Despite the amelioration attempts, Herold & Bailey (1996) were concerned about the salts entering the aquifer below the calcretes at Vaalharts (Figure 1.5). Their concern was based on the early work of Stewart et al. (1987) (as cited by Herold & Bailey, 1996) who estimated that only 20% of the salts added through irrigation from 1935 to 1984 reached the Harts River in return flow process. The remaining salts, which amounted to about 3 million tons, were retained somewhere in the irrigation area. This has become the focus of a study by Herold & Bailey (1996) in which they modelled hydro-salinity from 1975 to 1991.

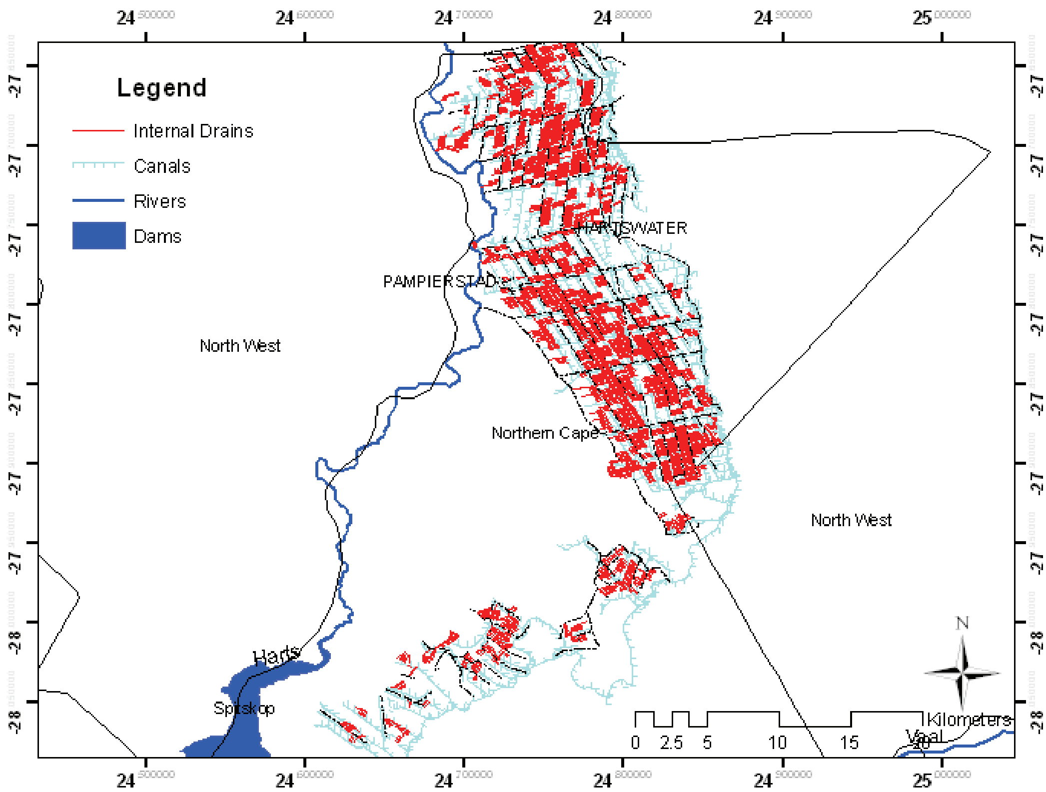


Figure 1.4 Map illustrating the distribution of the internal drainage systems installed at Vaalharts Irrigation Scheme. The map was produced with data provided by the Department of Agriculture (Personal communication: Mr C van Niekerk, Northern Cape Department of Agriculture, Kimberley).

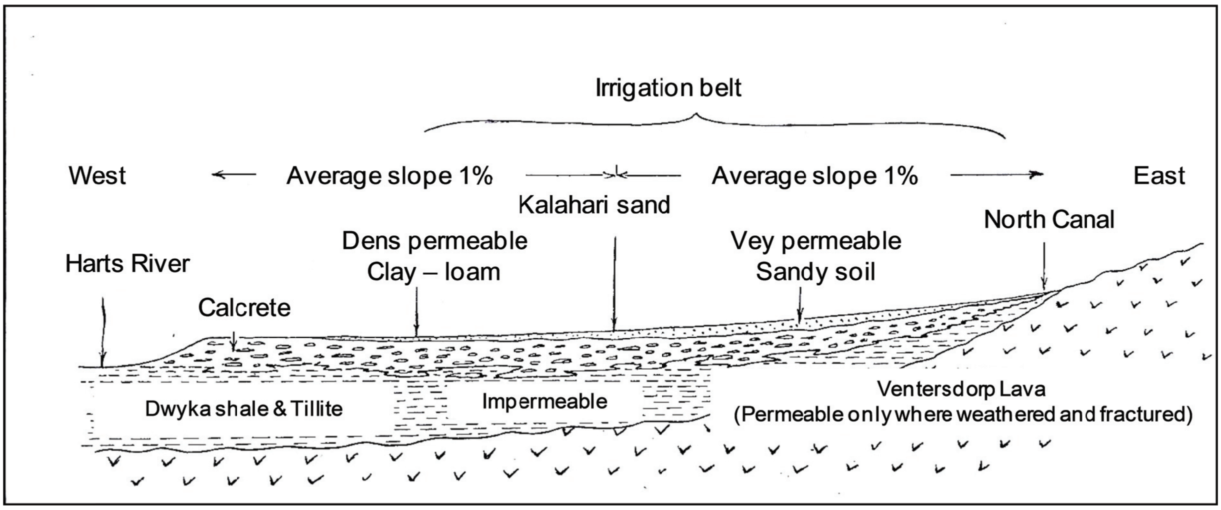


Figure 1.5 Conceptual geology for Vaalharts Irrigation Scheme as described by Temperley (1967) (Adapted from Ellington et al., 2004).

They found that 43% of the irrigated salt load actually drained to the Harts River. The 23% difference between the two studies was ascribed to historically inaccurate stream flow data at critical measuring points in the Harts River. With the modelling attempt Herold & Bailey (1996) estimated that 11% of the irrigated salt load was chemical inactivated by precipitation and adsorption in the irrigated area and hence effectively removed from the water phase. They argued that it is highly unlikely that the soil can continue to remove salts indefinitely. Therefore their concern was the remaining 46% salt load that percolates annually through fractures in the calcrete towards the aquifer. They postulated that once the aquifer reaches its storage capacity, this process will lead to a sudden 2-3 fold increase in the salt load of the Harts River. If their hypothesis should prove to be true about 100 Kton salts will be discharged annually to the Harts River.

The hypothesis of sudden salt reversal by Herold & Bailey (1996) was tested with measurements in a field study by Ellington et al. (2004). They reported the presence of calcretes throughout the scheme. However, the calcretes were more pronounced in the southern part of the scheme where gravels and clays were also observed. The shales were generally thicker in the northern side of the scheme compared to the southern side. Despite the heterogeneous geological formations, the water level over a year in the area was almost constant, varying between 1.6 and 2 m below the surface. No deep water tables were observed. However, salinity (100 to 270 mS m^{-1}) of the groundwater varied spatially and was associated with the geology. The groundwater contained high levels of nitrate (from cultivation practices), magnesium (from mineralizable shales) and sulphates (from irrigation water). There was no significant evidence of stratification concerning water quality in the aquifer. The majority of the tests indicated that the hypothesis of Herold & Bailey (1996) is probably unrealistic and that the mass return of salts to the Harts River is highly unlikely. However, these tests do not explain the fate of the applied salt at Vaalharts.

An alternative hypothesis was raised by Ellington et al. (2004), stating that the salts accumulate gradually in the groundwater underneath Vaalharts and in the process of flowing to the Harts River the salts are diluted by rainwater percolating towards the groundwater. They used the model MODFLOW to simulate water and salt migration over the Vaalharts region including Taung in the north and the Vaal River in the south. The model showed that groundwater does flow to the Harts River and not to the Vaal River. Outputs of the model revealed further that the salts in the groundwater are diluted, more in the veld than the irrigation area. This implies that the salts are discharged into the river, but at lower than expected concentrations. According to Ellington et al. (2004) this process explains the absence of high concentrations of salt in the Harts River, thus solving the main concern of Herold & Bailey (1996). Observations from boreholes verified the increase of salts in the groundwater underneath the irrigated area and the presence of a salt gradient from the irrigated area towards the river. Ellington et al. (2004) estimated that between 16 and 19 Kton salts are annually discharged into the Harts River. This represents 9-11% of the 179 Kton salts added annually through water (131 Kton) and fertilizer (48 Kton). The model estimated that 81.5% of the added salts is removed through tail-end water (17.9 Kton), artificial drainage (17.9 Kton), crop produce (26 Kton) and leaching (84 Kton), while only 1.8 Kton remains in the soil. Thus unaccounted salts amounted to 6-8%.

The research of Ellington et al. (2004) was followed with a detailed study by Verwey & Vermeulen (2011) on the influence of irrigation on the level, salinity and flow of groundwater in Vaalharts. Their measurements in at least 138 piezometers showed that the mean groundwater table was 1.65 meter below ground level (mbgl) in August 2008, 1.57 mbgl in November 2008, 1.56 mbgl in February 2009 and 1.76 mbgl in May 2009. Corresponding mean EC values at 400 mm below water table level in the piezometers were 160, 232, 191, and 183 mS m^{-1}. The water table levels related almost perfectly with the surface topography levels and when this regression equation was used in MODFLOW, the model confirms that water movement over Vaalharts is in the direction of the Harts River and not the Vaal River.

Van Rensburg et al. (2008) used the salt balance method of Aragües (1996) to determine the fate of salts at sites irrigated for variable time along the lower Vaal River, *viz*. Vaalharts (53 years), Spitskop (53 years), Wildeklawer (17-30 years), Zandbult (19-29 years) and Jackson (45 years). Salt additions resulting from farming practices varied between 79 ton ha^{-1} at Wildeklawer to 280 ton ha^{-1} at Jackson, with irrigation water and time of irrigation the major contributors of salt. Using virgin soils as references they showed that between 78% and 87% of the applied salts had been leached from the root-zone. These results imply that some soils with restricted natural drainage, or where the artificial drains were blocked, exhibited an increase in salt compared to its virgin state. Arcadia and Sepane soils falls in this category. There were instances where freely drained soils also showed a net build-up of salts due to irrigation methods that concentrate on saving irrigation water, without taking the leaching requirement into account. Van Rensburg et al. (2008) predicted further that if the current practices are sustained for the next 50 years the osmotic threshold of -280 kPa for wheat will be exceeded in the two clay soils mentioned.

1.5 Research approach

In addressing the stipulated objectives of this solicited project, literature was studied to formulate eventual best management strategies for salinity associated with irrigation at farm and scheme level (Chapter 2). Next, sites and measuring points were identified on Orange-Riet and Vaalharts Irrigation Schemes at which data were collected over four cropping seasons in order to study the mechanism of water and salt movement under a range of crops, soils and irrigation methods, with and without artificial drainage (Chapter 3). These measurements yielded sufficient data of good quality for the calculation of short term water and salt balances covering a large range of situations. It was thus decided to use a local model known to the project team to test scenarios of salinity management in the long term. The test and validation of SWAMP using independent data sets are presented in Chapter 4. In a successive series of simulations using experimental data, crop selection under irrigation (Chapter 5), response of soils to irrigation management (Chapter 6), effect of irrigation water salinity on crop production (Chapter 7) and irrigation scheduling methods (Chapter 8) were assessed by using SWAMP generated simulations. Based on the outcome of these simulations best management practices and guidelines are suggested in Chapter 9 for on-farm level and WUA level.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

No single strategy exits for managing the salt load associated with irrigated fields, farms and irrigation schemes. In most cases the implementation of a combination of practices is required. The most effective combination of practices depends upon economic, climatic, social and biophysical factors including irrigation water, soils and geo-hydrologic situations.

Management practices should form part of the planning of new irrigation development projects. During the initial planning and construction of an irrigation project, attention should be given to aspects, like suitability of water and soils for irrigation, depth to the groundwater, as well as the geo-hydrology and topography of the area. In existing projects it is often difficult or impossible to implement appropriate management strategies due to infrastructure constraints. In newly developed irrigation schemes, management strategies should be directed towards conserving water, preventing waterlogging and root zone salt accumulation as well as protection of the environment and ecology. Some management practices are therefore more suitable for on-field or on-farm application, while others are more suitable for implementation on a regional scale (Irrigation scheme level). The aim of the literature review was to provide insight into what strategies to consider in order to effectively and efficiently manage salinity associated with irrigation at farm and irrigation scheme level.

2.2 On-farm strategies for enhancing crop production and soil protection

On-farm strategies, which consist of agronomic, irrigation and drainage practices, must be applied by individual farmers on a field-by-field basis, since the cause and extent of salinity associated with irrigation in most cases originates from individual fields.

2.2.1 Selection of crops with salt tolerance adapted to the situation

Crops differ concerning the salinity level they can tolerate in the root zone before a reduction in yield realises. This provides the farmer with an opportunity to select crops that will produce satisfactorily at an existing salt concentration in the root zone and those expected to occur during the growing season. Generally the economic value of crops decreases with an increase in salt tolerance. There are not many varieties which are salt tolerant and still produce economic yields (Minhas, 1996). Most agricultural plants are relatively salt tolerant during germination, more sensitive during seedling establishment and emergence and during the phase change from vegetative to reproductive growth. Considerable evidence indicates that during the vegetative growth stage crop species are particularly salt sensitive (Du Preez et al., 2000).

It is important to consider the crop's salt tolerance during seedling development, especially because failure to establish a satisfactory plant population is a major factor limiting crop production. Pre-plant irrigation has to be done to ensure optimum soil water conditions for tillage and seedbed preparation. After planting, the salts in the planting zone move to, and accumulate at the surface via evaporation, especially where irrigation with relatively saline water is practiced. The germinating and emerging seeds can therefore be exposed to potential lethal salt concentrations. The objective of pre-plant irrigations with good quality water should be to leach salts out of the seedling zone wherever possible. Another option is to use post-plant irrigations to leach salts deeper into the soil. Soil crusting however can be a problem, especially in clay soils, when post-planting irrigation is done with good quality water. When a crust is likely to develop the planting rate can be increased to improve seedling emergence and establishment.

Other techniques for combating crusting are various forms of mulching and in the case of sodic soils, the application of amendments, such as gypsum, which will be discussed later.

A problem with selecting a crop with higher salt tolerance adapted to the situation could be a lack in the farmer's skills and knowledge in the production of the crop regarding the influence of various management practices on the yield versus salt concentration response curve. It will always be more acceptable to keep the salinity level of the soil below the threshold for the selected crop, by managing the salt balance in the root zone through irrigation and drainage strategies.

2.2.2 Irrigation strategies that prevent excessive salt accumulation in the root zone

2.2.2.1 Assessing the suitability of irrigation water

The first and certainly the most important characteristic for determining irrigation water suitability is the salt content as indicated by the electrical conductivity (EC_i, mS m^{-1}). An increase in the electrical conductivity of irrigation water and the amount irrigated will increase the salt load added to the root zone leading to more rapid salinization. All classification systems therefore recognise the detrimental effect of increasingly saline water on the suitability of irrigation water. As salinity increases, the suitability of water for irrigation decreases. The strategy to prevent excessive salt accumulation in the root zone is thus to irrigate with water of lower salinity.

Several other water quality characteristics need to be considered in the evaluation of its suitability for irrigation. With regard to the salt concentration in the root zone, saline, saline sodic or sodic soil conditions are the different types of problems related to the use of saline and/or sodic irrigation water (Gupta & Abrol, 1990; Singh et al., 1992; Tedeschi & Dell' Aquila, 2005). For assessing this classification of salinity and sodicity hazards of irrigation water, Figure 2.1 can be consulted (United States Salinity Laboratory Staff, 1969). According to this figure the sodium hazard of irrigation water will increase with an increase in the salinity hazard. This is because they attached much importance to the sodium hazard, since soil will attain an exchangeable sodium percentage (ESP) in equilibrium with the irrigation water faster for more saline water.

This classification does not cater for the effects of exchangeable sodium on swelling and dispersion in soils, which are counteracted by high electrolyte concentrations (Quirk & Schofield, 1955; Van der Merwe, 1973; Mace & Amrhein, 2001). When the electrolyte concentration of the soil solution increases the thickness of the diffuse electrical double layers surrounding clay colloids is suppressed. The soil sodicity hazard cannot therefore be assessed independently of the salinity hazard. For example with an increase in the SAR of the topsoil, the electrical conductivity of the infiltrating water should also be higher to prevent the likely reduction in infiltration rate due to swelling and dispersion of clay particles.

Salinity in the root zone reduces plant growth because of osmotic-induced plant water stress and specific ion effects on nutrition and toxicity. The negative effects associated with sodic soil conditions, include, reduced crop yield and quality as a result of sodium uptake through the roots of sodium sensitive plants; impaired soil physical conditions, as manifested by reduced soil permeability (infiltration rate and hydraulic conductivity) and an increased tendency for hard-setting (Department of Water Affairs and Forestry, 1996). These adverse soil physical conditions usually stunt growth before SAR or ESP levels rise to a level that is lethal to plants. Soil physical deterioration can occur at SAR levels as low as 5 to 8, when combined with low concentrations of salt (Van der Merwe, 1973; Mace & Amrhein, 2001).

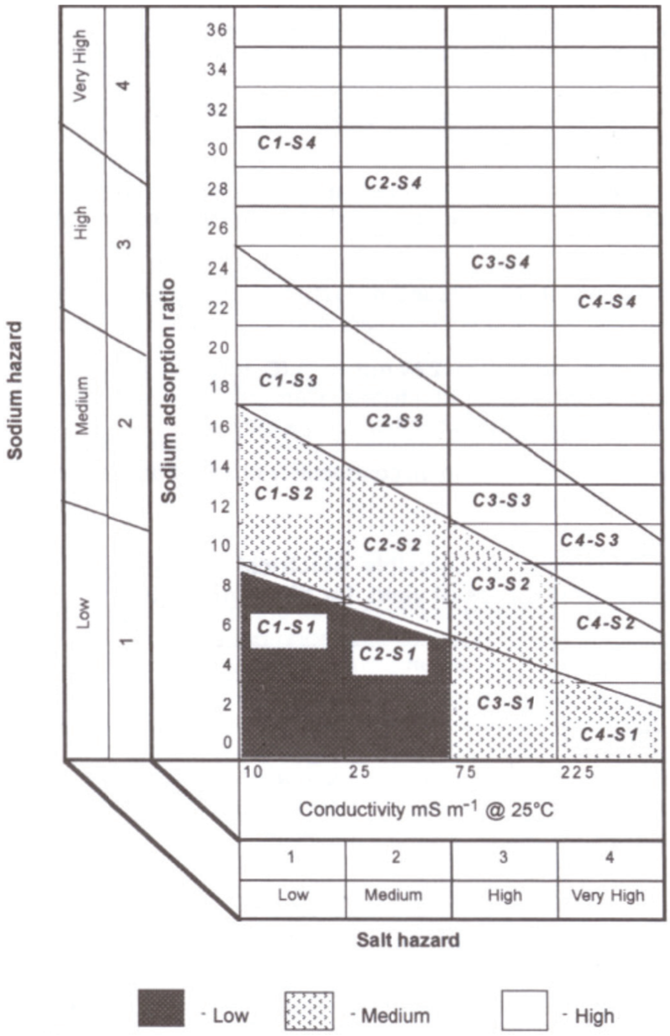


Figure 2.1 Salinity and sodium hazard of irrigation water based on the sodium adsorption ratio (SAR) and electrical conductivity (United States Salinity Laboratory Staff, 1969) as cited by the Fertilizer Society of South Africa (2007).

2.2.2.2 Irrigation methods

The distribution of water and salts in the root zone varies with the method of irrigation (Rhoades, 1997; Darwish et al., 2005; Sharma & Minhas, 2005; Paranychianakis & Chartzoulakis, 2005; Hillel & Vlek, 2005). Even after following the best design criteria, on-farm irrigation efficiency of surface irrigation methods is low (60-70%), resulting in excessive irrigation water losses and non-uniformity in water application (Minhas, 1996). The infiltrated depth of water is normally greatest at the upstream end of the furrow, basin or border. When the soil water deficit is merely replaced at the upstream end, the downstream end will be under-irrigated. By irrigating to refill the entire profile at the downstream end, causes deep percolation upstream.

The salinity hazard posed by surface irrigation can be minimised if it is properly designed. According to Rajput & Aggarwal, (1983) (as cited by Minhas, 1996) land needs to be properly levelled to ensure even distribution of water. The length of the water run, stream size, the slope of the soil and the cut-off ratio should closely follow the desired specifications which influence the uniformity and depth of water application for a given soil type. In Bernstein et al. (1955) and Bernstein & Fireman (1957) (as cited by Kruse et al., 1996), typical patterns of salt accumulation in ridges between furrows are illustrated together with the best seed placements for young plants to avoid the highest salt concentrations. Salts tend to accumulate in those regions of the seedbed where the water flow paths converge and water evaporates.

Sprinkle irrigation is an ideal method for irrigating evenly, frequently and with small quantities of water at a time, which results in a high irrigation frequency. However, when irrigation applications only provide in plant water and surface evaporation losses, salt will accumulate. Salt can therefore accumulate because very little water and salts will leach beyond the root zone. Leaching of salts can be accomplished with irrigations exceeding the crop water requirement. Leaching of salts will be more efficient with sprinkle irrigation because the water application rate should be lower than the infiltration capacity of the soil (Abrol et al., 1988). The lower pore water velocity and water content results in a larger portion of the applied water to flow through the soil matrix, thus reducing preferential or macro pore flow and subsequently more salts being removed per unit depth of water leached. Careful consideration should be given when using more modern mobile centre pivot irrigation systems. In arid and semi-arid areas leaching of excess salts from the root zone with centre pivots is almost impossible. The reason is probably because of the high application rates at the far end of the circular fields that are required for irrigations of more than 30 mm at a time (Du Preez et al., 2000). These high application rates can exceed the infiltration rate of the soil which will result in runoff. Most of the centre pivots cannot apply large enough amounts of water at a time required for salt leaching without excessive runoff from the outer circle.

Surface and sub-surface drip irrigation systems cannot apply water uniformly over the field but it can be used to leach the soil under the emitter frequently. Long-term use of drip irrigations may result in salt accumulation in the periphery of the wetted volume of soil, if rainfall is insufficient to leach out such accumulations (Hillel, 2000; Oron et al., 2002). In arid and semi-arid regions of the world where rainfall is very low, drip irrigation can enhance salt accumulation in the root zone. Soil salinity under drip irrigation affect crop yield less compared to other irrigation methods (Hanson & May, 2004). This is probably because of the regular and frequent supply of water that maintains a constantly higher matric potential in the soil.

It is often unavoidable to use poor quality water for irrigation. When saline or sodic irrigation water is used the selection of a suitable irrigation method depends on the capabilities of the specific method to minimise/avoid the risks associated with the use of those water. Aspects that need to be considered are summarized in Table 2.1.

2.2.2.3 Irrigation with multi quality water

Irrigation system type and water management strategies need to be taken into consideration when using saline/sodic water for irrigation. Water management strategies that can be considered include network dilution, where different quality water are blended in the supply network, soil dilution, where altering the use of good and poor quality water take place according to the availability and crop needs, and switching the use of water qualities during the growing season according to the critical stage of plant growth (Malash et al., 2005).

When saline and sodic water are blended the salinity and sodicity risk decreases due to the mutual dilution of the two types of water. Blending sodic water which contains more Na^{+} with saline water, containing Ca^{2+} and Mg^{2+}, the chemical combination of CO^{2-}, HCO^{2-} and Ca^{2+}, Mg^{2+} forms harmless salts

($CaCO_3$, $MgCO_3$, $Ca(HCO_3)_2$ and $Mg(HCO_3)_2$), which can precipitate in sodium affected soils. This will cause an increase in SAR and ESP of soil. Also, Na^+ is combined with Cl^- and SO_4^{2-} to form NaCl and Na_2SO_4 salts which are easily leached from the soil (Sheng & Xiuling, 1997). With this practice however the volume of good quality plant consumable water will be lowered.

According to Rhoades et al. (1992) the alternate application of better and low quality irrigation water is a more acceptable practice and offers an advantage over blending. Better crop yields were obtained where two different types of water qualities were applied separately, when available on demand, compared to mixing (Minhas, 1996; Sheng & Xiuling, 1997; Singh, 2004; Sharma & Minhas, 2005). Alternate use of saline water and fresh water, according to the salt tolerance of different crops and different growth stages, makes it possible to optimize the use of saline and fresh water, respectively (Sheng & Xiuling, 1997). Because germination and seedling establishment are the most salt sensitive growth stages for most crops, the better quality water should be utilised for pre-sowing irrigation and during the early stages of crop growth.

Table 2.1 Suitability of irrigation methods for irrigation with saline water (Pereira et al., 2002)

Irrigation method	Salt accumulation in the root zone	Foliar contact avoiding toxicity	Ability to infiltrate water and refill the root zone	Control of crop stress and yield reduction
Surface irrigation	Not likely except for under irrigated parts of the field, leaching requirement difficult to control	Not Possible	Adequate because large volumes of water are applied at each irrigation and water remains there until infiltration is complete	Adequate because salt is leached with large amount of water applied if water table is not present
Sprinkler irrigation	Not likely except for under irrigated parts of the field, leaching difficult or impossible with equipment designed for light and frequent irrigation	Severe leaf damage can occur if frequent irrigation is used	Salinity induced infiltration problems including soil crusting may cause very high runoff losses	Crop stress is likely to occur due to toxicity by contact with the leaves and fruit, and reduced infiltration thus yield losses may occur
Micro, drip and subsurface irrigation	Not likely to occur except for under irrigated parts of the field	Not likely to occur	Not likely to occur except where under-irrigation is practised	These systems are able to provide for crop stress and toxicity control. So yield losses are minimized

As mentioned earlier in Section 2.2.1, crop's salt sensitivity differed between growth stages. Thus water with higher salinity can be used during the growth stages when crops are least salt sensitive. Saline water can also be used for irrigating salt tolerant crops in rotation with a salt sensitive crop, where better quality water is used to leach salts that accumulated during the previous cropping season, before planting the salt sensitive crops.

Using a validated agro-hydrological model (soil water atmosphere plant, SWAP; Singh (2004) showed the practical implications of alternately using good and poorer quality water. It was concluded that it is possible to use saline water with an EC_i of up to 1400 mS m^{-1} alternately with canal water (30-40 mS m^{-1}) in a cotton-wheat crop rotation in both sandy loam and loamy sand soils. Pre-planting irrigations however must be done with canal water. Excess irrigation needs to be applied with an increase in salinity of the irrigation water to allow for salt leaching, a favourable salt balance in the root zone and acceptable osmotic potentials for root water uptake.

2.2.2.4 Irrigation scheduling

It is often recommended that irrigation applications on saline soils should be more frequent, which reduces the cumulative water deficits, both matric and osmotic, between irrigation cycles (Al-Tahir et al., 1997). This higher water availability will result in a higher ET which in turn results in higher yields (Yang et al., 2002) under such conditions. Minhas & Gupta (1993), according to Minhas (1996) recommended that the amount of water per application should be reduced in line with crop water requirements if the benefits of short irrigation intervals are to be achieved.

This practice is however controversial, because it promotes water uptake from shallow soil layers, an increase in unproductive evaporation losses from the soil surface, and when saline water is used, the salt load in the upper soil layers will be increased (Minhas, 1996). According to Sinha & Sinha (1976a, b), as cited by Minhas (1996) the salt concentration, and thus also the osmotic potential adjacent to roots in saline soils, is 1.5 to 2 fold higher than in the bulk soil. Higher transpiration rates will increase this effect indicating that keeping the soil wet by increasing the irrigation interval, may actually enhance the detrimental effect of salinity. By extending the irrigation interval, deeper roots will extract larger proportions of water from these zones. Ibrahim & Willardson (2004) emphasized that when irrigated soils have shallow water tables, salt will accumulate in the upper profile when the irrigation intervals are long. Short irrigation intervals in the presence of high water tables will maintain high water content in the upper soil layers, therefore lowering the upward flux of water and hence salts from the water table.

The objective with irrigation scheduling should be to meet only the seasonal crop water demand, thereby conserving water and reducing the amount of salts added to the root zone to ease the on-site and off-site environmental impacts of irrigation. When leaching of salts from the root zone is essential, separate management strategies should be applied, as will be discussed in the following paragraph.

2.2.3 Drainage strategies for controlling root zone salinity/sodicity and waterlogging

2.2.3.1 Leaching

Practical experience and scientific research contributed greatly towards improving the efficiency of water use (Bennie, 1995; Hillel, 2000; Caballero et al., 2001). The objectives with modern irrigation technology are conserving water through reducing transport and application losses, coupled with increased crop water use efficiency thus reducing the volume and salinity of leaching water (Hillel, 2000). It is recommended that periodic leaching should be applied when soil salinity has reached the threshold salinity level which will cause a reduction in crop yield (Du Plessis, 1986; Monteleone et al., 2004; Ehlers et al., 2007). Although leaching will always be effective, its efficiency will increase at higher soil salinity.

Ehlers et al. (2007) proposed that when the mean salinity of the root zone is below the threshold salinity level of the cultivated crop, it is better to irrigate according to the crop water demand in order to minimize the amount of applied salts. The assumption was made that freely drained conditions exist where added salts can be removed from the root zone, through natural leaching processes during periods of high rainfall. Under conditions where the accumulated salts exceed the removal by leaching, to the extent that crop production is hampered, the natural leaching of salts should be accelerated by irrigating more than the required crop water demand.

Irrigation water salinity and the amount of water applied will determine the quantity of salts added to, and therefore the increase in the salinity level of the root zone over a growing season. The relationship between root zone salinity (the electrical conductivity of a saturated soil extract, EC_e, mS m^{-1}) and the salinity of the irrigation water (EC_i, mS m^{-1}) can be calculated using a concentration factor. Under conditions of negligible leaching for low and high frequency irrigation systems, respectively, concentration factors of 2.79 and 1.79 can be used (Parker & Suarez, 1990). Ayers & Westcott (1985) used a concentration factor of 3.2 when 100% of evapotranspiration are applied. Ehlers et al. (2007) showed that the change in salinity of the root zone (ΔEC_{sw}) under shallow water table conditions can be predicted after each irrigation cycle using Equation 2.1:

$$\Delta \mathbf{EC_{sw}} = \left(\frac{(\mathrm{EC_i})(\mathrm{Cum\ IR})(0.0783)}{z}\right)(69.918) \qquad \mathbf{2.1}$$

where ΔEC_{sw} = increase in the mean EC_{sw} of the root zone per mm depth (mS m^{-1})
EC_i = electrical conductivity of the irrigation water (mS m^{-1})
Cum IR = cumulative irrigation (mm)
z = soil depth to restriction (mm).

When good quality water is used it will take several years before the increase in root zone salinity will require additional leaching. Irrigating with poorer quality water will however necessitate periodic leaching after a few seasons, in order to remove excess salts from the root zone. Excess salts refer to salts that need to be removed until an equilibrium level of electrical conductivity under the existing soil-irrigation-water-drainage conditions is reached. Leaching until 100% of excess salts are removed from the root zone will not be sustainable in the long run, due to off-site salinity disposal problems. When 70% of excess salts are removed, root zone salinity can be efficiently managed (Barnard et al., 2010).

Leaching curves that adequately describe the amount of water required to leach the soil to a predetermined level, were developed by Reeve (1957) and Dieleman (1963). The empirical equations derived from *in situ* determined leaching curves are however specific to the experimental conditions, soil and salinity characteristics and the initial salinity levels from which they were derived (Van der Molen, 1956; Talsma, 1966; Leffelaar & Sharma, 1977; Khosla et al., 1979; Pazira & Sadeghzadeh, 1999; Barnard et al., 2010). For saline loamy sand (Clovelly) and sandy loam (Bainsvlei) weakly structured apedal soils, respectively, the depth of leaching required (Dw, mm) can be estimated with Equation 2.2, irrespective of soil depth, soil salinity and irrigation water salinity (Barnard et al., 2010).

$$\mathbf{Dw} = \left(\frac{\ln\left(\frac{-y}{a}+1\right)}{b}\right)\mathbf{Ds} \qquad \mathbf{2.2}$$

Where y = 1 – (EC_{actual} – EC_i) / ($EC_{initial}$ – EC_i) or fraction of excess salts removed
EC_{actual} = target soil water salinity (mS m^{-1})
a = 1
b = -10.15 for a loamy sand soil and -7.35 for a sandy loam soil.
Ds = depth of soil (mm).

$EC_{initial}$ = EC of the soil water or from a saturated extract before leaching.
EC_{actual} = EC of the soil water or from a saturated extract after leaching.
EC_i = the electrical conductivity of the irrigation water.

For a saline to saline sodic silty clay-clay soil Equation 2.3 of Pazira & Sadeghzadeh (1999) and for a saline sodic sandy loam to silty loam soil Equation 2.4 of Leffelaar & Sharma (1977), can be used:

$$\mathbf{Dw = Ds\left(\frac{0.0761}{(y-0.023)}\right)} \qquad \mathbf{2.3}$$

$$\mathbf{Dw=Ds\left(\frac{0.062}{(y-0.034)}\right)} \qquad \mathbf{2.4}$$

Where y = $(EC_{actual} – EC_i) / (EC_{initial} – EC_i)$ or fraction of excess salts remaining.

Generally the control of salinity is easier in permeable sandy soils than less permeable clayey soils. The transport of chemicals by water movement through coarse and medium textured soils, results in a more uniform displacement of a resident soil solution by miscible displacement. Unfortunately, the same do not apply to clayey soils. In clayey soils, whether saline, saline-sodic or sodic, macropore or by-pass flow occurs when most of the water movement takes place through large structural pores or cracks. In structured high clay content soils unsaturated flow conditions will provide more efficient leaching of salts per unit depth of water leached (Tanton et al., 1995; Armstrong et al., 1998). Unsaturated flow conditions are promoted when water is applied at rates lower than the infiltration rate.

The infiltration and hydraulic conductivity of sodic soils are poor due to dispersion of clay particles. Instead of increasing the amount of leaching, it is advisable to decrease the sodium adsorption ratio by increasing the calcium content of the irrigation water. Thereby reducing the sodic nature of the soil will in turn increase the salt concentration and electrolyte content of the irrigation water, which will help maintain the permeability of the soil and prevent dispersion of clay. When the initial leaching with saline water is complete the salinity of the irrigation water can be gradually decreased to ensure that the soil is brought to the desired salinity level (Hillel, 2000).

2.2.3.2 Shallow water table management

The amount of water percolating deeper than the root zone should be minimized because the excess in drainage water eventually accumulate in a zone of water saturation that usually lies above a layer, of rock or clay that is impermeable to water movement. The upper surface of this zone of saturation is known as the water table. On-farm, the problem of excess leaching water is characterised by developing shallow water tables in or just below the potential root zone depending on the depth of the impermeable layer. These water tables are referred to as perched water tables to distinguish them from the deeper groundwater tables that develop from rainwater recharge prior to irrigation.

The sources of the excess water are primarily inefficient irrigation and excessive loss of water from supply canals or storage dams, contributing towards the presence of shallow water tables on irrigation farms, especially in irrigated soils with shallow depth or poor internal drainage (impermeable layer). Proper irrigation management and leaching practices must be maintained in order to prevent irrigated soils from becoming waterlogged and salt-affected. The installation of artificial drainage is a requisite, to ensure sustainable irrigation farming in the long run, when water is applied to soil in excess of its natural internal drainage capacity.

The objective with artificial drainage is the removal of excess water from the root zone, generally by lowering the water table or preventing its rise above some specified limit. It is carried out by means of installing drains, which may be ditches, pipes or mole channels into which water flows as a result of hydraulic gradients existing in the soil. The depth and spacing of internal drainage systems is of crucial importance. Table 2.2 shows the ranges of depth and spacing, generally used for placement of drains in fields (Hillel, 2000). Inefficient depth and placement will prevent a set of drains from lowering the water table to the extent necessary.

In general water table depths should be maintained at greater depth in more arid than in humid climate regions, because of the higher evaporation rate and more rapid increase in water table salinity. In soils where the salinity risk is higher, such as in medium and fine textured soils, the water table should also be kept at greater depths (Hillel, 2000). Where there is a mechanical limitation to the depth of drain placement, adjacent lines can be placed closer together to increase their effectiveness.

Table 2.2 Prevalent depths and spacing of drainage pipes in different soil types (Hillel, 2000)

Soil type	Hydraulic conductivity (mm day^{-1})	Spacing of drains (m)	Depth of drains (m)
Clay	1.5	10-20	1-1.5
Clay loam	1.5-5	15-25	1-1.5
Loam	1.5-20	20-35	1-1.5
Fine, sandy loam	20-65	30-40	1-1.5
Sandy loam	65-125	30-70	1-2
Peat	125-250	30-100	1-2

An advantage of shallow water tables is that they can be managed so that they contribute towards part of the crop water needs. Several reports indicate that shallow water tables can contribute significantly towards the water requirements of crops (Wallender et al., 1979; Ayars, 1996; Ehlers et al., 2003; Ghamarnia et al., 2004; Hornbuckle et al., 2005). The successful use of shallow water tables to supplement the water supply to crops will depend on water table depth, soil physical properties, soil and water table salinity and plant root distribution. Hornbuckle et al. (2005) showed that with a drainage system that uses weirs to control water table depths, combined with deficit irrigation scheduling to maximize the potential crop use of shallow water tables, significant reductions in drainage volumes and salt loads compared to unmanaged systems can be expected. Although the associated more rapid increase in root zone salinity is a drawback of this strategy, controlled drainage and mitigation of the effect is possible. Periods of controlled leaching and drainage can be implemented, for example, by allowing for free drainage following high rainfall, or providing for free drainage during the first or last irrigation of the season. With this strategy the soil salinity can be monitored and managed.

2.2.4 Salinity/sodicity reclamation strategies

Although salt-affected soils in South Africa often occur under natural conditions (de Villiers et al., 2003), the salt problems of most importance to agriculture arise when previously highly productive soils become unproductive, as a result of salinization and/or sodification, due to irrigation activities. Mitigation of saline and/or sodic soils is possible through soil and water amendments and bioremediation, provided that proper management practices are in place.

2.2.4.1 Water and soil amendments

Gypsum, sulphur or sulphuric acid are the most common soil amendments used to reclaim sodic soils, while gypsum, sulphuric acid and sulphur dioxide are used as water amendments (Paranychianakis & Chartzoulakis, 2005). Due to its solubility, low cost and availability, gypsum is the most commonly used amendment in South Africa.

When the salt concentration of irrigation water is sufficient to prevent dispersion of clays, the amount of gypsum required depends on the soil ESP, CEC and level to which the ESP should be reduced. In soils where the salinity effect is less significant and the main effect results from correction of the SAR, the amount of gypsum required depends on the amount of exchangeable sodium in the depth of soil. The amount of exchangeable sodium to be replaced will depend on the initial exchangeable sodium fraction, the soil cation exchange capacity, soil bulk density, the desired final exchangeable sodium fraction and the depth of soil to be reclaimed.

The efficiency of applied Ca^{++} to remove adsorbed Na^{+} is much greater in the presence of high exchangeable sodium percentages. At low exchangeable sodium percentages the efficiency of Na^{+} exchange is low because a greater fraction of applied Ca^{++} displaces exchangeable Mg^{++}. When Mg^{++} is dominant over Ca^{++} on the exchange complex the destabilizing effect of sodium will be enhanced decreasing of its stability (Hodskinson & Thornburn, 1995).

Besides having a residual exchange effect, gypsum also acts as an electrolyte once dissolved by rain or irrigation water. Gypsum contents and the soil water flux will influence gypsum dissolution rates. By lowering the water application rate, for example with sprinkle irrigation, more gypsum dissolves in a given volume of infiltrating water, which enhances the efficiency of exchange (Keren & Miyamoto, 1996).

The application of acids or acid-forming materials to soils with lime dissolves soil calcium carbonate to form gypsum or calcium chloride. Sulphur requires an initial phase of microbiological oxidation to produce sulphuric acid. Yahia et al. (1975), Prather et al. (1978) and Overstreet et al. (1951) (as cited by Keren & Miyamoto, 1996) reported results that favour sulphuric acid as an amendment over gypsum. Equivalent amounts of gypsum and sulphuric acid reduced soluble and exchangeable Na^{+} in the surface soil, to the same extent. Gypsum however produced smaller crop yield responses when compared with sulphuric acid. Swinford et al. (1985) found no large yield response differences between ameliorant treatments where gypsum (26 ton ha^{-1}), sulphur (6 ton ha^{-1}), filter-cake (350 ton ha^{-1}) and sulphuric acid (17 ton ha^{-1}) were applied.

Although effective drainage alone can play a major role in reclaiming sodic soils, the addition of ameliorants will accelerate the reclamation process (Swinford et al., 1985). The economics of soil reclamation can be debated on account of the amount of ameliorant required to ensure acceptable yield (Sharma et al., 2001). For example, gypsum application to soils normally ranges between 2 to 20 ton ha^{-1}, but amounts as high as 40 ton ha^{-1} are needed in areas with extremely high sodium levels (Paranychianakis & Chartzoulakis, 2005). Ham et al. (1997) observed however, similar increases in sugarcane yield on sodic soils (ESP < 25) by applying 2 ton ha^{-1} gypsum annually dissolved in the irrigation water instead of incorporating 10 ton ha^{-1} gypsum immediately into the soil.

2.2.4.2 Bioremediation

Many saline-sodic and sodic soils contain a source of Ca^{2+}, in the form of calcite ($CaCO_3$) at varying depths. These calcareous soils can be reclaimed without the application of amendments through the cultivation of certain salt-tolerant crops, a technique known as bioremediation, phytoremediation or biological reclamation (Qadir & Oster, 2002).

The cultivation of plants in calcareous saline sodic and sodic soils enhances CO_2 production by root and microbial respiration which increase the CO_2 partial pressure (PCO_2) in the root zone. The high CO_2 concentration in the root zone increases the solubility of calcite, and improvement of the soil physical properties due to root growth. The decrease in exchangeable Na^+ is a consequence of the increased Ca^{2+} concentrations in the soil solution, resulting in the replaced Na^+ to be leached from the soil with drainage water, which subsequently causes a reduction in soil sodicity. The roots of bioremediation plants also improve soil physical properties through the removal of entrapped air from larger conducting pores, generation of alternate wetting and drying cycles and the creation of macro-pores and improvement of soil structure (Qadir & Oster, 2004).

In a summary of 14 experiments, Qadir & Oster (2004) illustrate the effects of bioremediation and chemical treatment on decreasing soil sodicity in the root zone. The chemical treatments consisted of the application of gypsum in all experiments which caused a 62% decrease in original sodicity levels whereas a 52% decrease was measured for bioremediation treatments. Bioremediation worked well on coarse to medium textured soils, provided that excess irrigation was applied for leaching, and it was done when crop growth, and hence partial pressure CO_2, were at a peak. On highly sodic soils, the chemical treatments gave better results. Bioremediation will be successful when: i) the bioremediation crop is the first crop in the rotation; (ii) the bioremediation crop can be grown during a time that is not suitable for growing more profitable crops; (iii) the duration of the growing period should be sufficient to exploit the beneficial impact of the bioremediation crop and; (iv) more irrigation can be applied than the crop water requirements, to promote the downward movement of Na^+ from the root zone.

The depth of soil reclamation is an important parameter for judging the efficiency of the two reclamation approaches. In most comparative studies, reclamation with the gypsum treatments occurred in the zone where the amendment was incorporated. In the bioremediation treatments, amelioration occurred throughout the root zone. Different crops result in different depths of soil amelioration, which is influenced by the soil morphology, volume of roots and the depth of root penetration (Batra et al., 1997; Ilyas et al., 1997, as cited by Qadir & Oster, 2004). Generally plant species with higher production of biomass, combined with the ability to withstand ambient soil salinity and sodicity and periodic inundation, have been found to be more efficient for soil reclamation. Some of the most successful crops used as the first crop to accelerate soil bioremediation, together with some shrub species which have produced adequate biomass on salt-affected soils and/or through irrigation with saline-sodic water are listed in Table 2.3. As shown in the table, a number of plantation trees have also been used to reclaim sodic soils or for re-using drainage water as irrigation source.

Qureshi & Barrett-Lennard (1998), according to Qadir & Oster (2004), provided useful information regarding sources of seeds, nursery-raising techniques, land preparation and planting procedures for 18 different tree and shrub species having the potential for growth on salt-affected soils. Any change in cropping patterns or farm operations however, in order to include bioremediation or crop production with saline, saline-sodic and sodic water, is driven by the input costs involved, and the subsequent economic benefits.

Table 2.3 Some crops, shrubs and tree species for potential use in bioremediation of calcareous saline sodic and sodic soils compiled by Qadir & Oster (2004) from different sources

Crops	Kalar grass Sesbania Alfalfa Bermuda grass Sordan	Kumar & Abro, 1984; Malik et al., 1986 Ahmad et al., 1990; Qadir et al., 2002 Ilyas et al., 1990 Kelley, 1937; Oster et al., 1993 Robbins,1986
Shrubs	*Kochia scoparia L* *Salicornia bigelovii Torr.* *Echinochloa crusgalli* (L.) P. Beauv *Portulaca oleracea* L..	Garduno, 1993 Glenn et al., 1999 Aslam et al., 1987 Grieve & Suarez, 1997
Trees	*Terminalia arjuna* (Roxb. Ex DC.) Wight & Arn. *Prosopis juliflora* (Sw.) DC. *Dalbergia sissoo* Roxb. Ex DC., *Acacia nilotica* (L.) Willd. Ex Delile *Parkinsonia aculeate* (L.) and *Prosopis cineraria* (L.) Druce *Sesbania sesban* (L.) Merr. and *Tamarix dioca* Roxb. Ex Roth *Leucaena leucocephala* (Lam.) de Wit	Jain & Singh,1998 Bhojvaid et al., 1996 Kaur et al., 2002 Qureshi & Barret-Lennard, 1998 Singh, 1989 Qureshi et al., 1993

The limitations of bioremediation are (i) slower in action than chemical amendments, (ii) limited salt tolerance of a number of crop species to saline-sodic or sodic soils, when the use of chemical amendments under these conditions becomes inevitable, and (iii) the presence of inadequate amounts of calcite in the soil. The advantages are (i) low initial capital input, (ii) promotion of soil aggregate stability and creation of macro-pores that improve soil hydraulic characteristics, (iii) better plant nutrient availability in the soil during and after bioremediation, (iv) more uniform and deeper reclamation and (v) financial or other benefits from crops grown during reclamation (Qadir & Oster, 2002).

2.3 Strategies for managing water quality at irrigation scheme level for sustainable irrigation and environmental protection

As discussed earlier a prerequisite for sustainable irrigated agriculture on field or farm level is adequate leaching and drainage which prevents salts from accumulating in the root zone. These on-farm irrigation and drainage practices are however the major source contributing towards the salinization of surface and groundwater. Management of the salinization of surface and under-ground water, necessitate the implementation of comprehensive land and water use policies that incorporate the natural processes involved in the soil-plant-water, and associated geo-hydrologic systems (Rhoades, 1997).

The water-distribution network of all irrigation schemes in South Africa basically consists of a river and/or a dam, and a series of irrigation and drainage water conveyance canals. The river not only conveys water to various farms and/or irrigation canals, but also collects all the drainage water originating from irrigated areas. Strategies to consider for decreasing the salinity and/or sodicity in the rivers and groundwater resources affected by irrigation and drainage include: minimizing deep percolation; the interception and isolation of drainage water; re-use of drainage water for irrigation and avoidance of blending water for irrigation or disposal.

2.3.1 Minimizing deep percolation and interception of drainage

The natural seepage of groundwater from saline geological strata as river and irrigation return-flow, is regarded as a potential source of off-site river and soil salinization/sodification. Secondary river salinization in South Africa compares well to world trends (Ghassemi et al., 1995) and various studies have been conducted on the extent and causes of river salinization/sodification, in some of the largest irrigation areas in South Africa, which include the Mkuze, Usutu, Komati, Lomati, Breede, Berg, Sundays, Great Fish, Lower Orange, Harts, Vaal and Riet Rivers (Fourie, 1976; Stander, 1987; Kirchner et al., 1997; Moolman & Quibel, 1995; Du Preez et al., 2000; Hall & Du Plessis, 1984**;** Volschenk et al., 2005). In most of these studies irrigation return-flow was identified as being a major contributing factor in salinization/sodification of these rivers. In some cases however, upstream industrial activities did contribute to the deterioration of the river water quality.

Irrigation return flow can contribute towards river salinization/sodification by means of salt in the irrigation water that is concentrated by root water uptake and then leached from the root zone through drainage effluent; the mobilization of residual salts stored in alluvial and arid soils, the mobilization of salts that became available for dissolution during land preparation and by the displacement of saline groundwater. Drainage return-flow results from over irrigation or seepage from storage dams, leaking water conveyance systems or seepage from river bank irrigation.

As discussed in Section 2.2.3, the total salt load discharged from the root zone through percolating water should and can be reduced. Minimizing leaching reduces the amount of salts added to the soil and discharged from the root zone because it maximises the precipitation of salts in the soil. When the volume of water percolating to below the root zone is reduced, it minimises the uptake of weathered and dissolved salts from the soil and substrata (Rhoades, 1997). Salt contributions from soils and the substrata play a major role in determining the quality of the groundwater. When groundwater is discharged into a river through river bank seepage, it can either increase the salinity/sodicity of the river or have a freshening effect. A huge amount of soluble salt can be generated this way, especially where virgin soils are irrigated for the first time. Volschenk et al. (2005) estimated that the application of a 1000 mm per annum of relative good quality (30 mS m^{-1}) water on newly irrigated soils, will result in the accumulation of 2 ton of salt per hectare. Drainage from these soils could release on average an additional 3 to 10 tons of salts per hectare if the soil is drained within the first decade of vineyard development. Smedema & Shiati (2002) illustrated some typical or generic situations of irrigation-induced seepage patterns in Figure 2.2.

The flow patterns in Figure 2.2 illustrate different situations where high lying areas, with salts underneath, are irrigated and new salt distribution flow patterns towards the lower lying area are induced. This will contaminate firstly the adjacent lower lying soil (most probably high potential soils) and in the long run will induce seepage into the river system. Flow pattern (a) (Figure 2.2) demonstrates a situation of leakage from conveyance and storage systems that are erected on high lying areas to facilitate gravitational irrigation.

The flow pattern clearly shows that the water will mobilize any soluble salts underlying the leaking canal and transport these towards the lower lying irrigation land or into the river, causing serious deterioration of the land and water resources. Water managers should also be sensitive to the build-up of water tables as illustrated in Figure 2.2c, (before irrigation development) and Figure 2.2d, (after prolonged irrigation). In this case water and salts are transported from the under-lying stratum into the soil profile through capillary rise and are concentrated just above the water table as was also illustrated by Ehlers et al. (2007) in a lysimeter study.

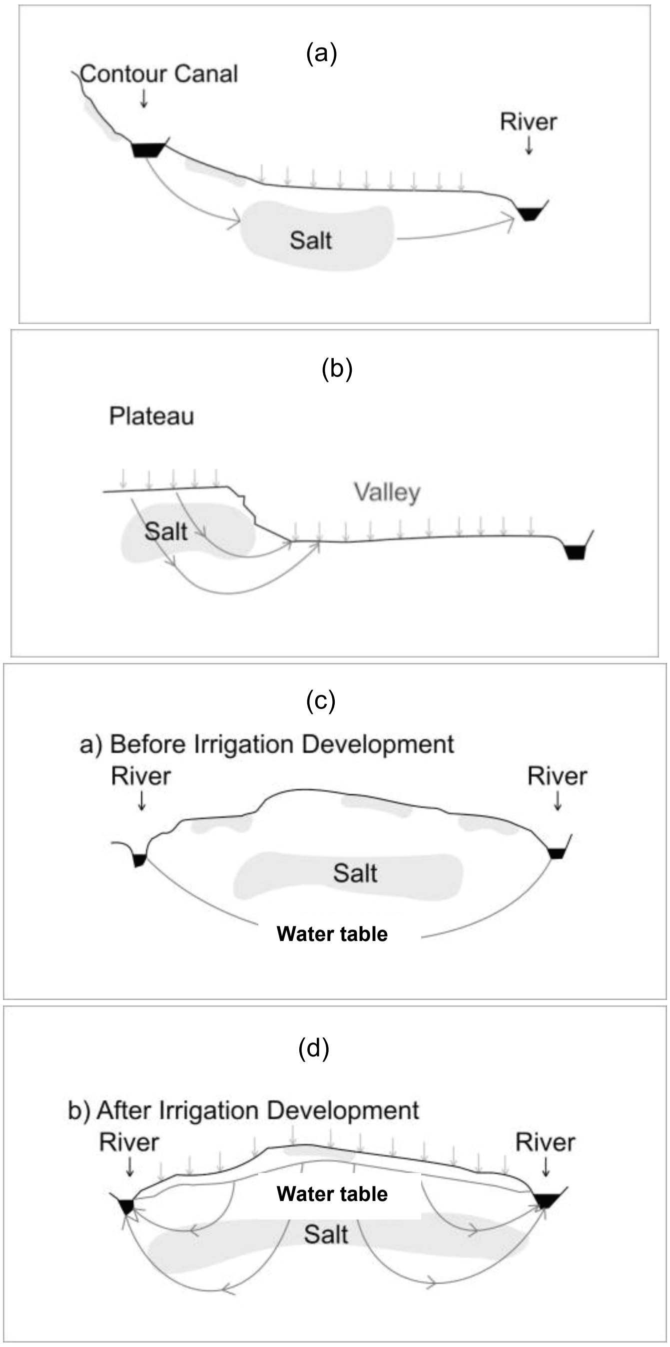


Figure 2.2 Illustrations of water and salt flow patterns in semi-arid areas based on the presentation of Smedema & Shiati (2002).

Minimized leaching reduces the volume of discharged drainage water and salt, but it increases the salt concentration of the drainage water. As explained previously, some leaching is essential for sustainable irrigation. The interception of saline drainage water before it is returned to surface or groundwater sources can be of substantial benefit.

For the reasons mentioned earlier, and as emphasised by Rhoades (1997), minimising leaching, which reduces deep percolation should be implemented to reduce off-site salinity pollution especially where the irrigated area is underlain by salt-laden sediments. In addition saline drainage water should be intercepted and conveyed separately. Intercepted drainage water can then be desalted, re-used, disposed of by pond evaporation or by injection into some isolated deep underground aquifer, or can be used as a water supply where the use of saline water is appropriate, as explained in Section 2.2.2.3. Desalinization of agricultural water is however, normally not economically feasible.

2.3.2 Interception, isolation and re-use of drainage water for irrigation

The goals of good irrigation management should be to minimize the amount of good quality water extracted from a source, to maximize the amount consumed as transpiration for biomass production and to ensure a minimum discharge of poorer quality drainage water. In the process of achieving these goals a gradual accumulation of salts occurs in the root zone of the cultivated crops. When the salt content of the root zone exceeds the threshold value of the least salt tolerant crops, removal of the excess salts through controlled leaching and drainage becomes essential. This drainage water needs to be disposed of in a responsible manner. The drainage water from a field or project still has value in terms of transpirational use by certain crops. It can be used to irrigate crops with a salt tolerance higher than the salinity of the drainage water.

A fundamentally sound strategy is to intercept drainage water from a designated area and to re-use it rather than it being returned to a river or better quality water source. This can be done by irrigating suitable salt tolerant crops or by using it to substitute or supplement lower salinity water during the growing phases of crops when the salt sensitivity is less critical or of a lower degree. Provision for implementation of this strategy should be made in the initial planning of the water conveyance infrastructure of the irrigation project, or in the replanning of existing projects. This strategy is recommended for situations where high quality water is available early in the growing season but is either too expensive, or the supply is limited by for example drought restrictions to meet the total seasonal crop water requirements. Blending of low quality drainage water with better quality water should preferably be avoided, for reasons that will be discussed in Section 2.3.3. One of the best known examples where this strategy has been implemented is in the San Joaquin Valley of California, USA (Letey, 1994). When shallow water tables are present, this strategy can be combined with deficit irrigation to promote the contribution of water table uptake towards the crop water requirement, as has been discussed in Section 2.2.3.2.

According to Grattan & Rhoades (1996), the long-term feasibility of this strategy would likely be increased when implemented in a project, whether regional, or as in the case of South Africa, on a WUA scale. This permits the reuse of drainage water in designated suitable areas to avoid or control excessive build-up of salts that can affect other water users. For example up-slope soils, where later release of salts can damage down-slope soils, should be avoided. The second generation drainage water from a primary re-use area can be further diverted to another dedicated re-use area where more salt tolerant crops or trees are grown or to regionally approved evaporation ponds or treatment plants. Apart from supplementing the supply of irrigation water, the ultimate objective of drainage water re-use is to avoid blending and to protect downstream water quality.

2.3.3 Blending water for irrigation or disposal

Before the practical implications of blending water of differing qualities can be discussed, it is important to understand the concept of plant usable water. Plant growth, and therefore the amount of biomass produced, is directly proportional to the amount of water consumption through transpiration. Water in the soil pores contains dissolved salts. Adhesion of water molecules to salt ions (osmotic effect) and soil colloids decrease the free energy of the pure water. Only soil water with a higher free energy than the water in the root xylem can be taken up by plants and can be defined as “usable water”. An increase in the salt concentration (salinization) and decrease in the volume of soil water (soil drying) decrease the free energy and the amount of usable pure water. In the process of transpiration, the pure water taken up by the plant roots from the salty soil solution is transpired into the atmosphere, and the salts are concentrated in the remaining unused soil water. The continuous removal of pure water through transpiration, and the associated accumulation of salts in the root zone, gives rise to a gradual decline in the volume of plant usable water in the root zone, even when the soil is wet.

When the salinity of the soil water exceeds the critical threshold value for the cultivated crop, transpiration and growth will decline. The situation can be alleviated by removing the excess salts from the root zone through leaching. The salinity of the drainage water will therefore be higher than that of the irrigation water and the percentage of plant usable water will be much less. After this explanation it should be obvious that not all of the water applied as irrigation can be consumed by plants, because of the presence of salts in the water.

The practice of blending or diluting excessively saline water with good quality water supplies should only be undertaken after careful consideration of how it will affect the volumes of plant usable water in the combined and separate supplies. Rhoades (1997) listed several case studies in which the feasibility of blending of water was investigated. Most cases refer to river systems in which water is diverted upstream for irrigation and drainage water is returned downstream. As was reported by Du Preez et al. (2000) the long term mean EC of the diverted Vaal River irrigation water increased from 52 mS m^{-1} to a downstream value of 72 mS m^{-1} after addition of drainage water from the Vaalharts Irrigation Scheme via the Harts River.

The results from most of the case studies reported by Rhoades (1997) showed that blending of too saline water with good quality water results in a smaller volume of potentially consumable water in the combined supply compared to that of the good quality water fraction itself. The amount by which usable water is reduced will depend on the relative volumes and qualities of the drainage and receiving water before blending, and the salt tolerance of the crops to be produced. It is essential that the merits of blending should be evaluated on a case-by-case basis.

A principle that should always be kept in mind is that when the salinity level of drainage water exceeds the critical threshold value of the crop in mind, no additional consumptive use benefit can be gained from blending it with lower salinity water. It can thus be concluded that a strategy based on blending or diluting drainage water with good quality water, to increase water supplies or meet discharge pollution standards, may be inappropriate in most situations.

2.4 Salinity management strategies and irrigation planning

Many of the past irrigation developments took place without making provision in the infrastructure for managing the inevitable salt accumulation and likely waterlogging that will take place over time. Although the knowledge which is the basis of suitable salinity management strategies is available, the implementation thereof may be partial or non replicable, due to restrictions in the infrastructure. It is essential that an effective salinity management strategic plan should be incorporated in the planning of an irrigation project. In the design of a salinity management plan, many salt source and control factors should be considered, *inter alia* the following:

i) suitability of the soils for the irrigation and installation of artificial drainage if required;
ii) residual salt content of the soils;
iii) irrigation water quality;
iv) topography and its effect on subsurface salt movement;
v) type and amounts of irrigation;
vi) climatic conditions
vii) reliability of the irrigation water supply and
viii) level of irrigator's management skills.

Factors affecting the options for the management of the drainage water that need to be considered in a management plan are the following:

i) the need for interception of drainage water separate from irrigation tail-end water for re-use as irrigation or controlled disposal;
ii) environmental impact of the additional influx of water and mobilization of salts;
iii) re-use of drainage water for the cultivation of more salt tolerant crops in designated areas;
iv) re-use of drainage water in the same area to supplement irrigation during specific periods;
v) environmental impact and acceptability of different drainage-water blending or dilution options and
vi) the most acceptable manner for disposal of the salt load in drainage water.

Once a decision has been taken on the most appropriate way to manage the generated salt load, provision should be made for adapting the water conveyance network to allow for the implementation of the strategies within an acceptable time frame.

2.5 Conclusions

The following best management strategies for managing salinity on an individual field and/or farm were formulated:

- Use of efficient irrigation systems and scheduling practices aimed at minimizing water application and reducing losses.
- Utilization of shallow water tables to supplement the crop water requirement and reduce the irrigation requirement.
- Monitoring of root zone salinity, in order to decide when to apply controlled leaching for removal of excess salts in the root zone.
- Interception, isolation and re-use of unavoidable leaching water for the irrigation of a succession of crops with increasing salt tolerance.
- Selection of crops with salt tolerance adapted to the situation.

Various means can be used on a regional scale to dispose of the ultimate unusable final drainage effluent originating from irrigated fields and/or farms. Regional or Water User Association (WUA) scale best management strategies therefore include:

- Interception, isolation and re-use of drainage water for irrigation and/or disposal.
- Blending of drainage water with better quality water for irrigation or disposal.

Infrastructure should be provided and managed on a project scale for the collection, re-use, treatment and/or disposal of drainage water. This should be done in a responsible manner, causing the least environmental degradation. Water conveyance and storage structures should be maintained to avoid or minimize leakage losses.

The soil water balance as well as the subsequent salt balance is widely used in assessing management practices, because of its clear conceptual basis. Thayalakumaran et al. (2007) argued that a favourable salt balance in the potential root zone is critical for preventing salt accumulation to ensure sustainable production. In soils with shallow water tables, in or just below the potential root zone, managing a favourable salt balance is often not practical or necessarily beneficial. This is because salinity can occur over time spans sufficiently long enough for temporal variations in climate, vegetation cover and management practices to cause significant variations. Managing the water balance in order to prevent waterlogging, and the remobilization of salt stored in the underlying strata, is considered to be the most important where water tables occur within or just below the potential root zone (Thayalakumaran et al., 2007).

With the practical implementation of these formulated best management practices, farmers and WUAs can ensure that farms and irrigation schemes operate at a sustainable biophysical level.

CHAPTER 3
MATERIALS AND METHODS

3.1 Description of irrigation schemes

3.1.1 Location and layout

The research was conducted in the central part of South Africa on farms located within the Orange-Riet and Vaalharts Irrigation Schemes (Figure 3.1). Orange-Riet Irrigation Scheme (Orange-Riet) is located between the Orange River and the Riet River in the Free State, with a small area positioned in the Northern Cape (Figure 3.2). The scheme falls under the Upper Orange Water Management Area (WMA) within the component sub-areas Riet/Modder and Vanderkloof.

North of Orange-Riet and situated between the Harts River and the Vaal River in the Northern Cape lies the Vaalharts Irrigation Scheme (Vaalharts) (Figure 3.2). Vaalharts falls under the Lower Vaal WMA within the component sub-area Harts.

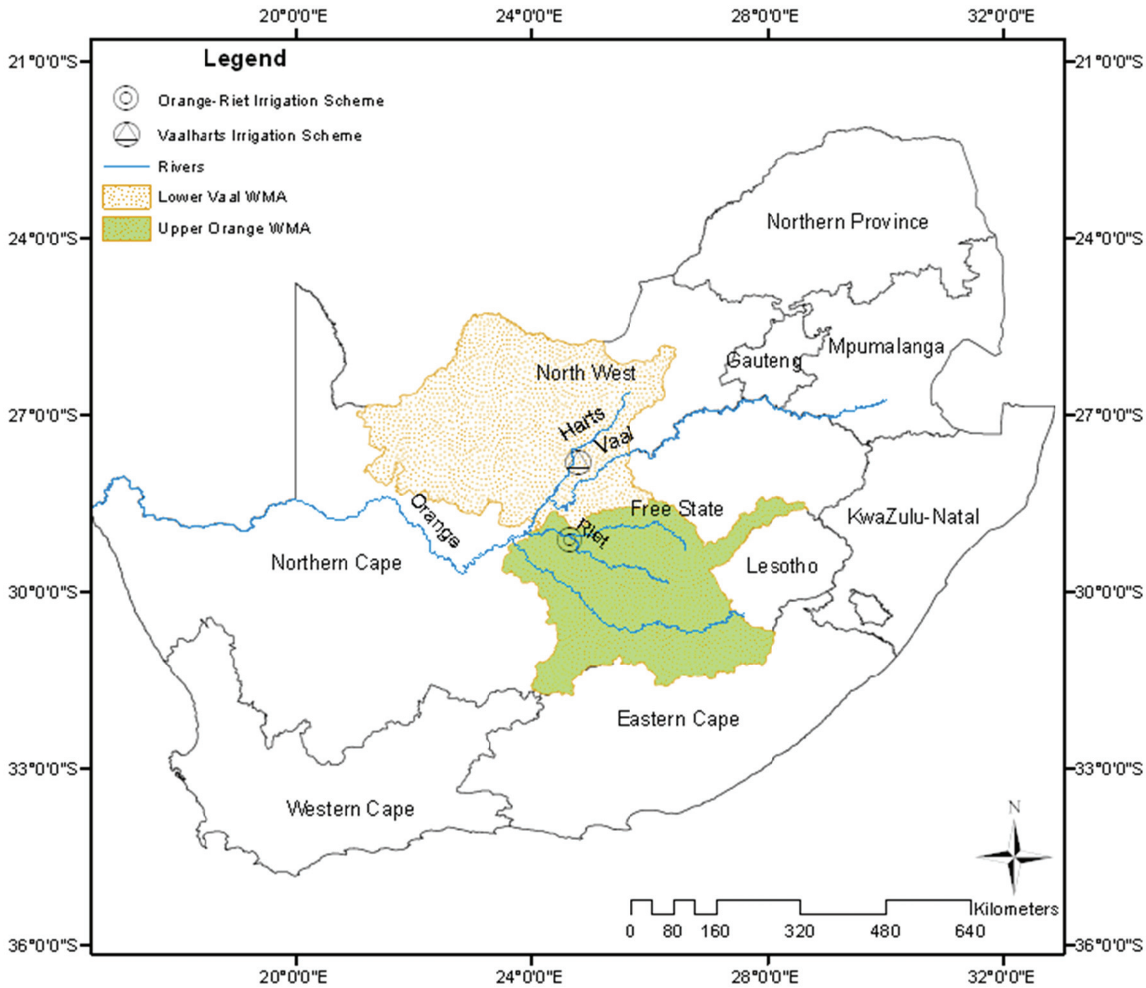


Figure 3.1 Location of Orange-Riet and Vaalharts Irrigation Schemes within the Upper Orange and Lower Vaal Water Management Areas (WMA), South Africa.

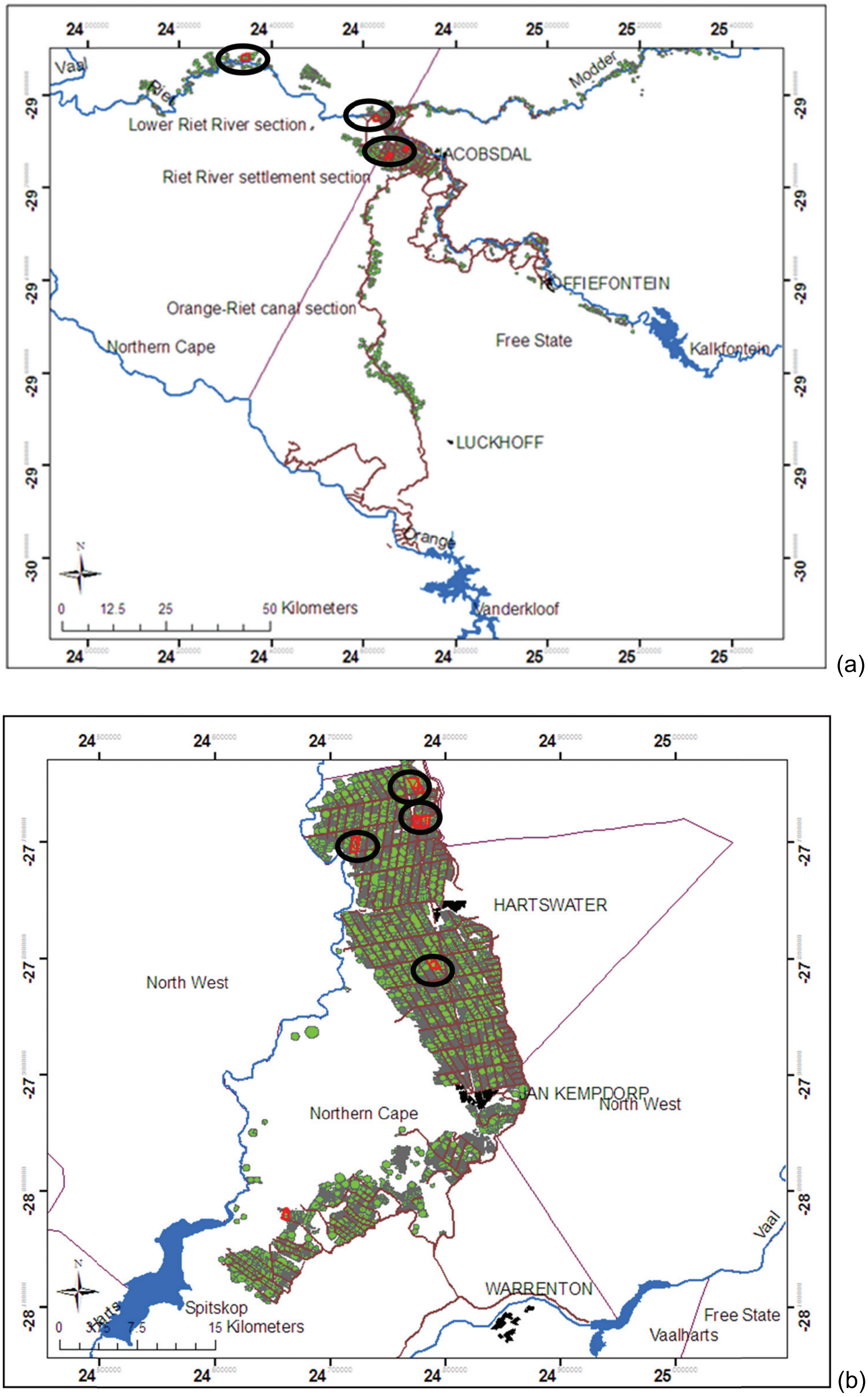


Figure 3.2 Layout of Orange-Riet (a) and Vaalharts (b) Irrigation Schemes, including the geographical position of all the measuring points.

Orange-Riet receives its water from the Vanderkloof Dam, from where it is conveyed and distributed to the different sections of the scheme via canal systems that stretch over 297 km (Figure 3.2). Along the Orange-Riet canal section of the scheme, 3970 ha are irrigated, while in the Riet River Settlement and Scholtzburg section 8045 and 637 ha are irrigated, respectively (Figure 3.2). Tail-end and drainage water from the Settlement section of the scheme is transferred into the Riet River, which is conveyed downstream to the Ritchie (97 ha) and Lower Riet (3938 ha) sections of the scheme (Ninham Shand, 2004).

Vaalharts Weir on the Vaal River, just upstream of Warrenton, diverts water into the Vaalharts main canal which supplies the North, West, Klipdam-Barkley and Taung canals (Figure 3.2). The canal system comprises 1176 km of concrete-line canals supplying irrigation water to four sections, *viz*. Vaalharts, Barkly West, Spitskop and Taung with 29 181, 2555, 1663 and 6424 ha, respectively. In addition, 314 km of concrete-line drainage canals were built to convey both storm-water and subsurface drainage water out of the irrigation scheme via the Harts River.

3.1.2 Climate

Data was obtained from the Agricultural Research Councils Institute for Soil, Climate and Water (ARC-ISCW) in Pretoria, using the weather stations Riet Rivier (29°05S 24°42E), Jacobsdal (29°00S 24°57E), Drieplotte (29°03S 24°38E), Vaalharts (27°57S, 24°50E), Magogong (27°40S, 24°44E), Jan Kempdorp (27°57S, 24°50E), Jan Kempdorp (27°54S, 24°51E), Magogong (27°42S, 24°55E) and Pampierstad (27°45S, 24°43E). This data indicates that Orange-Riet and Vaalharts are located in a semi-arid zone; rainfall is 397 and 427 mm per year for Orange-Riet and Vaalharts, respectively, and the atmospheric evaporative demand 1740 and 1647 mm, respectively, with aridity indexes of 0.23 and 0.26, respectively (Table 3.1).

Table 3.1 Long-term mean maximum (Max T) and minimum (Min T) temperature, reference evaporative demand (ETo) and rainfall per month at Orange-Riet (or) and Vaalharts (v) Irrigation Schemes (raw data courtesy of ARC-ISCW, Pretoria)

Month	Mean Max T (˚C)		Mean Min T (˚C)		Mean ET$_o$ (mm)		Mean Rainfall (mm)	
	or	v	or	v	or	v	or	v
Jan	32	32	16	17	223	200	60	71
Feb	31	31	16	16	178	150	64	83
Mar	29	30	14	14	165	139	64	63
Apr	25	27	9	10	122	117	43	37
May	22	22	3	5	97	86	15	21
Jun	18	19	0	1	74	69	8	5
Jul	18	20	-1	1	80	74	8	3
Aug	21	22	1	3	98	98	9	4
Sep	25	26	6	7	140	136	11	9
Oct	27	28	10	11	163	172	33	34
Nov	29	31	13	14	184	195	40	49
Dec	30	32	15	16	217	211	42	48
Mean	**26**	**27**	**8**	**10**	-	-	-	-
Total	-	-	-	-	**1740**	**1647**	**397**	**427**

Rainfall mainly occurs in the form of thunder showers during the summer months at both schemes. From November to April the long-term rainfall at Orange-Riet and Vaalharts is normally more than 40 mm per month with a mean of 52 and 59 mm, respectively, for these months. The long-term maximum temperatures between November and March at Orange-Riet are above 30°C with minimum temperatures of between 13 and 16°C. For Vaalharts the minimum temperatures varies between 14 and 17°C with a mean long-term maximum of 31°C for these months. During the winter months the maximum temperatures are around 18°C at Orange-Riet and 20°C at Vaalharts. The long-term mean minimum temperatures during June and July at Orange-Riet and Vaalharts are just below and above 0°C, respectively.

3.1.3 Geology

The geology of Orange-Riet was derived from the 1:250 000 geological maps 2924, 2922, 2824 and 2822 obtained from the Council for Geoscience, Pretoria (Appendix 3.1). The geology of the Vaalharts area was derived from 1:250 000 geological map 2724 Christiana, also obtained from the Council for Geoscience, Pretoria (Appendix 3.2). This information was supported by the studies of Gombar & Erasmus (1976), Rosenstrauch (1935), Ellingon et al. (2004).

Orange-Riet Irrigation Scheme: The physiography of the area can be described as a flat monotonous landscape comprising large plains studded with flat-topped hills, capped by Jurassic dolerite intrusions. The low lying areas are underlain by easily weathered shale, siltstone and sandstone of the Ecca Group (Zawada, 1992). The rocks within the study area vary in age as well as mineral composition. Archaean granite of the Swazian era (early Archaean) represents the basement and is classified as the oldest rocks in the study area.

These granitic outcrops are located 6 km to the south-east of Ritchie along the southern bank of the Riet River as well as 4 km to the west of the same town on the northern bank of the Riet River. The granite can be described as leucocratic and medium crystalline, consisting of visible biotite flakes (Zawada, 1992). Outcrops of the Makwassie Formation of the Ventersdorp Super Group occur approximately 4 km to the southwest of Ritchie, on the northern and southern banks of the Riet River. Andesitic outcrops are found to the west and north of the town of Ritchie, along the Riet River. Outcrops of the Dwyka Group of the Karoo Supergroup are situated between 15 and 25 km from Douglas on the northern and southern banks of the Riet River.

Mudstone, siltstone and shale outcrops of the Prince Albert – and Tierberg Formations of the Ecca Group, Karoo Supergroup are located in the Jacobsdal area as well as on the northern and southern banks of the Riet River, approximately halfway between the towns of Ritchie and Douglas. Further outcrops of the Ecca Group are found along the Orange-Riet Canal as well as between Koffiefontein and Jacobsdal (Zawada, 1992). A thin sliver of Adelaide Subgroup of the Beaufort Group (Karoo Supergroup) is located within the Joostenberg to the north of the town of Vanderkloof, to the east of the Orange-Riet Canal. Quaternary calcrete and windblown sand is found along the Riet River between Jacobsdal and Ritchie and next to the same river between Koffiefontein and Jacobsdal as well as Ritchie and Douglas. Similar deposits are also located along the Orange-Riet Canal. Circulating groundwater, rich in calcium carbonate ($CaCO_3$), was introduced into the upper beds of Ecca Group shales. Evaporation of water close to the surface led to the precipitation of the calcrete. The windblown sand is red in colour and is composed primarily of quartz and subsidiary feldspar minerals. Dolerite dykes and sills intruded into the sediments of the Karoo Super Group during one of the phases of Gondwana break-up in the Jurassic period. The dykes are generally 1 to 10 m in width and several km long (Zawada, 1992). These dykes and sills are abundant in the eastern part of the study area between the towns of Ritchie and Koffiefontein as well as Ritchie and Vanderkloof. The sills and dykes appear to be absent in the area surrounding the town of Douglas or at least no outcrops are visible as a result of abundant Quaternary cover.

Vaalharts Irrigation Scheme: The area is essentially bordered by two plateaus on the east and west sides of the Harts River Valley (Gombar & Erasmus, 1976; Liebenberg, 1977). This valley slopes towards the south. Due to the low gradient of the Harts River and no incising by the river itself, very little topographical changes can be observed within the valley (Gombar & Erasmus, 1976; Liebenberg, 1977). The general surface flow pattern tends to be towards the Harts River.

The rocks within the study area vary in age as well as mineral composition. Rocks older than the Archaean Ventersdorp Supergroup are referred to as basement. Basement rocks of the study area comprise the Archaean Kraaipan Group sediments and volcanic rock, which are also the oldest rocks within the study area. Localised outcrops of the Kraaipan Group are situated 8 km east of Jan Kempdorp (Schutte, 1994; Liebenberg, 1977). Within the study area the latter consists of banded iron formation (BIF), feldspatic gritstones, sandstones and breccia. These outcrops are, however, dominated by BIF (Schutte, 1994).

Outcrops of the Archaean Ventersdorp Supergroup are located on the eastern boundary of the Harts River Valley. The Ventersdorp outcrops consist of basaltic and andesitic lavas as well as pyroclastic material in the form of breccias and tuffs (Schutte, 1994). The Kameeldoorns Formation forms the base of the Ventersdorp Supergroup in the study area (Klipriviersberg Group is absent) with localized outcrops between Hartswater and Jan Kempdorp. The latter Formation comprises granitic conglomerates as well as sandy and tuffaceous sediments and limestones (Liebenberg, 1977). The Makwassie Formation overlies the Kameeldoorns Formation and consists predominantly of andesitic lavas (Liebenberg, 1977). Localised outcrops of the Makwassie Formation are found to the east of the town of Taung (Schutte, 1994).

The overlying Rietgat – and Allanridge Formations, of the Ventersdorp Supergroup, cover most of the study area (Liebenberg, 1977). Sandstone, tuff, limestones and andesitic lavas comprise the Rietgat Formation whilst basalt and andesite are found within the Allanridge Formation. The latter formation covers and essentially underlies most of the eastern flank of the Harts River Valley. The Schmidtsdrif – and Cambellrand Subgroups of the Proterosoic to Archaean Transvaal Supergroup (previously Griqualand West Supergroup) border the western flank of the Harts River Valley. The Schmidtsdrif Subgroup consists predominantly of dolomite and limestone as well as subsidiary quartzite and shale, and crops out towards the northwest of Taung (Liebenberg, 1977). The Cambellrand Subgroup comprises similar lithological units to the Schmidtsdrif Subgroup and consists of dolomite, limestone, chert as well as subsidiary shales and quartzite (Schutte, 1994).

The floor of the Harts River Valley consists of sediments of the Permo-Triassic Karoo Supergroup as well as intruded Jurassic dolerite dykes and sills (Liebenberg, 1977). The Dwyka Group of the Karoo Supergroup rests unconformably upon the Transvaal Supergroup and this unconformity represents a period of extensive erosion extending for more than 1700 Ma (Liebenberg, 1977). Although outcrops are localized, good exposures of the Dwyka Group sequence can be found between the towns of Hartswater and Jan Kempdorp. The base of the Dwyka Group comprises shale with lenses of tillite, sandstone and black shales (Schutte, 1994). No further outcrops of the Karoo Supergroup are found within the area.

Tertiary calcrete overlies most of the Transvaal – and Ventersdorp Supergroup, whilst Quaternary windblown sand covers the central part of the valley. Localised outcrops of Jurassic dolerite intrusives are found on the western part of the Harts River Valley.

3.1.4 Soils

Orange-Riet Irrigation Scheme: The soil survey of the area below the Kalkfontein Dam downstream to Jacobsdal was conducted by Rosenstrauch (1935). At that time pedology in South Africa was in its infancy and there was no classification system. Soil was classified in terms of its origin or parent material, *viz*. alluvial, colluvial, aeolian (further divided into a deep sandy class > 2.4 m, and a shallow sandy class < 2.4 m), and residual soils formed from shale. There were two main classes of alluvial soils, *viz*. light and heavy alluvial soils. Klintworth (1953) subsequently distinguished a third class, an intermediate alluvial soil. Dohse (1981) converted these soil classes into soil types based on the binomial soil classification system for South Africa (MacVicar et al*.,* 1977), and produced a 1:50 000 soil map. The lower Riet area was surveyed by Botha & Schoeman (1986), Schoeman & Geers (1988) and Geers (1989).

Vaalharts Irrigation Scheme: The detail soil survey on irrigation suitability of Vaalharts conducted during 1932-34 (Rosenstrauch, 1935) was used to compile a soil map. They classified the soil in terms of its origin or parent material, *viz*. windblown (aeolion), water transported and alluvial types. The aeolian soil type is further divided into red sand, red sand overlaying lime and red sand on rock. The water transported soils are divided into colluvial, colluvial overlaying lime, Rutland's colluvial soil type and colluvial on rock. The alluvial soil types are divided into Vleipan and Vlei-Morefield.

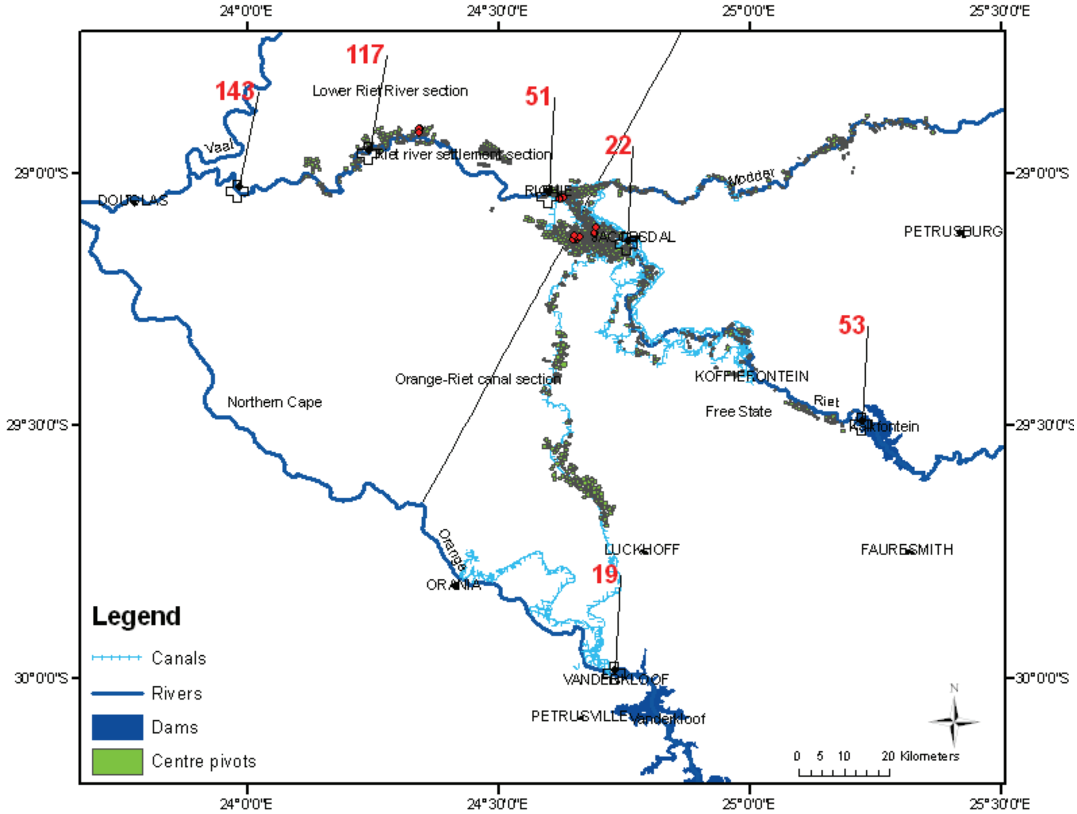
The above mentioned soil types at both schemes were converted to the current soil classification system used in South Africa (Soil Classification Working Group, 1991). Detail (1:6000) soil maps on linen, stored at the Institute for Soil, Climate and Water (ARC-ISCW), were first scanned and then geo-referenced before each line was digitized. These maps were used to compile the 1:50 000 soil maps of Orange-Riet (Appendix 3.3) and Vaalharts (Appendix 3.4). The majority soil forms occurring at Orange-Riet and Vaalharts are the deep sandy to sandy loam soils of the Hutton form, reasonably deep sandy soils of the Kimberley and Plooyesburg forms, and deep sandy loam to sandy clay soils of the Hutton and Kimberley forms (Appendix 3.3 and 3.4).

3.1.5 Dam and river water quality

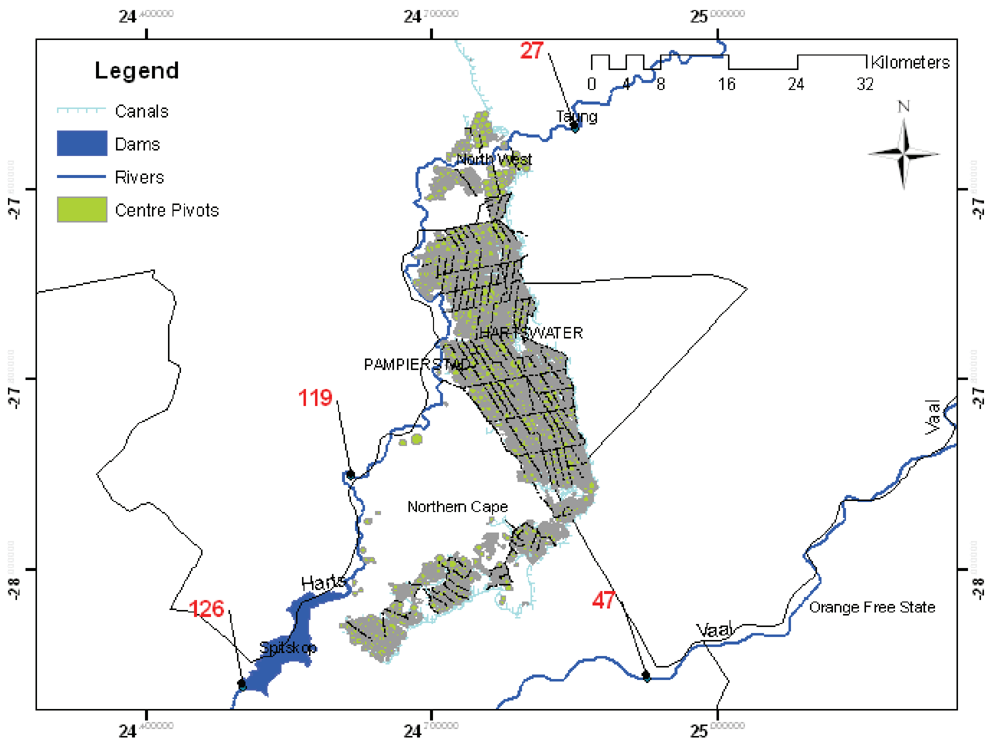
The mean long-term electrical conductivity (EC) and sodium absorption ratio (SAR) of the dams and river water, using data provided by DWAF for the period 1970-2006, were calculated for the measuring stations in the schemes as indicated in Figure 3.3 for Orange-Riet (a) and Vaalharts (b), respectively. At no time did the SAR of all the measuring stations within the two irrigation schemes rise above 10 and subsequently has a low sodium hazard (S1) (United State Salinity Laboratory Staff, 1969).

Orange-Riet Irrigation Scheme: According to the United States Salinity Laboratory Staff (1969) guidelines, the EC values show that water quality deteriorates along the conveyance system starting with a high quality water (C1 water, EC_i = 19 mS m^{-1}) at the Orange-Riet canal, changing to a C2 class (EC_i = 51 mS m^{-1}) at Ritche and then to a C3 class at Soutpansdrift (Lower Riet River Section; EC_i = 117 mS m^{-1}). At Ritchie the EC varied between 25 and 90 mS m^{-1} and at Soutpansdrift between 115 and 210 mS m^{-1}.

Vaalharts Irrigation Scheme: From the Vaalharts Barrage the scheme receives relative good quality irrigation water (C2), with a mean long-term EC of 47 mS m^{-1}.



(a)



(b)

Figure 3.3 Mean long-term electrical conductivity (mS m^{-1}) of dams and rivers at Orange-Riet (a) and Vaalharts (b) Irrigation Schemes for the period 1970-2006.

The addition of the salt load of the drainage water from the scheme changes the mean long-term EC of the Harts River from 27 mS m^{-1} at Taung Dam to 119 mS m^{-1} at Espagsdrif ending with a mean long-term EC of 126 mS m^{-1} at Spitskop Dam. Water leaving the Scheme can therefore be classified as C3 water and poses a high salinity hazard. At Vaalharts barrage the mean annual EC varied between 25 and 87 mS m^{-1}, while at Taung, Espagsdrif and Spitskop Dam the mean annual EC varied from 15-50, 75-270 and 25-190 mS m^{-1}, respectively.

3.2 Layout of measuring points

Measuring points were selected to include a variety of bio-physical conditions at root zone scale, *viz*. irrigation water qualities, soil types, crops, irrigation systems and soils that are artificially drained. Different managers were also incorporated. Thus, no irrigated field is similar and each of the measuring points was seen as a unique opportunity to obtain information on water and salt management practices by farmers at Orange-Riet and Vaalharts.

Measuring points with dimensions of 4 m x 4 m were set up in a crop field. In fields with artificial drainage systems, two measuring points were established, one on the drainage line and the other some distance away depending on the line spacing and type of drainage system. Two neutron access tubes (2000 mm), one piezometer (perforated 63 mm PVC tubes and 3000 mm deep) and a rain gauge were installed at each measuring point. Measurements at these measuring points were conducted over four seasons (two winters and two summers) from July 2007 to June 2009. A total of 30 measuring points were established as indicated in Table 3.2.

Geographically related measuring points on the same farm were grouped as sites (Table 3.2). The geographic position of the sites within Orange-Riet and Vaalharts is depicted in Figure 3.2, with sites 1 to 4 and 13 and 14 located at Orange-Riet and Sites 5 to 12 at Vaalharts. Sites were grouped into water sources, *viz*. those which extracted water from the Orange River, Vaal River or those which use blended water from the Orange, Modder, Riet and Lower Riet Rivers as well as drainage water (Table 3.2).

3.3 Data acquisition

3.3.1 Weekly measurements

Weekly measurements at every experimental area or measuring point consisted of rainfall, irrigation, soil water content, water table depth, drainage from artificial drainage system if any, as well as electrical conductivity of the irrigation water, water table and drainage water. Rainfall and irrigation were measured with rain gauges placed on the soil surface. An area of 6 m^2 was cleared around each rain gauge in order to prevent interference by the crop. Soil water content was measured with a calibrated neutron probe. The depth of the water table was measured manually by using an electronic device, while the volume of drainage water flowing from the artificial drainage systems was measured with a bucket and converted to L min^{-1}.

The electrical conductivity of the irrigation water, water table and drainage water, were measured with a calibrated handheld Ecoscan (Con6) Electrical Conductivity Meter. Water was manually collected with a bailer from the piezometers and with 100 ml bottles from the rain gauge and drainage system.

3.3.2 Seasonal measurements

Representative soil samples were taken at 300 mm depth intervals to, where possible, a depth of 1800 mm at the beginning and end of each growing season, using standard auguring procedures, at every experimental area or measuring point.

Table 3.2 Selected measuring points at Orange-Riet and Vaalharts Irrigation Schemes

Water source	Irrigation Scheme	Site	Measuring points	Irrigation system	Water table	Drainage system
Orange River	Orange-Riet	1	or4	Centre pivot	Yes	Yes
			or5		Yes	No
		2	or6	Sprinkler	Yes	Yes
			or7		Yes	No
		1	or8		Yes	Yes
			or9		Yes	Yes
			or10		Yes	No
			or11		Yes	No
		3	or12	Centre pivot	Yes	Yes
			or13		Yes	No
		4	or14		No	Yes
			or15		No	No
Vaal River	Vaalharts	5	v1	Flood	Yes	Yes
			v2	Sprinkler	Yes	No
		6	v3	Linear	Yes	No
		7	v4		Yes	Yes
		5	v5	Sprinklers	Yes	Yes
		8	v6	Centre pivot	Yes	Yes
			v7		Yes	No
		9	v8	Flood, Centre pivot	Yes	Yes
		10	v9		Yes	Yes
		11	v10	Centre pivot	Yes	No
		12	v11		Yes	Yes
			v12		Yes	Yes
Blended	Orange-Riet	13	or1		Yes	No
			or2		Yes	Yes
		14	or17		No	No
			or19		No	No
			or18		No	No
			or20		No	No

The soils were dried at 40°C, crushed to pass through a 2 mm sieve and analyzed using standard methods (The Non-Affiliated Soil Analysis Work Committee, 1990). The analysis included a saturation extract to determine electrical conductivity (EC_e, mS m^{-1}), Na, K, Ca, Mg, Cl, SO_4, PO_4 and NO_3, as well as the soluble (60% ethanol in water) and extractable (1N NH_4OA_c at pH 7) Na, K, Mg and Ca (The Non-Affiliated Soil Analysis Work Committee, 1990). The concentrations of cations were determined through atomic absorption spectrometry. Representative irrigation, water table and drainage water samples were taken during the same time periods as those mentioned above and also analyzed for dissolved cations (Ca, Mg, Na and K) using standard procedures (The Non-Affiliated Soil Analysis Work Committee, 1990).

After each season, the farmers were visited to discuss the results obtained during that specific season. Questions like the previous crop grown on the field, planting date, plant density, cultivation practices, type of fertilizers used and amount of fertilizers applied, pest and/or weed control, harvest date and yield were asked in the form of a questionnaire.

The different crops within the experimental area or measuring point were harvested at maturity from 16 m^2, dried, weighed and threshed to determine the seed mass and total above-ground biomass.

3.3.3 Soil classification, physical and chemical properties

Geographical-related measuring points with similar soils were grouped as sites. Soils in these different sites were classified according to the Taxonomical System of South Africa (Soil Classification Working Group, 1991). Representative soil samples were taken at 300 mm depth intervals for physical and chemical analysis. The soils were dried at 40°C, crushed to pass through a 2 mm sieve and analyzed using standard methods described in The Non-Affiliated Soil Analysis Work Committee (1990). The analysis included particle size distribution determined with the pipette method, pH_{Water}, P (Olsen), soluble (60% ethanol in water) + exchangeable (1N NH_4OAc at pH 7) cations (Ca, Mg, Na and K), the cation exchange capacity (CEC, NH_4OAc), exchangeable Cu, Fe, Zn and Mn as well as organic C and N.

3.3.4 Soil hydraulic properties

Soil hydraulic properties were determined at all the sites of the different soil types. This was mainly done to provide *in situ* measured inputs for SWAMP in order to improve the estimations made by the model. At ten locations, varying in silt-plus-clay content and water table depth, the internal drainage experiment of Hillel et al. (1972) was carried out on a 2.5 m x 2.5 m monolith with a depth of 1.8 m or until the water table was reached (Figure 3.4).

Figure 3.4 Example of a monolith at Orange-Riet Irrigation Scheme for determining the internal drainage parameters of the soil.

To inhibit the lateral movement of water the monolith was isolated by a plastic sheet. Two neutron access tubes and a piezometer were installed in the centre of the monolith. Prior to the start of the drainage cycle, the monolith was continuously wetted for 24 hours at which time it was presumed to be field saturated. When free water disappeared on the soil surface the drainage test was initiated. To minimize extreme temperature fluctuations at the surface and minimize evaporation, the soil surface was covered with a layer of thick pink (5 cm cotton wool). Soil water content (neutron probe), water table depths (piezometers) and time were monitored for a period of 30 days. The double ring procedure was used to determine the *in situ* saturated hydraulic conductivity of the 0-300 mm and 300-600 mm soil depths (Figure 3.5). The third depth was determined just above the water table. If no water table was present, a soil depth of 1500-1800 mm was used. Undisturbed core samples with a volume of 672 cm^3 (10.5 cm diameter and 7.7 cm height) were collected at 300 mm depth intervals. A core sampler was horizontally forced into the soil using a 12 ton hydraulic jack (Figure 3.6) to ensure sampling with minimum disturbance. Both ends of the core samples were trimmed and sealed with masonite boards to prevent any soil disturbance during transportation. The bulk densities were determined after drying the samples at 75°C for three days until the weights were constant.

Figure 3.5 Example of the double ring method used to determine saturated hydraulic conductivity at the 300 mm soil depth.

Figure 3.6 Illustration of how undisturbed soil samples for bulk density determination were obtained. The core sampler was gently pressed into the soil using a hydraulic jack.

3.3.5 Irrigation system evaluation

Only the centre pivot irrigation systems were evaluated. Each centre pivot irrigation system was evaluated by placing 30 rain gauges evenly apart. The amount of irrigation in the rain gauges was determined at a low (20%) and high (100%) speed. The uniformity coefficient, an indication of how much the application at the different measuring points deviates from the average application for the centre pivot, was calculated with Equation 3.1 and the distribution uniformity with Equation 3.2.

$$\mathbf{CU_H = 100\times 1\,\frac{\sum\left|y_i\text{-}\vec{y}_g\right|}{\sum R_i y_i}} \qquad \mathbf{3.1}$$

$$\mathbf{DU_{lg} = \frac{Weighed\ average\ application\ (lowest\ 25\%)}{Weighed\ average\ application\ (total\ system)}\times 100} \qquad \mathbf{3.2}$$

Where CU_H = Heermann and Hein uniformity coefficient (%)
R_i = distance of rain gauge at point I from the pivot centre (m)
y_i = application depth at point I as collected in the rain gauge (mm)
$\vec{y}_g$ = weighed average application of the total system (mm)
DU_{lg} = distribution uniformity (%).

The amount of water pumped into the system compared to the amount of water measured in the rain gauges (application efficiency) and system efficiency, which is the combination of the application efficiency and the distribution uniformity were calculated with Equation 3.3 and 3.4, respectively.

$$\mathbf{GA = \frac{Qt}{10A}}$$

$$\mathbf{AE = \frac{\vec{y}_g}{GA}100} \qquad \mathbf{3.3}$$

$$\mathbf{SE = \frac{AE\times DU_{lg}}{100}} \qquad \mathbf{3.4}$$

Where GA = gross application (mm)

Q	= centre pivot flow rate (m^3 $hour^{-1}$)
t	= rotation time (hours)
A	= total wetted area of centre pivot (ha).

3.4 Calculations and estimations: Soil water and salt balances

The soil water and salt balances are based on the principle of conservation of mass, where any change in water or salt of a given volume or depth of soil must be equal to the difference between water or salt added and lost from the same volume. It is therefore important to define the boundaries of the volume or system under consideration. With regard to root zone induced salinity the volume or soil depth that were used consisted of 2000 mm since this is the potential rooting depth of most agricultural crops. In the case of a restrictive soil layer, the root zone was then taken as the depth to the restrictive layer. The soil water balance for an irrigated field is illustrated by Equation 3.5 and the salt balance by Equation 3.6, while a conceptual illustration of the soil water and salt balances are provided in Figure 3.7.

$$\pm \mathbf{D} = \Delta \mathbf{W}_{\mathbf{Soil}} - \mathbf{R} - \mathbf{I} + \mathbf{E} + \mathbf{T} + \mathbf{AD} \qquad \mathbf{3.5}$$
$$\pm \mathbf{D} = \mathbf{WTU} - \mathbf{P}$$

$$\pm \mathbf{S_D} = \Delta \mathbf{S}_{\mathbf{Soil}} - \mathbf{S_F} - \mathbf{S_R} - \mathbf{S_I} + \mathbf{S}_{\mathbf{Crop}} + \mathbf{S}_{\mathbf{AD}} \qquad \mathbf{3.6}$$
$$\pm \mathbf{S_D} = \mathbf{S}_{\mathbf{WTU}} - \mathbf{S_P}$$

Where ΔW_{Soil} = change in water content of the potential root zone for an irrigated field between two successive measurements, using a (-) for a decrease an a (+) for an increase (mm)

R	= amount of rainfall (mm)
I	= amount of irrigation (mm)
E	= amount of evaporation (mm)
T	= amount of transpiration (mm)
AD	= amount of water lost through artificial drainage (mm)
±D	= a positive value is a net gain of water to the soil through upward drainage (+D, mm) or water table uptake and a negative value a net loss of water from the soil through downward drainage (-D, mm) or deep percolation
WTU	= amount of water from the water table contributing to evapotranspiration (mm)
P	= amount of water percolating towards the water table (mm)
ΔS_{Soil}	= change in salt content of the soil for an irrigated field (kg ha^{-1}) between two measurements, suing a (-) for a decrease and a (+) for an increase (mm)
S_F	= net amount of salts applied through fertilizers (kg ha^{-1})
S_R	= amount of salts applied through rainfall (kg ha^{-1})
S_I	= amount of salts applied through irrigation (kg ha^{-1})
S_{Crop}	= amount of salts removed by the crop (kg ha^{-1})
S_{AD}	= amount of salts removed though artificial drainage (kg ha^{-1})
$\pm S_D$	= a positive value is a net gain of salt to the soil through upward drainage (+D, mm) or water table uptake, and a negative value a net loss of salt from the soil through downward drainage (-D, mm) or deep percolation
S_{WTU}	= amount of salt added as a result of water table uptake (kg ha^{-1})
S_P	= amount of salt percolating towards the water table (kg ha^{-1}).

Changes in soil water content, rainfall, irrigation and drainage from artificial drainage systems were all measured, of which the latter mentioned also apply to the change in salt content of the soil, salts added through rainfall and irrigation as well as salts removed through the artificial drainage system.

The net amount of salt applied through fertilization (S_F, Equation 3.6) was calculated as the difference between salt applied through fertilizers and salt removed by the crop. It was assumed that 50% of the total salt addition through fertilization was removed by the crop. This amount is equal to approximately 3-5% of the seed yield, which was determined from seed yield measurements of Ca, K, Mg, Na, P and N at the various measuring points.

Total salt addition through fertilization were obtained from the linear relationship between the amount of fertilizer applied (kg ha^{-1}) and the change in electrical conductivity of a 300 mm soil layer (Equation 3.7). This relationship was determined from fertilizer solutions with different concentrations, the electrical conductivity of which was measured. The different fertilizer solutions were prepared to represent a range of fertilizer applications with different types of fertilizers by farmers at Orange-Riet and Vaalharts. The assumption was made that all the fertilizers were applied to a 300 mm soil layer and the soil water content was near the upper limit of plant available water.

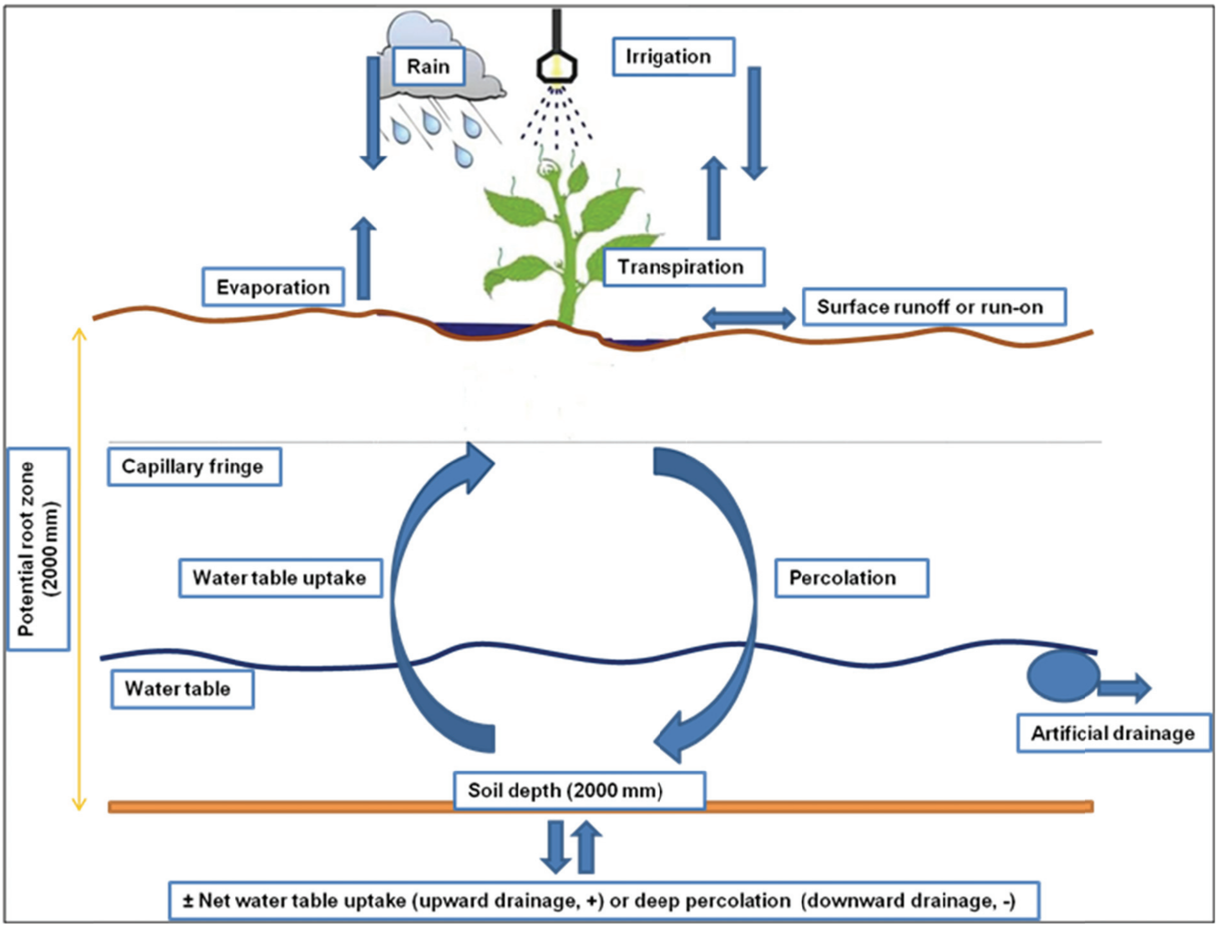


Figure 3.7 Conceptual illustration of the soil water and salt balance for the potential root zone (2000

mm) of an irrigated field.

$$\Delta \mathbf{EC_{0\text{-}300} = 0.1783(FI)} \qquad (R^2 = 0.85)$$

$$\Delta \mathbf{EC_{0\text{-}300} = 0.3326(NaCl\ or\ KCl)} \qquad (R^2 = 0.99) \quad \mathbf{3.7}$$

Where $\Delta EC_{0\text{-}300}$ = change in electrical conductivity of a 300 mm soil layer due to a specific amount of fertilizer applied (mS m^{-1})

FI = amount of fertilizer applied (kg ha^{-1}).

Evaporation from bare and converted soil surfaces, transpiration, water and salt transport through water table uptake and the movement of water and salt from the top of the soil downward through percolation into the water table were estimated with SWAMP. These estimations together with how to combine them with the *in situ* measurements of soil water content, rainfall and irrigation for the purpose of solving Equations 3.5 and 3.6 will be discussed in Chapter 4.

CHAPTER 4
WATER AND SALT BALANCE QUANTIFICATION THROUGH MODELLING: DEVELOPMENT, VALIDATION AND APPLICATION OF SWAMP

4.1 Introduction

Evaluating and managing irrigation-induced salinity is doomed to fail without the adequate quantification of water and salt fluxes through soils. Water and salt transport through soils depends on soil water processes, which are strongly influenced by rainfall, irrigation, evaporation, transpiration, capillary rise, groundwater flow and drainage. Providing good approximations requires the integration of soil water and salt movement, to accurately quantify these processes. This unfortunately is not always possible in the field, because of the difficulty involved in measuring these processes. Combining field measurements with a functional modelling approach can therefore be useful, and is generally accepted in on-farm and regional water and soil assessment of irrigation-induced salinity.

Various models are available both worldwide and in South Africa for integrating and estimating the processes involved in water and salt movement along the soil-plant-atmosphere continuum pathway. Researchers however find it difficult to decide which appropriate model to use, since most suitable models are a combination of empirical and mechanistic models where the governing equations are solved analytically or numerically (Lascano, 1994). The so-called research models or mechanistic water and salt transport models are generally not suitable for management purposes. They do however comprehensively integrate the knowledge of the processes controlling soil water and salt movement. Empirical water and salt transport models are less intensive and are commensurately less quantitative in their ability to predict water and salt movement under field conditions, and are therefore mostly used as management models.

Water and salt balance models are therefore generally favoured because of their conceptual basis, which makes them equally applicable as research or management models. From several water and salt balance models that are available, the specific application, accuracy of prediction, inputs required and experience of the user of the model will be the fundamental factors determining the most appropriate water and salt balance model to use.

With these factors in mind and for the purpose of this report it was decided to use the **S**oil **W**ater **M**anagement **P**rogram, SWAMP (Bennie et al., 1998) in order to estimate the components of the soil water balance not measured in the field. Estimations of evaporation from bare and converted soil surfaces, water uptake by crops and subsequent soil drying, contribution of water tables to water uptake by crops and water transport from the top of the soil downwards through percolation were verified by Bennie et al. (1998) and Ehlers et al. (2003). A brief summary of the mathematical algorithms used in estimating these components will be discussed, while the adjusting parameters that were used during this study regarding crop development and soil hydraulic properties will also be provided. For the purpose of this report, a data set obtained from the Department of Agriculture, Free State, (Personal communication: Mr K Snyman, Free State Department of Agriculture, Bloemfontein) will be used to compare measured evapotranspiration and soil water content data from Orange-Riet Irrigation Scheme with estimations made by SWAMP. This was done mainly to confirm the findings of Bennie et al. (1998) and Ehlers et al. (2003) with an independent data set.

It was however necessary to add an additional subroutine to simulate the effect of soil salinity on crop yield, the transport of salt through water table uptake and the movement of salt from the top of the soil downward through percolation. The mathematical algorithms adopted in estimating these aspects will therefore be described. Verification of these mathematical algorithms will be done by comparing measured data from Ehlers et al. (2007) to estimations made with SWAMP. Finally, the functional approach in applying the model in order to numerically solve the soil water (Equation 3.5) and salt balance (Equation 3.6) equations for a measuring point will be described.

4.2 Simulation procedures

The following inputs are required by SWAMP to simulate the soil water and salt balance over a growing season for a specific crop under irrigated conditions.

- i) Planting date
- ii) Growing season length
- iii) Target yield
- iv) Mean evaporative demand of the atmosphere for the growing season
- v) Presence or absence of a water table
- vi) Number of soil layers, thickness and silt-plus-clay percentage of each layer
- vii) Volumetric soil water content at the start of the season for every layer
- viii) Salt concentration at the start of the season for every layer
- ix) Salt distribution coefficient
- x) Mean salt concentration, electrical conductivity, of the water table for the season.
- xi) Various soil adjustment parameters. Use default values if not provided (Bennie et al., 1998; Ehlers et al., 2003)
- xii) Various crop development parameters. Use default values if not provided (Bennie et al., 1998)
- xiii) Date and amount of rainfall and/or irrigation
- xiv) Salt concentration (electrical conductivity) of irrigation water

4.2.1 Water balance

A detail description of the structure, flow diagram and subroutines of SWAMP is given by Bennie et al. (1998). Crop water uptake from a shallow water table was later incorporated into SWAMP by Ehlers et al. (2003). A flow diagram linking the different subroutines in SWAMP is given in Figure 4.1.

Estimations of evaporation from a bare soil surface are based on the principle that empirical coefficients, for the Rose and Ritchie equations, are calculated from soil water content and texture. The evaporation rate or cumulative evaporation on a daily basis from the time it rained or the soil was irrigated, is then subsequently calculated with these equations. Calculation of evaporation from covered soil surfaces initially follows the same procedure as described above. To reduce the calculated cumulative evaporation, a factor equal to one minus the fractional shading of the soil surface is used.

Total seasonal water requirement for a given yield of a crop is calculated with the De Wit-equation (from Hanks & Rasmussen, 1982) using the maximum biomass production, maximum transpiration requirement and mean seasonal atmospheric evaporative demand. Total seasonal transpiration is converted to daily transpiration, using a generated growth curve equation for calculating the relative daily transpiration requirement for the season. The parameters used for describing the different growth stages are provided in Table 4.1.

Soil water depletion with depth, are calculated using the profile water supply rate approach of Bennie et al. (1998). The procedure is based on the principle that drying of a soil layer is proportional to the ratio between the layer water supply rate and the profile water supply rate. When the profile water supply rate of a specific day is larger than the estimated daily transpiration, the daily soil water depletion will be equal to the transpiration or root water uptake. If the profile water supply rate is less than the required estimated daily transpiration, soil water depletion will be equal to the profile water supply rate. This will also indicate the onset of soil-induced crop water stress (more detailed discussion in Section 4.2.2.1).

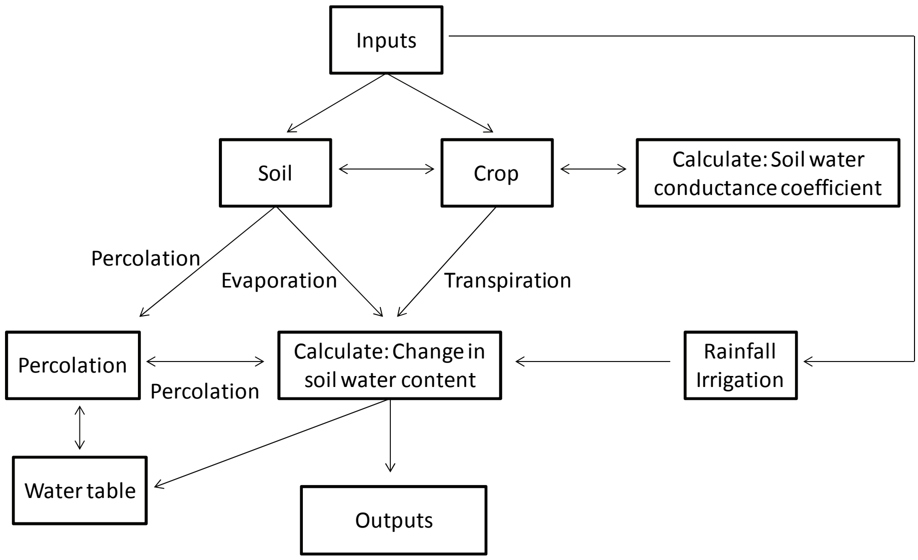


Figure 4.1 Flow diagram of the SWAMP model showing the interaction between the different subroutines.

When present, the contribution of a water table to daily transpiration can also be estimated by SWAMP. This contribution is simulated according to the upward cascading approach, where the maximum upward flux from the water table is related to a specific height above the water table (Ehlers et al., 2003).

Table 4.1 Crop parameters used in SWAMP to describe the different growth stages of the crops that were grown during the study at farms located within Orange-Riet and Vaalharts Irrigation Schemes

Crop	**Maize**	**Wheat**	**Groundnuts**	**Peas**	**Cotton**	**Sunflower**
m (Crop specific factor)	220	145	143	71	184	20
End of establishment phase (A’, days)	15	40	20	35	20	20
End of Vegetative growth phase (B’, days)	65	90	50	70	90	50
End of reproductive development phase (C’, days)	110	130	140	120	140	90
End of physiological maturation phase (D’, days)	130	148	165	130	180	150
Relative crop water requirement at end of phase A’ (a’)	0.4	0.2	0.3	0.2	0.2	0.4
Relative crop water requirement at end of phase D’ (d’)	0.25	0.5	0.4	0.5	0.3	0.2

The sum of the daily water uptake from all the layers within the capillary zone is taken as the total contribution of the water table to the daily crop transpiration. This happens only when daily transpiration or root water uptake is less than the maximum upward flux rate through a layer. When daily transpiration or root water uptake is more than the maximum upward flux rate through a layer, daily water table uptake is equal to the maximum upward flux rate.

The water entering the first soil layer through rain or irrigation is divided between the soil layers with the cascading principle, according to which the soil layers are wetted from the top to the upper limit of plant available water. The excess amount of water is transported downward within the soil profile as percolation (Hillel, 1998), until the last soil layer is reached, from where the surplus water is transported out of the soil profile as deep percolation (Hillel, 1998). In the absence of a water table and when the soil is wetter than the upper limit of plant available water, SWAMP uses a logarithmic drainage curve to calculate deep percolation (Equation 4.1):

$$\mathbf{DR} = \frac{\mathbf{a}}{\mathbf{exp}^{\frac{(\mathbf{b}-\mathbf{W})}{\mathbf{a}}}} \qquad \mathbf{4.1}$$

Where DR = drainage rate (mm day^{-1})
W = soil water content of potential root zone (mm)
a and b = drainage coefficients, depending on soil texture.

The coefficients of the drainage curves are derived from the mean silt-plus-clay content of the potential root zone. These coefficients were determined for soils with silt-plus-clay contents that ranged from 16 to 47%. During this project three additional drainage curves were done on soils with mean silt-plus-clay contents for the rooting depth of 9, 16 and 65%, respectively, to improve the accuracy of the drainage curve coefficients. Equation 4.2 represents the improved equations for estimating the drainage curve coefficients:

$$\mathbf{a = 45.72\text{-}1.334\left(Silt\text{+}Clay_{Root\ zone}\%\right)\text{+}0.011(Silt\text{+}Clay_{Root\ zone}\%)^2} \qquad (R^2 = 0.88)$$

$$\mathbf{b' = 70.99\text{+}11.67(Silt\text{+}Clay_{Root\ zone})\text{-}0.117(Silt\text{+}Clay_{Root\ zone}\%)^2} \qquad (R^2 = 0.91)$$

$$\mathbf{b} = \frac{\mathbf{(b')(Depth\ of\ root\ zone)}}{\mathbf{1000}} \qquad \mathbf{4.2}$$

The texture derived coefficients of the drainage curves are also used to calculate the upper limit of plant available water. Other soil hydraulic properties like soil water content at saturation and the lower limit of plant available water are calculated from empirical texture (silt-plus-clay) derived coefficient (Bennie et al., 1998).

4.2.2 Salt balance

4.2.2.1 Effect of salinity on root water uptake and yield

The De Wit relationship between yield and evapotranspiration remains the same for water stress (drought) and salinity stress conditions (Stewart et al., 1977; Ehlers et al., 2007). Yield is subsequently reduced because salinity increases the total plant water stress through its effect on the osmotic potential of the soil water. Crop water uptake and subsequently soil drying are proportional to the potential water supply rate of the soil profile (Bennie et al., 1988). As the soil is drying, the water potential difference between the root xylem and the surrounding soil solution decreases and results in less water being taken up when compared to conditions of normally adequate water supply. The soil layer water supply rate for a specific soil layer on a specific day for non-saline conditions is calculated with Equation 4.3. For non-saline conditions total soil water potential was taken as only the matrix potential:

$$\mathbf{LWSR_{(i)\,(d)} = F_{sr\,(i)} \ln\left(\frac{\theta_{(i)(d)}}{\theta_{o\,(i)}}\right)\left(\pi Lv_{(i)}\right)^{0.5}\left|\Psi_{g\,(i)(d)}-\Psi_{p}\right| z_{(i)}} \qquad \textbf{4.3}$$

Where LWSR = layer water supply rate (mm day^{-1})
F_{sr} = soil water conductance coefficient (mm^3 water mm^{-1} roots kPa^{-1} day^{-1})
Lv = root density (mm roots mm^{-3} soil)
θ_o = volumetric soil water content where $\Psi_g = \Psi_p$ (mm mm^{-1})
θ = volumetric soil water content (mm mm^{-1})
Ψ_g = matric potential (-kPa)
Ψ_p = critical leaf water potential where plant stress sets in (-kPa)
z = depth of soil layer (mm)
$_{(i)}$ = soil layer number i
$_{(d)}$ = day number.

Calculation of the different parameters used in Equation 4.3 is presented in Bennie et al. (1998).

Summation of the water supply rates for all the soil layers in the entire potential root zone results in Equation 4.4, the integrated potential profile water supply rate of the root zone

$$\mathbf{PWSR_{(d)} = \sum_{i=1}^{n} LWSR_{(i)}} \qquad \textbf{4.4}$$

where PWSR = profile water supply rate (mm day^{-1}).

Water uptake from a specific soil layer or root water uptake is then calculated with Equation 4.5

$$\mathbf{\Delta\theta_{(i)(d)} = \left(\frac{T_{(d)}}{z_{(i)}}\right)\left(\frac{LWSR_{(i)(d)}}{PWSR\,(d)}\right)} \qquad \text{where} \qquad \mathbf{\frac{LWSR_{(i)(d)}}{PWSR_{(d)}} = DR_{(I)(d)}} \qquad \textbf{4.5}$$

where $\Delta\theta_{(i)(d)}$ = water uptake from soil layer i on day d (mm)
T = transpiration (mm day^{-1}) or root water uptake from layer i on day d
$DR_{(i)(d)}$ = depletion ratio for layer i on day d.

When the profile water supply rate is larger than the demand of the crop, crop water uptake (T_d) is equal to the crop water demand. When the profile water supply rate ($PWSR_d$) is equal to or less than the crop water demand then soil induced crop water stress will begin. Crop water uptake (T_d) during this period is then taken as equal to the profile water supply rate.

To incorporate the effect of salinity on the profile water supply rate, the matric potential (Ψ_g,-kPa) in Equation 4.3 was replaced by the total potential (Ψ_t, -kPa), *viz*. matric plus osmotic (Ψ_o,-kPa) potential (Equation 4.6):

$$\mathbf{\left|\Psi_{t\,(i)(d)}\right| = \Psi_{o\,(i)(d)} + \Psi_{g\,(i)(d)}}$$

$$\left|\Psi_{o\,(i)(d)}\right| = \left[\frac{\left(\left(EC_{e\,(i)(d)}\right)(c_1)\right)(c2)}{\theta_{(i)(d)}}\right]\theta_{s\,(i)} \quad \mathbf{4.6}$$

Where Ψ_t = total potential (kPa)
Ψ_o = osmotic potential (kPa)
EC_e = electrical conductivity of a saturated extract for the soil layer (mS m^{-1})
θ_s = saturated volumetric soil water content (mm mm^{-1})
c_1 = constant used to convert electrical conductivity (mS m^{-1}) to total dissolved salts (mg L^{-1}) taken as 7.5 (Ehlers et al., 2007)
c_2 = constant used to convert total dissolved salts (TDS, mg L^{-1}) to osmotic potential (kPa), taken as 0.072.

The relationship (c_2 = 0.072) between soluble salt concentration and osmotic potential were derived as proposed by Borg (1989) with Equation 4.7 from soil water sample data of Ehlers et al. (2007) taken with ceramic suction cups at different soil depths. From all these data a minimum, maximum and mean relationship of 0.063, 0.083 and 0.072 were calculated:

$$c_2 = c_{Na^+} + c_{Ca^{++}} + c_{Mg^{++}} + c_{SO_4} + c_{Cl^-} + c_{K^+}$$

$$c_k = \left[\frac{(R)(T)}{1000}\right]\left[\frac{(n)(f)}{m}\right] \quad \mathbf{4.7}$$

Where k = components Na^+, Ca^{++}, Mg^{++}, SO_4^{--}, Cl^- and K^+
R = gas constant (8.31 kPa L mol^{-1} °K^{-1})
T = absolute temperature, taken as 298.15 °K (25°C)
n = 1 (All salts are assumed to be completely dissociated)
m = molecular mass of component k (g mol^{-1})
f = fraction of component k that contributes to the total mass of soluble salts in the solution.

The volumetric soil water content (θ_o, Equation 4.3) of a soil layer where the total soil water potential is equal to the critical leaf water potential, was replaced with θ_t, in order to accommodate the effect of salinity. As a result, the volumetric soil water content where total potential is equal to the critical leaf water potential will increase with an increase in soil salinity.

Decreasing osmotic potential, due to higher salt contents, results in lower total soil water potential and a corresponding decrease in the potential difference between the root xylem and surrounding soil ($\Psi_{t(i)(d)} - \Psi_p$, Equation 4.3). Because of an increase in θ_t with an increase in salinity the ln $\theta_{(i)(d)} / \theta_{t(i)}$ ratio in Equation 4.3 will decline more quickly towards 0. The combined effect of both these components results in a decline of the LWSR, at the same water content, with increasing salinity. As a result less water will be taken up from a layer thus increasing the lower limit of plant available water, the onset of soil plus salinity induced crop water stress and a lower yield.

4.2.2.2 Salt added by rainfall and irrigation

Runoff takes place when the rainfall and/or irrigation intensity are higher than the infiltration intensity of the soil, while run-on occurs when water flows on to the field from surrounding higher-lying areas.

Effective rainfall and irrigation that infiltrates the soil are subsequently calculated with Equation 4.8. When not provided as an input, SWAMP assumes runoff and/or run-on to be negligible:

$$\mathbf{Eff_{R+I\,(d)} = R_{(d)} + I_{(d)} - R_{Off\,(d)} + R_{On\,(d)}} \qquad \mathbf{4.8}$$

Where Eff_{R+I} = effective rain (R) and/or irrigation (I) water infiltrating the soil (mm)
R = measured rainfall (mm)
I = measured irrigation (mm)
R_{Off} = runoff (mm)
R_{on} = runoff (mm).

The electrical conductivity of the water infiltrating the soil, as rainfall and/or irrigation, is calculated with Equation 4.9. The electrical conductivity of rain water is taken as 2 mS m^{-1} (Equation 4.9):

$$\mathbf{EC_{Eff_{R+I\,(d)}} = \frac{\left[\left(Eff_{R\,(d)}\right)\left(EC_R\right)\right]+\left[\left(Eff_{I\,(d)}\right)\left(EC_i\right)\right]}{\left(Eff_{R+I}\right)_{(d)}}} \qquad \mathbf{4.9}$$

Where $EC_{Eff_{R+I}}$ = electrical conductivity of the effective rain and/or irrigation water infiltrating the soil (mS m^{-1})
EC_R = electrical conductivity of the rain water, taken as 2 (mS m^{-1})
EC_i = electrical conductivity of the irrigation water (mS m^{-1}).

The amount of salt added to the soil profile by rain and/or irrigation water, on a specific day, is then calculated with Equation 4.10:

$$\mathbf{S_{R+I\,(d)} = \left(Eff_{R+I\,(d)}\right)\left(c_3\right)\left(EC_{Eff_{R+I\,(d)}}\right)} \qquad \mathbf{4.10}$$

Where S_{R+I} = salt added by effective rain and irrigation water (kg ha^{-1})
C_3 = constant used to convert electrical conductivity (mS m^{-1}) to kg salt ha^{-1} mm^{-1} water, taken as 0.075.

4.2.2.3 Salt content of different soil layers

Since the electrical conductivity of the different soil layers at the start of the season is entered as inputs, the electrical conductivity of each layer on day 0 is set equal to the entered values. The salt contents of the different soil layers on day 0 are subsequently calculated with Equation 4.11

$$\mathbf{S_{(i)\,(d=0)} = \left[\left(EC_{e\,(i)(d=0)}\right)\left(c_3\right)\right]\left(\theta_{s\,(i)}\right)\left(z_{(i)}\right)} \qquad \mathbf{4.11}$$

where S = salt content of the soil layer (kg ha^{-1}).

Salts are mainly transported downwards and upwards as mass flow by water. The downward cascading principle, overflow of water from one layer to the next, used in SWAMP to simulate the movement of water governs therefore the downward movement of salt, while the upward cascading principle governs (Ehlers et al., 2003) the upward movement of salt due to water table uptake. Accordingly the salt content of each soil layer changes when salt is added or removed by water flowing into or out of it when rainfall and/or irrigation as well as water table uptake occurred. Water uptake by roots leads to salt concentrating in a layer.

Firstly, in calculating water movement from the top of the soil profile downward the deficit, which is the difference between the upper limit of plant available water and actual simulated soil water content, of each soil layer for every day, is calculated with Equation 4.12:

$$\mathbf{Def_{(i)(d)} = \left(\theta_{ULPAW(i)} - \theta_{(i)(d)}\right)\left(z_{(i)}\right)} \qquad \mathbf{4.12}$$

Where Def = water deficit of soil layer (mm)
θ_{ULPAW} = upper limit of volumetric plant available water for the soil layer (mm mm^{-1}).

During every rain and/or irrigation event, all the effective rain and/or irrigation water application flows into the first soil layer (Equation 4.13):

$$\mathbf{Inf_{(i=1)(d)} = Eff_{R+I\,(d)}} \qquad \mathbf{4.13}$$

where Inf = inflow of water into the first soil layer (mm).

Excess water will flow from one layer into the next layer when the difference between the quantative inflow of water into a layer is more than the amount required to wet the layer to the upper limit of PAW (Def). These processes will repeat themselves until a soil layer is reached, where the inflow is less than the deficit (Equation 4.14):

$$\mathbf{Inf_{(i)(d)} = Inf_{(i-1)(d)} - Def_{(i-1)(d)}} \qquad \mathbf{4.14}$$

The amount of applied water remaining in a specific soil layer is equal to its deficit when the inflow of water into this layer is larger than the deficit (Equation 4.15). When the inflow is smaller than the deficit the amount of water applied to the layer is equal to the inflow of water into the layer (Equation 4.16).

$$\mathbf{AP_{(i)(d)} = Def_{(i)(d)}} \text{ When } \mathbf{Inf_{(i)(d)} > Def_{(i)(d)}} \qquad \mathbf{4.15}$$

$$\mathbf{AP_{(i)(d)} = Inflow_{(i)(d)} - Outf_{(i)(d)}} \text{ When } \mathbf{Inf_{(i)(d)} < Def_{(i)(d)}} \qquad \mathbf{4.16}$$

$$\mathbf{Inf_{(i+1)(d)} = Outf_{(i)(d)} = Inf_{(i)(d)} - Def_{(i)(d)}}$$

where AP = amount of water added to specific layer, through rainfall and/or irrigation (mm).

The general principle adopted in calculating the amount of the salt entering and leaving a soil layer (kg ha^{-1}) through this inflow and outflow of water is to multiply the concentration (mS m^{-1} x 0.075) of this water by its volume (mm). The salt content of the first soil layer is calculated from the salt content of the previous day plus the amount of salts added to the first soil layer through rainfall and irrigation plus the amount of salts added through water table uptake minus the amount of salts removed from the first soil layer through percolation (Equation 4.17). The concentration of the irrigation water and water table are provided as inputs, while the concentration or electrical conductivity of the water leaving the first soil layer through percolation is calculated with Equation 4.18.

$$S_{(i=1)\,(d)} = S_{(i=1)\,(d-1)} + \left[\left(EC_{Eff_{R+I\,(d)}}\right)(c_3)(Eff_{R+I})\right] + [(EC_{WT})(c_3)(WTU_{(i)(d)})] - \left[\left(EC_{p\,(i=1)(d)}\right)(c_3)\left(Inf_{(i=1)(d)} - AP_{(i=1)(d)}\right)\right] \qquad \mathbf{4.17}$$

$$EC_{p\,(i=1)(d)} = \left[\frac{S_{(i=1)(d-1)} + \left[\left(EC_{Eff\ R+I(d)}\right)(c_3)\left(Eff_{R+I(d)}\right)\right] + [(EC_{WT})(c_2)(WTU_{(i)(d)})]}{\left(W_{Sat(i=1)}\right)(c_3)}\right](DC) \qquad \mathbf{4.18}$$

Where S = salt content of a specific soil layer (kg ha^{-1})

EC_{WT} = electrical conductivity of the water table (mS m^{-1})

WTU = water table depletion or uptake (mm)

EC_p = the electrical conductivity of the water leaving the specific soil layer through percolation (mS m^{-1})

W_{Sat} = soil water content for a specific soil layer at saturation (mm)

DC = distribution coefficient (dimensionless).

Equation 4.18 calculates the amount of salts added to the first layer through rainfall and/or irrigation water and water table uptake. This amount of salt is subsequently converted to a concentration, which is referred to as the maximum potential concentration of the water leaving the layer. In porous medium like soil however, salt is displaced by mass flow and molecular diffusion. The salt transport approach used in this study is mainly based on the downward or upward mass transport of solutes through soil pores, which is generally assumed to be the net effect of convection. It is based on the macroscopic approach and only takes into consideration the mean pore water velocity over many soil pores (Hillel, 1998). In reality the flow velocity is not equally distributed, because the flow velocity is higher in the larger pores than in small ones and is higher in the centre of a pore than along its wall. Solute mixing caused by this uneven distribution of flow velocities is called dispersion. Since diffusion also occurs in the cavities formed by the pores, the solution is mixed by a combination of dispersion and diffusion (miscible displacement), which is combined by including a single distribution coefficient (DC) in Equation (4.18). In other words the potential maximum concentration of the water leaving the soil layer is multiplied by the distribution coefficient, which actually determines the amount of salt leaving the soil layer through percolation.

The salt content of the remaining soil layers on a specific day is calculated using the same procedure. The only difference is that the salt content of the water added to a layer is calculated from the salt concentration (electrical conductivity) of the layer above (Equation 4.19) plus salts added through water table uptake. The electrical conductivity of the water leaving the specific soil layer through percolation on a specific day is calculated with Equation 4.20 by adopting the same principle of multiplying the potential maximum concentration of the water leaving the layer with the distribution coefficient.

$$S_{(i)\,(d)} = S_{(i)\,(d-1)} + \left[\left(EC_{p\,(i-1)(d)}\right)(c_3)(Inf_{(i-1)(d)} - AP_{(i-1)(d)})\right] + [(EC_{WT})(c_3)(WTU_{(i)(d)})] - \left[\left(EC_{p\,(i)(d)}\right)(c_3)(Inf_{(i)(d)} - AP_{(i)(d)})\right] \qquad \mathbf{4.19}$$

$$EC_{p\,(i)(d)} = \left[\frac{S_{(i)(d-1)} + \left[\left(EC_{p(i-1)(d)}\right)(c_3)\left(Inf_{(i-1)(d)} - AP_{(i-1)(d)}\right)\right] + [(EC_{WT})(c_3)(WTU_{(i)(d)})]}{\left(W_{Sat(i)}\right)(c_3)}\right](DC) \qquad \mathbf{4.20}$$

To convert salt content (kg ha^{-1}) to electrical conductivity, which is related to salt concentration (mS m^{-1}), Equation 4.21 is used:

$$\mathbf{EC_{e\,(i)(d)}} = \frac{\mathbf{S_{(i)(d)}}}{\mathbf{(W_{Sat})(c_3)}} \qquad \mathbf{4.21}$$

The total amount of salts that are removed until an equilibrium electrical conductivity is reached, under specific soil-irrigation-water-drainage conditions, can be referred to as excess salts (Barnard et al., 2010). Under ideal conditions this equilibrium will be reached when the mean salinity of the soil profile equals the salinity of the irrigation water. It was proposed that the salinity of the top 50 mm of soil be used as the equilibrium value under the existing soil-irrigation-water-drainage conditions (Khosla et al., 1979; Pazira & Sadeghzadeh, 1999). In SWAMP, a preselected equilibrium value, referred to as EC_{Min}, can be entered as an input to prevent the electrical conductivity of the soil becoming less than EC_{Min}. When not entered, SWAMP will only decrease the electrical conductivity of the soil to half the electrical conductivity of the effective rain and/or irrigation water infiltrating the soil.

4.3 Validation of SWAMP under non-saline conditions

4.3.1 Inputs and assumptions

Data was collected by the Department of Agriculture, Free State, (personal communication K. Snyman) on irrigation-scheduled fields without water tables on farms located at the Orange-Riet Irrigation Scheme. Atmospheric evaporative demand, evapotranspiration, soil water content, silt-plus-clay and yield data were measured during a maize and wheat growing season. Simulations for the same two growing seasons were done using SWAMP with the following inputs. Maize was planted on the 18th of December 2006 with a growing season of 130 days to physiological maturity, while wheat was planted on 2 July 2007 with a growing season of 148 days to physiological maturity. The mean measured atmospheric demand over the growing season for maize as 5.7 mm day^{-1} and for wheat 5.1 mm day^{-1} was used. The measured yield for maize, 13000 kg ha^{-1} and for wheat 9000 kg ha^{-1}, were used as target yields. The crop parameters used in the simulations are provided in Table 4.1.

Six soil layers, 300 mm thick, with silt-plus-clay contents that ranged between 11% and 13% were used to set up the model. Volumetric soil water content of each soil layer (mm mm^{-1}) at the start of the season was set equal to the measured values, while soil salinity was set at 20 mS m^{-1}. Measured rainfall and/or irrigation data during the maize and wheat seasons were used as inputs, while the salinity of the irrigation water was set equal to 20 mS m^{-1}.

4.3.2 Results and discussion

The measured and simulated cumulative evapotranspiration values are compared in Figure 4.2 for the maize and wheat seasons, respectively. During the entire season of both crops, the simulated values compared well to the measured values. For maize a total of 747 mm of water was applied and for wheat a total of 622 mm. Measured evapotranspiration for maize amounted to a total of 694 mm and 627 mm for wheat, while 673 mm and 606 mm were simulated for maize and wheat, respectively. The measured and simulated soil water content of an 1800 mm deep soil profile during the maize and wheat seasons are shown in Figure 4.3. During both seasons no percolation of water beyond the root zone occurred because the soil water content never exceeded the drained upper limit or upper limit of plant available water. For the maize season the soil water content varied between 139 and 259 mm for the 1800 mm deep profile, while for the wheat season it varied between 152 and 230 mm for the 1800 mm deep profile. The good comparison between measured and simulated evapotranspiration and soil water content values is an indication of the reliability with which the water balance components are simulated by SWAMP during a growing season.

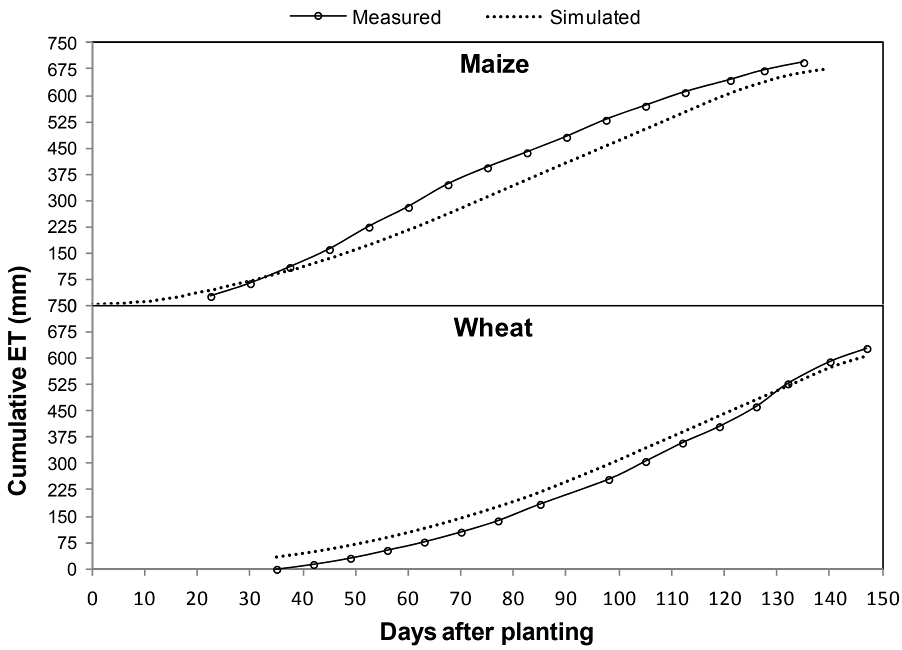


Figure 4.2 Cumulative measured and simulated evapotranspiration (ET) for the maize and wheat growing season.

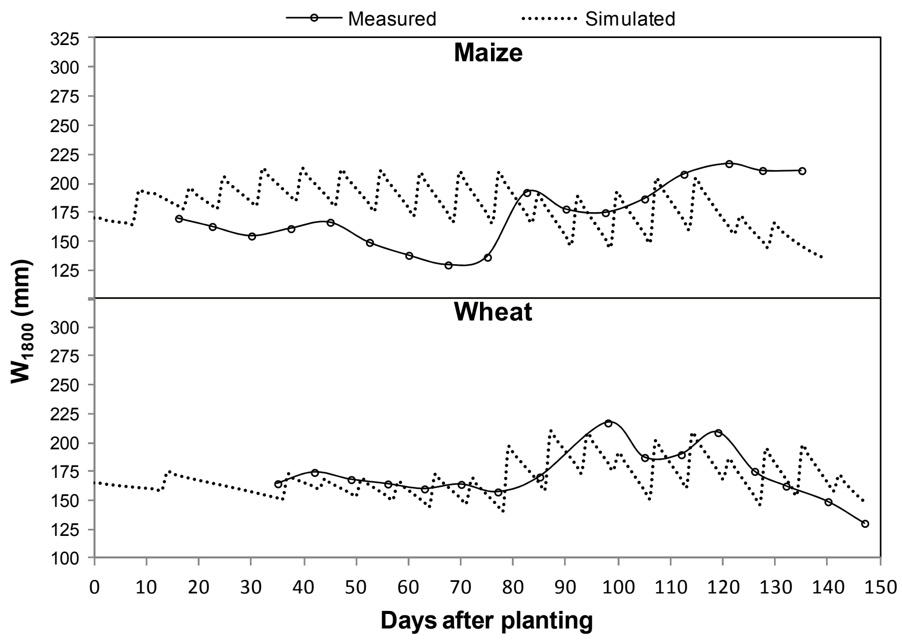
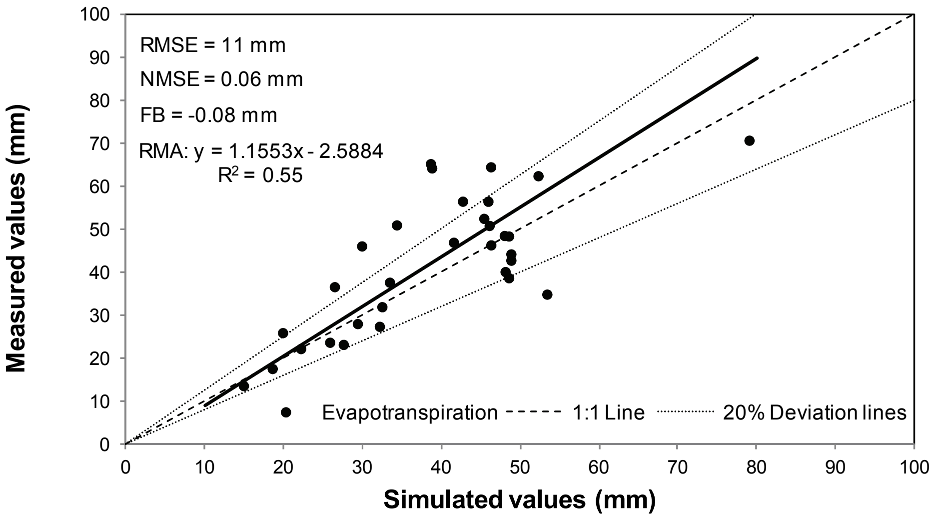
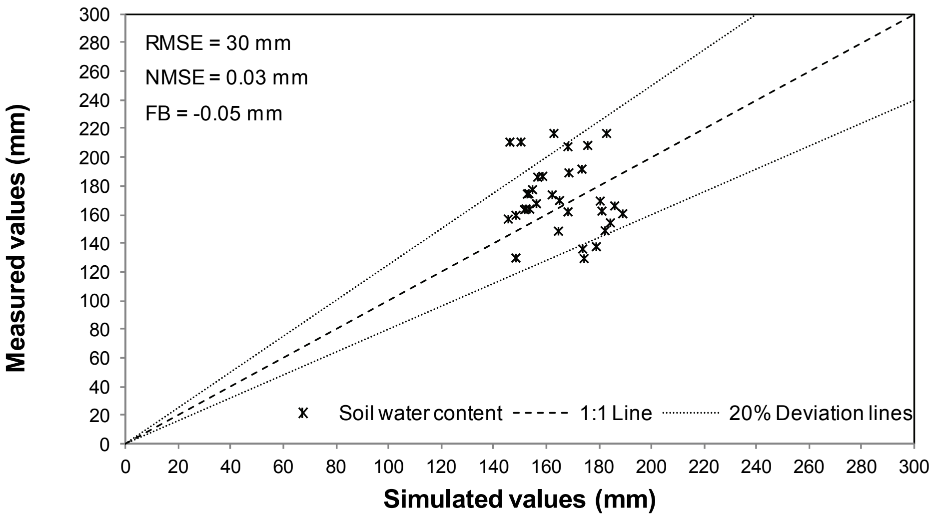


Figure 4.3 Measured and simulated soil water content for an 1800 mm deep soil profile (W_{1800}) during the maize and wheat growing season.

Difference-based (simulated – measured) and correlation-based (simulated versus measured) analysis as provided by IRENE (software to evaluate model performance; Fila et al., 2001) were used to compare weekly measured evapotranspiration (Figure 4.4a) and soil water content (Figure 4.4b) values with simulated values of SWAMP. The performance of the model was deemed acceptable when the root mean square error (RMSE) < 20% of the mean measured values, the normalized mean squared error (NMSE) ≤ 0.5 and -0.5 ≤ fractional bias (FB) ≤ +0.5 (Kumar, 2000, as cited by Fila et al., 2001). For both simulations of evapotranspiration and soil water content during the maize and wheat seasons all the difference-based indices were better than the required criteria.



(a)



(b)

Figure 4.4 Statistical comparison of simulated evapotranspiration (a; ET) and soil water content (b; W_{1800}) data during a maize and wheat season, against an independent measured data set.

For the correlation-based analysis the simulated evapotranspiration and soil water content values were regressed against the measured values. To validate simulated = measured, the difference between 0 and the intercept and between 1 and the slope, of the regression was separately and simultaneously tested with IRENE, according to the reduced major axis method (RMA). The results showed that the intercept and slope of the simulated versus measured evapotranspiration regression did not differ significantly from 0 and 1, respectively. This was also true when the slope and intercept were simultaneously tested against 0 and 1, respectively. These results confirm the difference-based analysis and suggest a significant coherence between simulated and measured evapotranspiration.

The slope of the soil water content simulated versus measured regression differed significantly from 1, while the intercept and slope differed simultaneously from 0 and 1, respectively. The correlation-based analysis shows that the soil water content measurements were clustered. It was concluded that despite this limitation in the data set, SWAMP, can reasonably accurately simulate soil water content during the growing season of a crop. This is true because the majority of the soil water content data points were within the 20% deviation lines and because the difference-based analysis was below the criteria. This validation exercise, using recent cultivars at Orange-Riet, was done to confirm the validations reported by Bennie et al. (1998).

4.4 Validation of SWAMP under saline conditions

4.4.1 Inputs and assumptions

Data from a lysimeter trial conducted by Ehlers et al. (2007), to quantify the effect of soil salinity on crop growth and water use of maize, was used to verify the salt balance subroutines included in SWAMP. The lysimeter facility comprised 30 lysimeters, 15 per soil type, *viz*. Clovelly and Bainsvlei, arranged in two parallel rows under a moveable rain shelter. The soils were irrigated with different water quality treatments and the water uptake from the water table was recharged, by keeping the water table at a constant depth of 1200 mm from the surface, using water with a 25, 150, 300, 450 and 600 mS m^{-1} electrical conductivity. These five water quality treatments (T1 to T5) were replicated three times per soil type.

The crop water uptake of each lysimeter from the 0-600 mm soil layer was calculated as the difference between the drained upper limit (DUL) and the soil water content measured with a neutron probe on a weekly basis. The water deficit was applied as weekly irrigations. Root water uptake from the 600-1200 mm soil layer was recharged by capillary rise from the water table, by applying water from the bottom on a daily basis. For both soils the capillary fringe exceeded 600 mm (Ehlers et al., 2003). Salt accumulation in the soils was therefore based on the assumption that all the salts added through irrigation, and water table recharge, accumulated in the soil, because there was no deep percolation from the lysimeters.

Only one simulation per treatment for both soils was done with the following inputs. Maize was planted on 17 December 2004 with a season length of 138 days and a mean atmospheric demand for the season of 6 mm day^{-1}. Measured yields for the control treatment of the Clovelly and Bainsvlei soils amounted to 14500 and 13000 kg ha^{-1}, respectively, which were used as inputs for all the simulations of the different treatments. Six soil layers, 300 mm thick, were entered with a distribution coefficient of 0.7 and 0.3 for the Clovelly and Bainsvlei soils, respectively. The silt-plus-clay contents ranged from 8 to 9% for the Clovelly soil and from 10 to 24% for the Bainsvlei soil, as described in Ehlers et al. (2007). Measured soil adjustment factors regarding the drainage curve (a and b' values) were used. The electrical conductivity of the different soil layers were set equal to the measured values at the start of the season. The same crop parameters as shown in Table 4.1 were used. Rainfall was zero because a rain shelter was used and the electrical conductivity of the irrigation water and the water table was set equal to the values of the different treatments, *viz.* 25, 150, 300, 450 and 600 mS m^{-1}.

4.4.2 Results and discussion

In the simulations of all the treatments for both soils no salt leaching occurred. All the salts applied through irrigation therefore accumulated in the soil profiles, while salts were distributed upward through water table recharge or capillary rise, which corresponds to the conditions at the lysimeter trial.

To evaluate the accuracy of SWAMP, as described in Section 3.4, in simulating upward and downward salt movement, the measured electrical conductivity of each soil layer for both soils at the end of the season was plotted against simulated results in Figure 4.5. All the differenced-based indices were better than the criteria, while the intercept of the simulated versus measured regression did not significantly differ from 0, which suggests that the estimates were not biased. The slope of the simulated versus measured regression differed however significantly from 1, which shows that the model has a slight tendency to under estimate soil salinity at a specific depth.

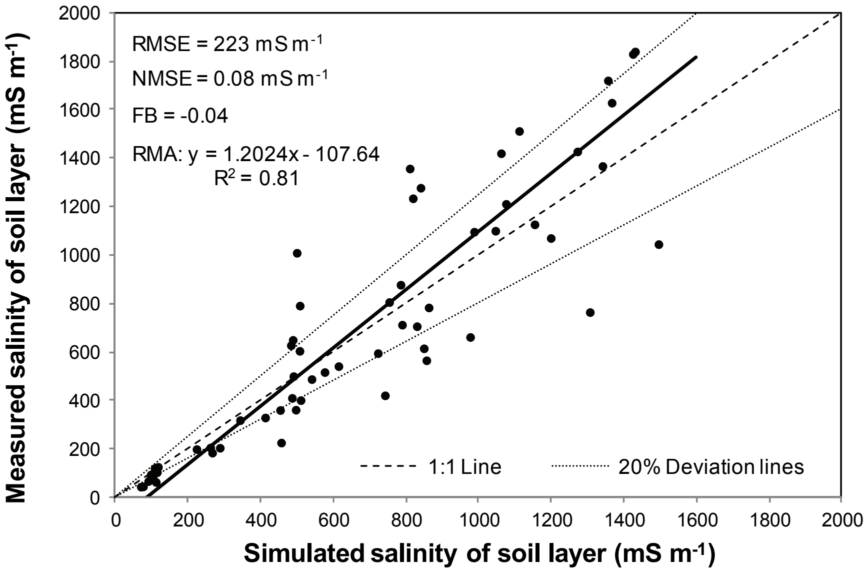


Figure 4.5 Statistical comparison of the electrical conductivity over a depth of 1800 mm ($EC_{e\ 0\text{-}1800}$) at the end of the season, for the lysimeter trial of Ehlers et al. (2007), simulated by SWAMP, against measured results.

The maximum measured yield, mean salinity of the season and evapotranspiration under these conditions, which consist of various soil salinities and water applications, are shown in Table 4.2. The measured evapotranspiration for the various treatments of both soils did not correspond to the irrigation applied. This is as can be expected since the remaining crop water requirement came from the water table, which was at a depth of 1200 mm from the soil surface. Although the soil was kept wet at the drained upper limit, the measured yields decreased drastically with an increase in mean salinity for the season from 14654 to 4264 kg ha^{-1} for the Clovelly soil and from 12618 to 4543 kg ha^{-1} for the Bainsvlei soil. The simulated yields mean salinity for the season and evapotranspiration for all the treatments of both soils, compared well with the corresponding measured values under the same conditions. To obtain a comparison of the decline in yield and evapotranspiration with increasing soil salinity between the measured and simulated values the following procedure was used. The control yield and evapotranspiration value of a soil was taken as 1, and the other treatment values were expressed as fractions of 1 to obtain relative values. The measured relative yield and evapotranspiration values for both soils were plotted against the corresponding simulated values, as shown in Figure 4.6.

Table 4.2 Irrigation, maximum obtainable yield, mean salinity for the season ($EC_{e\ Season}$) and evapotranspiration (ET) for the different treatments as measured by Ehlers et al. (2007), as well as the corresponding simulated results

Soil type	Treatment (EC_i, mS m^{-1})	Irrigation (mm)	Measurements			Simulations		
			Yield (kg ha^{-1})	$EC_{e\ Season}$ (mS m^{-1})	ET (mm)	Yield (kg ha^{-1})	$EC_{e\ Season}$ (mS m^{-1})	ET (mm)
Clovelly	**Control (20)**	**390**	14654	139	800	14132	95	871
	T2 (150)	**352**	13345	489	727	11827	308	772
	T3 (300)	**270**	10587	734	591	8337	542	608
	T4 (450)	**258**	7553	968	483	6115	705	468
	T5 (600)	**233**	4264	1272	381	4370	910	436
Bainsvlei	**Control (20)**	**348**	12618	84	778	12789	84	768
	T2 (150)	**337**	12339	400	761	10761	293	739
	T3 (300)	**254**	10158	721	639	7795	488	549
	T4 (450)	**246**	7596	912	501	5427	687	413
	T5 (600)	**259**	4543	1105	461	3703	920	369

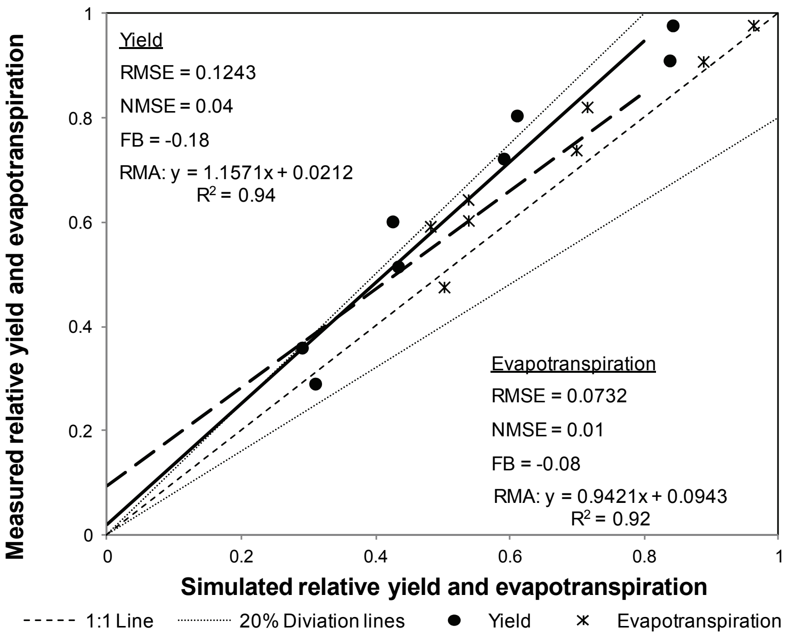


Figure 4.6 Statistical comparison of the measured relative yield and evapotranspiration of Ehlers et al (2007) to corresponding simulations made with SWAMP, under the same conditions.

An excellent comparison between simulated and measured relative yield and evapotranspiration was obtained, as confirmed by the statistical parameters given in Figure 4.6. The differenced-based indices were below the criteria, while the intercept and slope of the regressions did not differ significantly from 0 and 1, respectively. This test is therefore proof that the procedures used in SWAMP to simulate the decline in maize yields and evapotranspiration with an increase in soil salinity corresponded well with real time measured data.

4.5 Validation of the salt leaching subroutine

4.5.1 Inputs and assumptions

The lysimeters used by Ehlers et al. (2007) were, after termination, of their experiments reclaimed by leaching. This was done with irrigation water that had an electrical conductivity of 75 mS m^{-1}, as described in Ehlers et al. (2007). Only the leaching data of the most saline soil profile (Treatment 5), for both soils, were compared to simulations made by SWAMP using the following inputs. A fallow simulation option was chosen with a 50 day leaching period (Ehlers et al., 2007). The measured soil water content at the drained upper limit of both soils and the measured salinity values were entered at the start of the simulations. Five soil layers 300 mm thick were selected, using the measured silt-plus-clay contents. The irrigation inputs consisted of two 50 mm irrigations per week for seven weeks which amounted to a total of 700 mm. A distribution coefficient of 0.95 and 0.8 was used for the Clovelly and Bainsvlei soils, respectively, while EC_{Min} was set equal to the salinity of the irrigation water (75 mS m^{-1}).

4.5.2 Results and discussion

A comparison of the measured and simulated salt concentrations per soil layer for both soils and the seven sampling dates during the leaching experiment, are given in Figure 4.7.

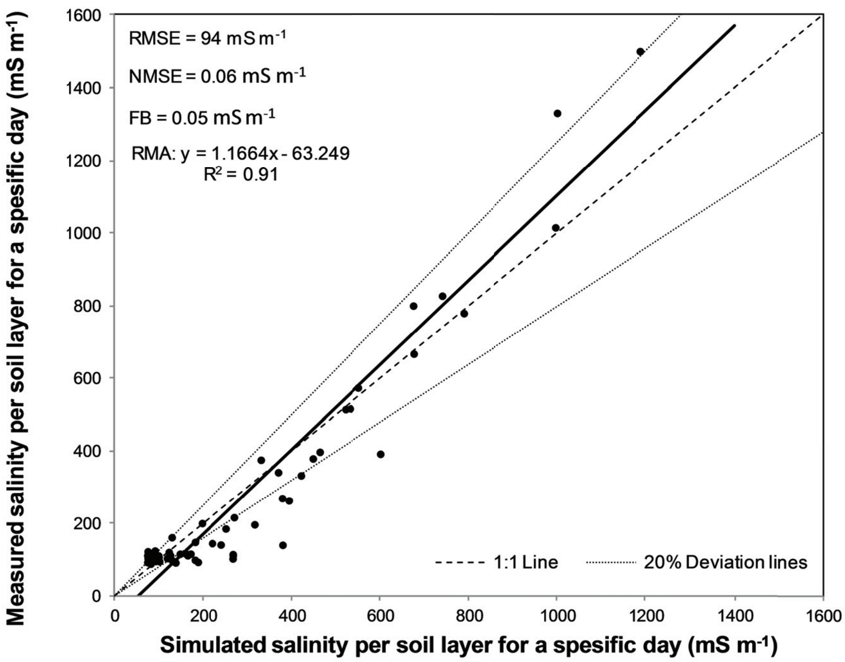


Figure 4.7 Statistical comparison of measured salinities per soil layer of both soils for the most saline soil profiles (Treatment 5) taken seven times during the leaching experiment done by Ehlers et al. (2007), against the values obtained by simulating the leaching experiment.

In the actual experiments soil water was extracted, using ceramic suction cups, installed at depths of 300, 500, 700, 900, 1100 and 1500 mm from the soil surface, and the electrical conductivity of the extracts were determined seven times during the leaching experiment for both soils (Ehlers et al., 2007). Data of only the most pronounced saline soil profile (Treatment 5) for both soils that were leached are shown here. According to the differenced-based and correlation-based analysis, a good comparison between simulated and measured salt concentrations was obtained for both soils, at the selected distribution coefficients. The slope of the simulated versus measured regression differed significantly from 1, which shows that the model has a slight tendency to under estimate soil salinity.

4.6 Applying SWAMP to numerically solve the soil water and salt balance equations

As described in Chapter 3 (materials and methods) various measurements were done at a location within an irrigated field, which was combined with modelling in an attempt to accurately solve the soil water and salt balance for an irrigated field.

4.6.1 Soil water balance

4.6.1.1 Conceptual approach

In order to quantify the soil water balance components, the approach was to set the soil water content at the start of the simulation (day 0) equal to the measured values and keep the depth of the water table constant during the simulation period. Measured weather, soil, rainfall and irrigation conditions at the specific measuring point were entered as inputs in SWAMP, while run-on and runoff was assumed to be negligible. Under water table conditions, simulated by SWAMP, only the measured soil water contents above the capillary fringe can be entered as input values. The soil water contents within the capillary fringe and the water table are calculated as default values by SWAMP from input silt-plus-clay contents. Small differences between the measured and SWAMP-estimated soil water contents at the start of the simulation, were observed. In order to define the boundary conditions and calibrate the model to the CPN neutron probe soil water measurements, the observed difference between the measured and estimated soil water content at day 0, were subtracted from every estimated value during the entire simulation period.

Since the depth of the water table remains constant, water table uptake by the crop as estimated with SWAMP, is recharged through lateral groundwater inflow and/or percolation from the top of the soil downward. As water percolates from the top of the soil downward, it ends up in the water table, from where it is used again through capillary rise into the root zone. The difference between water table uptake and percolation, estimated with SWAMP, represents therefore the net amount of water entering the potential root zone through water table uptake or what is lost through deep percolation (Equation 4.22)

$$\pm \mathbf{D} = \mathbf{WTU_{(e)}} - \mathbf{P_{(e)}} \qquad \mathbf{4.22}$$

where $WTU_{(e)}$ = estimated contribution of water table to water uptake by crop (mm)

$P_{(e)}$ = amount of estimated water percolating from the top of the soil downward, recharging the water table (mm)

$\pm D$ = a positive value is a net gain of water to the soil through upward drainage (+D, mm) or water table uptake, and a negative value a net loss of water from the soil through downward drainage (-D, mm) or deep percolation.

This net amount of water entering or leaving the potential root zone estimated with SWAMP can also be calculated with Equation 4.23, which will be equal to:

$$\pm D = W_{Soil\ (e)} - R_{(m)} - I_{(m)} + E_{(e)} + T_{(e)} \qquad 4.23$$

where $\Delta W_{Soil\ (e)}$ = change in estimated soil water content of the potential root zone (mm)
$R_{(m)}$ = amount of measured rainfall (mm)
$I_{(m)}$ = amount of measured irrigation (mm)
$E_{(e)}$ = amount of estimated evaporation (mm)
$T_{(e)}$ = amount of estimated transpiration (mm).

In order to improve the accuracy of quantifying the soil water balance components for the potential root zone in the field, the measured soil water content and artificial drainage were used, as shown by Equation 4.24.

$$\pm D = W_{Soil\ (m)} - R_{(m)} - I_{(m)} + E_{(e)} + T_{(e)} + AD_{(m)} \qquad 4.24$$

where $\Delta W_{Soil\ (m)}$ = change in measured soil water content of the potential root zone (mm)
$R_{(m)}$ = amount of measured rainfall (mm)
$I_{(m)}$ = amount of measured irrigation (mm)
$E_{(e)}$ = amount of estimated evaporation (mm)
$T_{(e)}$ = amount of estimated transpiration (mm)
$AD_{(m)}$ = amount of measured artificial drainage (mm).

The net amount of water entering or leaving the potential root zone, calculated with Equation 4.24, will however not be equal to the value calculated with Equation 4.22. Percolation from the top of the soil downward, as estimated with SWAMP, was assumed to be a parameter that is not accurately estimated. Through a process of iteration, percolation from the top of the soil downward towards the water table were increased or decreased in order to match values obtained with Equations 4.22 and 4.24, resulting in Equation 4.25.

$$WTU - P_{(i)} = W_{Soil\ (m)} - R_{(m)} - I_{(m)} + E_{(e)} + T_{(e)} + AD_{(m)} \qquad 4.25$$

where $P_{(i)}$ = amount of estimated water percolating from the top of the soil downward determined through iteration (mm).

4.6.1.2 Solution through measurements, calculations and estimations

In Figure 4.8 the measured rainfall, irrigation, soil water content, water table depth and outflow from the artificial drainage, that were used to numerically solve the soil water balance for this specific measuring point, are shown. The crops grown comprised of two wheat and maize seasons including two fallow periods during which the maize crop was drying.

Included in Table 4.3 are the duration of the simulation period (days), the measured yield and harvest index entered in SWAMP, as well as the mean atmospheric demand for the specific season and depth of water table which were kept constant. Measured silt-plus-clay contents at 300 mm depth intervals to a depth of 2000 mm were entered, while the same crop parameters as given in Table 4.1 were used with a rooting depth equal to the depth of the water table.

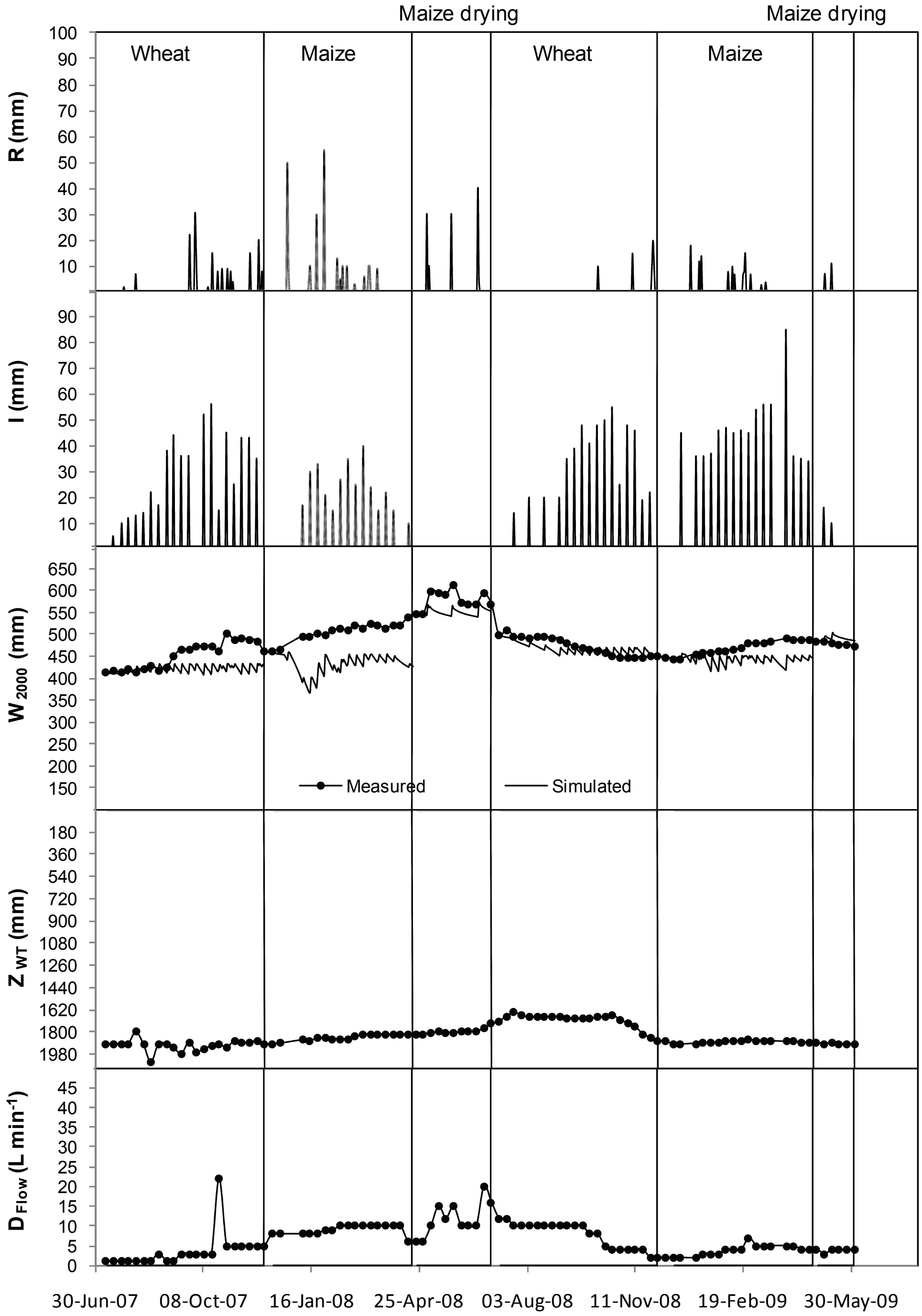


Figure 4.8 Distribution of measured rainfall (R), measured irrigation (I), measured and estimated water content of a 2000 mm deep soil (W_{2000}), measured water table depth (Z_{WT}) and measured flow from a drainage system (D_{Flow}) over two years at a measuring point.

The actual measured water contents of the soil layers were entered at the start of each simulation in SWAMP (Figure 4.7). The results in Table 4.4 show that during the first wheat season, the soil starting with a total water content of 412 mm, received 177 mm rain and 561 mm irrigation, while 198 mm water was taken up by the crop from the water table. Evaporation during the season resulted in a loss of 61 mm and the wheat crop used in total 569 mm as transpiration, while 10 mm drained from the artificial drainage system. Because the depth of the water table remained constant, a total of 248 mm percolated from the unsaturated zone to the water table. From this water a total of 198 mm was used again by the crop through capillary rise. A net total of 50 mm were therefore lost from the potential root zone. Using the same approach the following conclusions can be drawn regarding the other seasons.

Table 4.3 Simulation period (days), measured yield, measured harvest index, mean atmospheric demand for the simulation period and water table depth which were kept constant during the simulation period

Simulation	Wheat	Maize	Maize drying	Wheat	Maize	Maize drying
Days	148	131	71	148	131	36
Yield (kg ha^{-1})	7334	15892	-	6172	16510	-
HI	0.48	0.60	-	0.43	0.6	-
ETo $_{Season}$ (mm day^{-1})	5.44	6.06	3.22	5.25	4.65	2.54
Water table depth (mm)	1900	1895	1820	1711	1895	1890

Table 4.4 Net gain (+D) or loss (-D) of water from the potential root zone (2000 mm) through upward or downward drainage for a measuring point as calculated from the change in soil water content (ΔW_{Soil}), rainfall (R), irrigation (I), evaporation (E), transpiration (T) and artificial drainage (AD) or calculated from water table uptake (WTU) and percolation towards the water table (P)

Simulation		Wheat	Maize	Maize drying	Wheat	Maize	Maize drying
ΔW_{Soil}	**mm**	48	78	21	-49	42	-11
R		177	237	115	65	115	18
I		561	329	0	550	739	26
E		61	38	56	48	39	29
T		569	715	0	516	565	0
AD		10	22	16	23	10	3
± *D*		***-50***	***203***	***-22***	***-77***	***-198***	***-23***
WTU		198	265	0	251	203	0
P		248	62	22	328	401	23

For the second wheat season an excess of 328 mm percolated from the unsaturated zone to the water table. The water table contributed a total of 251 mm to evapotranspiration through capillary rise, which resulted in a net loss of 77 mm from the potential root zone. During the first maize season excess rain and/or irrigation water resulted in a total of 62 mm to percolate to the water table, while water table uptake amounted to a total of 265 mm. This resulted in a subsequent net gain of water to the potential root zone of 203 mm. During the second maize season the opposite occurred with a net loss of water from the potential root zone amounting to 198 mm. The purpose here was to provide a description of the processes followed in quantifying the soil water balance components under water table conditions. Detailed results and conclusions of the soil water balance for this specific measuring point will be provided in chapters to follow.

4.6.2 Salt balance

4.6.2.1 Conceptual approach

In order to quantify the salt balance components, the approach was to set the salt content of the soil at the start of a simulation period equal to the measured values. If no measurements were available, a simulation from the point where measured values are available was first done. The estimated salt content of the soil at the end of this period then provided the values for the start of the specific simulation period.

The net amount of salts that were applied through fertilizers by the farmer was added to the salinity of the first soil layer at the start of the simulation. This amount was obtained by multiplying the amount of fertilizers applied by the farmer during the season with a factor, and subtracting the salts removed by the crop, as explained in Section 3.4. Salinity of the irrigation water and the water table, required as inputs by SWAMP, was taken as the mean measured salinity for the simulation period.

The measured amounts of irrigation and rainfall, which were used as inputs in SWAMP, and the estimated water table uptake were used to calculate the upward and downward movement of salt within the soil profile according to the cascading principle (Section 4.2.2.3). With iteration the distribution coefficient was increased or decreased until the salinity of the soil at the end of the simulation period was equal to the corresponding measured values. The distribution coefficient represents, as explained in Section 4.2.2.3, the ratio between the measured and simulated amounts of salts actually transferred from one layer to another (Equation 4.26):

$$\pm S_D = S_{WTU\ (e)} - S_{P(e)} \qquad 4.26$$

Where $S_{WTU\ (e)}$ = estimated amount of salt added as a result of water table uptake (kg ha^{-1})
$S_{P\ (e)}$ = estimated amount of salt percolating towards the water table (kg ha^{-1})
$\pm S_D$ = a positive value is a net gain of salt to the soil through upward drainage (+D, mm) or water table uptake and a negative value a net loss of salt from the soil through downward drainage (-D, mm) or deep percolation.

This net effect can also be calculated with Equation 4.27, which will be equal to Equation 4.26.

$$\pm S_D = \Delta S_{Soil\ (e)} - S_{F\ (m)} - S_{R\ (m)} - S_{I\ (m)} \qquad 4.27$$

Where $\Delta S_{Soil\ (e)}$ = estimated change in salt content of the soil (kg ha^{-1})
S_F = measured amount of salts applied through fertilizers (kg ha^{-1})
S_R = measured amount of salts applied through rainfall (kg ha^{-1})
S_I = measured amount of salts applied through irrigation (kg ha^{-1}).

To improve the accuracy of quantifying the components of the salt balance for the potential root zone in the field, the measured amount of salts removed through artificial drainage was included in Equation 4.27. The estimated and measured change in salt content of the soil for the simulation period will be equal as a result of using a distribution coefficient, as explained earlier. Equation 4.27 changes to Equation 4.28:

$$\pm S_D = \Delta S_{Soil\ (m)} - S_{F\ (m)} - S_{R\ (m)} - S_{I\ (m)} + S_{AD\ (m)} \qquad 4.28$$

Where S_{AD} = measured amount of salts removed though artificial drainage (kg ha^{-1}).

Combining Equation 4.26 and Equation 4.28, result in Equation 4.29:

$$\mathbf{S_{WTU}\text{-}P_{(i)} = \Delta S_{Soil\,(m)}\text{-}S_{F\,(m)}\text{-}S_{R\,(m)}\text{-}S_{I\,(m)}\text{+}S_{AD\,(m)}} \qquad \mathbf{4.29}$$

Where $P_{(i)}$ = amount of estimated salt percolating towards the water table that was adjusted to accommodate measured artificial drainage (kg ha^{-1}).

4.6.2.2 Solutions through measurements, calculations and estimations

Figure 4.9 shows the change in measured mean electrical conductivity of the soil (0-2000 mm), simulated mean electrical conductivity of the soil, measured electrical conductivity of the irrigation water and measured electrical conductivity of the water table during the two year measuring period for the same measuring point as shown in Figure 4.8.

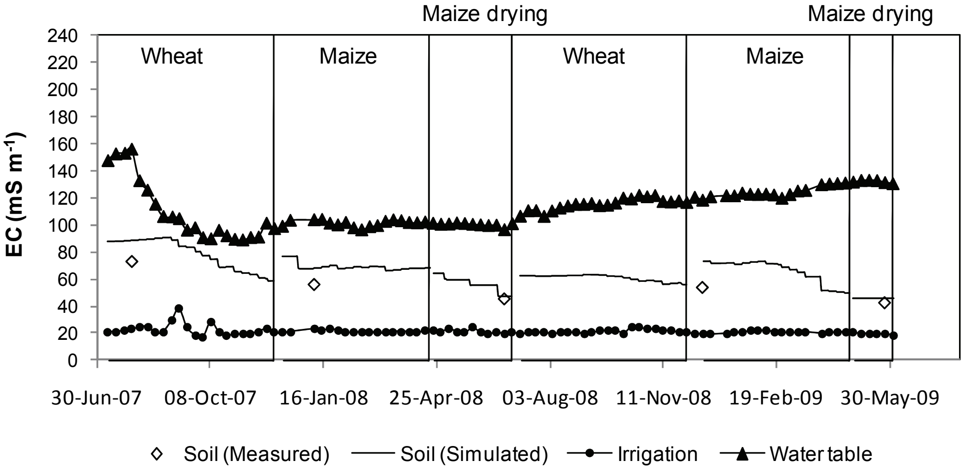


Figure 4.9 Measured mean electrical conductivity (EC) of the soil, simulated mean electrical conductivity of the soil, measured electrical conductivity of the irrigation water and measured electrical conductivity of the water table during the two year measuring period for the same measuring point as shown in Figure 4.7.

The simulated soil salinity corresponds well to the measured soil salinity during the entire measuring period of two years. The slight difference between measured and simulated soil salinity at the start of each season is attributed to the net amount of salts applied through fertilizers.

Table 4.5 shows that during the first wheat season a total of 387 and 952 kg ha^{-1} of salts were added through the application of fertilizers and rainfall-plus-irrigation, respectively. The water table supplied an additional 1633 kg ha^{-1} to the potential root zone, while 3666 kg ha^{-1} was transported towards the water table. This resulted in a net total loss of salt from the potential root zone, during the first wheat season, of 2033 kg ha^{-1}, decreasing the salt content of the soil by 781 kg ha^{-1} over the length of the season. For the first maize season, after the application of a total 1100 kg salts ha^{-1} through fertilizers and rainfall-plus-irrigation, a net 277 kg salt ha^{-1} were gained to the potential root zone through upward drainage resulting in the salt content of the soil to increase by 1151 kg ha^{-1}. During the fallow maize drying period the salt content of the soil was decreased by 1730 kg ha^{-1} of which 1593 kg salts ha^{-1} were removed by percolation. For the second wheat, maize and maize drying period, a net total of 658, 1263 and 239 kg ha^{-1} of salts were removed by leaching, respectively. This was insufficient because the salt content of the soil increased by 281 and 186 kg ha^{-1} during the second wheat and maize seasons. During the second maize drying period the salt content of the soil decreased by 225 kg ha^{-1}. As with the soil water balance the aim here was to describe, through example, the quantification of the salt balance components under water table conditions. Detailed results and conclusions of the salt balance for this specific measuring point will be provided in Chapter 5.

Table 4.5 Net gain (+S_D) or loss (-S_D) of salt from the potential root zone (2000 mm) through upward or downward drainage for a measuring point as calculated from the change in salt content of the soil (ΔS_{Soil}), salt from rainfall (S_R), salts from irrigation (S_I), net amount of salts from fertilizers (S_F) and salts from artificial drainage (S_{AD}) or calculated from salt transport through water table uptake (S_{WTU}) and salt transport through percolation towards the water table (S_P)

Simulation		**Wheat**	**Maize**	**Maize drying**	**Wheat**	**Maize**	**Maize drying**
$\Delta \mathbf{S_{Soil}}$	kg ha^{-1}	-781	1151	-1730	281	186	-225
$\mathbf{S_F}$		387	448	0	286	419	0
$\mathbf{S_{R+I}}$		952	652	17	876	1126	44
$\mathbf{S_{AD}}$		87	225	154	223	96	29
$\pm S_D$		***-2033***	***+277***	***-1593***	***-658***	***-1263***	***-239***
$\mathbf{S_{WTU}}$		1633	2004	0	2161	1887	0
$\mathbf{S_P}$		3666	1727	1593	2819	3150	239

4.7 Conclusions

This chapter provided valuable insight into the upward and downward movement of water and salt in the potential root zone due to rainfall, irrigation, evaporation, transpiration, capillary rise and drainage as estimated with the SWAMP model. The mathematical algorithms describing these processes were reviewed first, while the effect of this upward and downward movement of water and salt on crop growth and yield were also provided. Verification of SWAMP under non-saline and saline conditions was done in order to finally apply the model to numerically solve the soil water and salt balance equations for a measuring point. SWAMP basically uses the cascading principle in transporting water and salt up and down in the potential root zone, while the effect of water deficit and salinity on crop growth and yield are described by the layer water supply rate. The approach is based on the principle that drying of a soil layer is proportional to its potential water supply rate, which depends on its water content and salinity.

Differenced-based and correlation-based analysis of measured versus estimated evapotranspiration and soil water content data confirmed validations under non-saline conditions as reported by Bennie et al. (1998) and Ehlers et al. (2003). It was concluded that the model can accurately estimate the transport of salt into and out of the potential root zone as well as the effect of salt accumulation on transpiration and yield. From these findings it can therefore be concluded that the model can be used successfully to numerically solve the soil water and salt balance equations for a measuring point as well as be used in simulations in order to assess the long-term effect of crop selection under irrigation, response of soils to irrigation, suitability of irrigation water and irrigation scheduling.

CHAPTER 5
ASSESSING CROP SELECTION UNDER IRRIGATION

5.1 Introduction

Crop yield under irrigation, with regard to irrigation-induced salinity, is influenced by a complex interaction of topographical, meteorological, biological, edaphic (soil- and water-related) and anthropogenic (management) conditions. Due to the range of crops varying in salt tolerance, farmers have the opportunity to select crops that will produce satisfactorily under given soil, water and management conditions and those expected to occur during the growing season.

This strategy is however complicated by increasing pressure on farmers to deliver produce on a continuous basis at affordable prices, and of the highest quality to consumers without damaging the environment. Farmers compete not only nationally but also internationally within highly volatile and aggressively contested world commodity markets. In addition end users are persistent in their opinion that produce needs to be safe for consumption. From a farming perspective these demands resulted in crop choices and rotation systems, especially with regard to the semi-arid central part of South Africa, that are based mostly on economic stability with little emphasis on sustainable water and salt management.

According to the Water User Associations of Orange-Riet and Vaalharts Water, farmers in these regions grow mainly wheat, maize and lucerne. Other crops also planted in these study areas, but on a much smaller scale are barley, groundnuts, peas, cotton, potatoes, pecan nuts and grapes.

Given the fact that the total yield of any of these crops in succession, for a given year, is higher than for a single crop, double cropping is a popular crop rotation system under irrigation. Double cropping involves the harvesting of two successive crops per year (Vigel & Nielsen, 1998) and are a popular practice because the rotation system provides an opportunity to increase land productivity and conservation principles. It’s often combined with dual plantings, where two crops are simultaneously cultivated but on different portions of a field, which is promoted amongst farmers as a strategy for reducing peak water demand. Double cropping creates longer crop intervals (how frequently the crop is grown), which is an important conservation principle to sustain economical yield in the long term (Peterson & Varvel, 1989; Lund et al., 1993; Porter et al., 1997).

A problem associated with intensive cropping systems under irrigation is that of increasing soil salinity resulting in reduced crop growth and yield. Salt accumulation in the potential root zone of specific crops, beyond the threshold salinity, can however be managed. Essentially these management practices involve measures controlling water and salt addition and/or removal from the potential root zone for a selected crop (Van Schilfgaarde, 1990; Letey, 1994; Rhoades, 1997; Hillel & Vlek, 2005). Additionally the yield versus salt concentration response curve of crops can be modified by different fertilizer applications, irrigation methods and frequencies, and a combination of soil, water and environmental factors (Meiri & Plaut, 1985). The problem, however, with this approach is that farmers require specialised skills and knowledge in applying the management practices necessary to alter the yield versus salt concentration response curve for a selected crop. It is therefore easier to manage the water and salt addition and/or removal from the potential root zone, which also governs the off-site environmental impacts of irrigation and drainage.

Unfortunately little evidence suggests that farmers are looking at crop choices and rotation systems from the perspective of sustainable water and salt management practices. This is probably because the negative effects, associated with irrigation-induced salinity, are only gradually growing in importance. However as conservation and water demand management policies in South African irrigated agriculture continues to gain importance (Pott et al., 2009), pressure is escalating on users to become more water use efficient. This increasing emphasis on more efficient water use has emphasised the importance of crop choices and rotation systems, because root zone salt accumulation becomes more prominent with more efficient water use and less leaching of salts by over-irrigation.

The first objective in this chapter will be to assess the effect of popular crop selection and rotation systems presently used at Orange-Riet and Vaalharts on soil salt and water regimes under different conditions. This will be done in order to determine the principle mechanisms involved in ensuring sustainable water and salt management, with regard to crop choices and rotation systems. Secondly the long-term effect of optimal water and salt management practices on specific crop selections will be assessed without consideration of the socio-economic effects.

5.2 Methodology

5.2.1 Experimental approach

Firstly results obtained from *in situ* measuring points will be used to assess different water and salt management practices under current crop rotation systems and irrigation scheduling practices on sandy loam soils with shallow water tables. Secondly simulations will be used in order to show the effect of improved or optimal water and salt management practices on soil salinity and yield under different crop rotation systems for sandy loam soils with and without water tables. With optimal water and salt management, an attempt was made to apply only the specific crop water requirement for the various crops, in order to obtain a maximum potential yield. Sandy loam soils were chosen as they are extensively irrigated at Orange-Riet and Vaalharts.

5.2.2 *In situ* assessment

5.2.2.1 Perspective on agronomic practices

The materials and methods of the on-farm measuring points that were used to obtain realistic information on farming practices at Orange-Riet and Vaalharts, were discussed in Chapter 3. From this the agronomical practices were summarized as follows.

Winter crops grown during the study period consisted of mainly wheat, barley and peas, while maize, groundnuts and cotton were planted in the summer. Crop rotation systems employed by farmers consisted of mainly double and fallow cropping. With double cropping a wheat – maize rotation was planted alternately for two years, or only for one year where after either wheat or maize were replaced by barley and groundnut, respectively, in the second year. Fallow crop rotation systems consisted mainly of producing three crops combined with one fallow period over two years (Table 5.1).

Details on general agronomical practices employed by farmers in the study areas obtained from data of the different measuring points, are summarised in Table 5.2. In these study areas, wheat, barley and peas were generally planted in June or July, while maize and groundnuts were planted in October, November or December. Seeding densities for wheat, barley and peas varied between 75 and 150 kg ha^{-1} with a mean of 104 kg ha^{-1}, while the mean plant density for maize was 83 000 plants ha^{-1} which varied between 74 000 and 100 000 plants ha^{-1}. Between 114 and 156 kg seed ha^{-1} were planted for groundnuts with a mean of 130 kg ha^{-1}, while for cotton only 18 kg seed ha^{-1} was planted. For all the measuring points a mean total of 222, 149 and 93 kg ha^{-1} nitrogen were applied for wheat, barley and peas, respectively, while maize, groundnuts and cotton received a mean total between the measuring points of 251, 149 and 247 kg ha^{-1}, respectively.

Table 5.1 Summary of crop rotation systems employed by farmers during the period July 2007 to July 2009 at the various measuring points located on farms within Orange-Riet and Vaalharts Irrigation Schemes

Crop rotation system	**1st Year (2007-2008)**	**2nd Year (2008-2009)**
Double cropping	Wheat – Maize	Wheat – Maize
	Wheat – Maize	Barley – Maize
	Wheat – Maize	Wheat – Groundnuts
Fallow cropping	Wheat – Maize	Fallow – Maize
	Wheat – Maize	Wheat – Fallow
	Wheat – Maize	Barley – Fallow
	Wheat – Maize	Fallow – Groundnuts
	Wheat – Maize	Fallow – Cotton

Table 5.2 Summary of agronomic practices used by farmers during the period July 2007 to July 2009 at the various measuring points located on farms within Orange-Riet and Vaalharts Irrigation Schemes

Season		**Winter**			**Summer**		
Crop		Wheat	Barley	Peas	Maize	Groundnuts	Cotton
Botanical name		*Triticum aestivum*	*Hordeum vulgare*	*Pisum sativum*	*Zea Mays*	*Arachis hypogaea*	*Gossypium hirsutum*
Planting date		June July	July	July	October December	November December	December
Plant density (kg ha^{-1})	**Mean**	112	82	120	83 167	130	18
	SD	26	12	-	10 962	19	-
Total N (kg ha^{-1})	**Mean**	222	149	93	251	149	247
	SD	40	18	-	35	32	-
Total P (kg ha^{-1})	**SD**	35	32	17	31	35	33
	SD	11	9	-	6	16	-
Total K (kg ha^{-1})	**Mean**	37	43	50	41	42	52
	SD	18	11	-	8	11	-

SD = standard deviation

Phosphate application varied between 15 and 66 kg ha^{-1} with a mean of 33 kg ha^{-1} between the measuring points for all the crops, while potassium amounted to a mean of 40 kg ha^{-1} and varied between 7 and 67 kg ha^{-1}.

5.2.2.2 Description and location of selected measuring points

The two measuring points (v6 and v7) that were selected represents a dual cropping system where two successive double crop rotations were established on the one half of the field and a double crop rotation (wheat-maize) followed by a winter fallow-groundnuts rotation on the other half of the field (Figure 5.1). Thus, two crops were simultaneously cultivated under the centre pivot in three of the four seasons. It was decided to select these measuring points since they represent most of the popular crop choices (wheat, maize, peas, groundnuts and cotton), rotation systems (double and fallow cropping) and agronomic practices at Orange-Riet and Vaalharts.

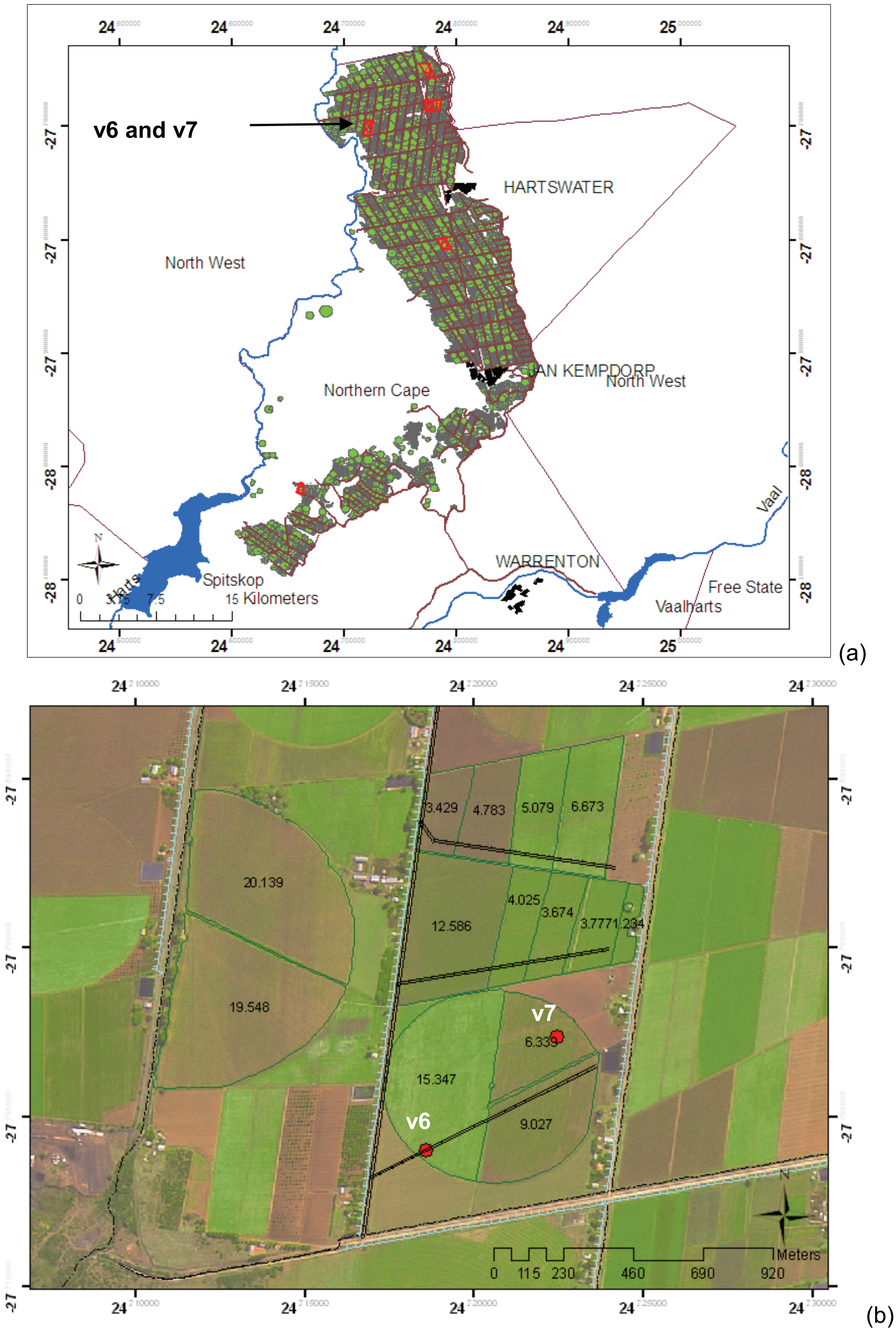


Figure 5.1 Geographical positions of measuring point v6 and v7 within Vaalharts Irrigation Scheme (a) and location of the measuring points on the irrigated field (b).

The irrigated field was located in K-block within the north canal section of the Vaalharts Irrigation Scheme (Figure 5.1a). For the two year duration of the study period, the area under the centre pivot was divided into halves as indicated in Figure 5.1b. On the western side (v6), production was directed to harvest two crops per year, peas and groundnuts in the first year and wheat and cotton in the second year, thus, a consecutive double cropping rotation named the PGWC rotation. On the eastern half (v7) a wheat-maize double crop was established in the first year, followed by a winter fallow-groundnut rotation in the next year. The rotation system was named WMFG, referring to the first letters of the crops utilized. Thus, dual cropping was practised in three of the four seasons.

The artificial drainage lateral of v6 is approximately 760 m in length, but was unfortunately blocked during the entire measuring period. The drainage lateral conveys water in a westerly direction to a central drainage pipe which then further transports the effluent to the main concrete drainage canal located to the south.

The soil was classified as a deep Hutton form and Stella family with a fluctuating water table. The mean silt content, clay content, bulk density, saturated hydraulic conductivity, pH_{Water}, cation exchange capacity, electrical conductivity of a saturated extract and sodium adsorption ratio of a saturated extract for soil samples taken at the start of the measuring period are presented in Table 5.3.

Table 5.3 Mean silt content, clay content, bulk density (ρ_b), saturated hydraulic conductivity (K_{Sat}), pH_{Water}), cation exchange capacity (CEC), electrical conductivity of a saturated extract (EC_e) and sodium adsorption ratio of a saturated extract (SAR_e) for soil samples taken at the start of the measuring period for measuring points v6 and v7

Soil properties	**Soil depth (mm)**						**Mean**
	0-300	**300-600**	**600-900**	**900-1200**	**1200-1500**	**1500-1800**	
Silt (%)	4.60	5.30	4.70	4.40	4.10	8.00	**5.18**
Clay (%)	5.30	4.70	7.00	6.70	7.30	9.00	**6.67**
ρ_b (kg m^{-3})	1.776	1.758	1.766	1.780	-	-	**1.770**
K_{Sat} (mm h^{-1})	15.67	11.78	9.95	-	-	-	**12.47**
pH_{Water}	7.03	7.40	7.93	8.00	8.00	7.55	**7.65**
CEC (cmol$_c$ kg^{-1})	4.87	4.47	3.03	2.67	2.47	6.05	**3.93**
EC_e (mS m^{-1})	78.00	50.00	64.00	90.00	81.00	90.00	**75.50**
SAR_e	1.20	1.80	2.00	2.90	3.40	3.00	**2.38**

Details on the agronomical practices are summarised in Table 5.4. Accordingly the farmer used conventional tillage techniques for land preparation, i.e. mouldboard plough as the primary cultivation method supported by a deep rip cultivation before the planting of groundnuts and cotton. The disc plough was used to mix excess residue into the soil. A tine cultivator (tiller) was used for final seed bed preparation. Wheat residue was either burnt or mixed into the soil with a disk or mouldboard plough depending on the time available before the next planting. High value residue (peas and groundnuts) were baled and removed from the field. Fertilizer application rates were within the general guidelines as proposed by the Fertilizer Society of South Africa (2007). For wheat, a mean between the two measuring points of 222, 40 and 50 kg ha^{-1} nitrogen, phosphorus and potassium, respectively, was applied, while maize received 225, 33 and 50 kg ha^{-1}, respectively. With respect to nitrogen, phosphorous and potassium, groundnuts received a mean of 136, 31 and 46 kg ha^{-1}, respectively, while 93, 17 and 50 kg ha^{-1}, respectively, for peas was applied and 247, 33 and 52 kg ha^{-1}, respectively, for cotton.

Table 5.4 Summary of agronomic practices followed during the four crop seasons at measuring points v6 and v7

Measuring point v6				
Crop rotation	**Peas**	**Groundnuts**	**Wheat**	**Cotton**
Cultivar	Solara	Aqua	Duzie	-
Planting dates	July 2007	December 2007	June 2008	December 2008
Harvesting dates	14 November 2007	May 2008	1 December 2008	25 July 2009
Planting density	120 kg ha^{-1}	120 kg ha^{-1}	150 kg ha^{-1}	18 kg ha^{-1}
Fertilizer applied	75 kg ha^{-1} MAP (33) 300 kg ha^{-1} KAN (28) 100 kg ha^{-1} KCl (50)	300 kg ha^{-1} 2:3:4 (30) 321 kg ha^{-1} LAN (28)	375 kg ha^{-1} 2:3:4 (30) 325 kg ha^{-1} LAN (28)	75 kg ha^{-1} MAP (33) 412 kg ha^{-1} LAN (28) 103 kg ha^{-1} KCl (50) 250 kg ha^{-1} Ureum (46)
Total kg N ha^{-1}	93	168	209	247
Total kg P ha^{-1}	17	30	38	33
Total kg K ha^{-1}	50	40	50	52
Pest management	Galliant	-	MCPA – 0.5 L ha^{-1} Buctril – 0.75 L ha^{-1}	Treflin – 1 L ha^{-1} Temik – 8 kg ha^{-1} Roundup Metamidofos Thionex Pix Harnas Speedup
Cultivation practices	Maize residue was incorporated with a plough; disc, tiller & plant	Bale residue, plough, rip, disc & plant	Bale residue, tiller cultivator, disc, tiller & plant	Burn, rip, disc & plant - After harvest - Bale residue
Measuring point v7				
Crop rotation	**Wheat**	**Maize**	**Fallow**	**Groundnuts**
Cultivar	Duzzie	Pannar 6126	-	Aqua
Planting dates	12 June 2007	15 Decmber 2007	-	5 November 2008
Harvesting dates	29 November 2007	12 June 2008	-	25 July 2009
Planting density	150 kg ha^{-1}	80 000 plant ha^{-1}	-	114 kg ha^{-1}
Fertilizer applied	182 kg ha^{-1} MAP (33) 720 kg ha^{-1} KAN (28) 100 kg ha^{-1} KCL (50)	150 kg ha^{-1} MAP (33) 335 kg ha^{-1} LAN (28) 100 kg ha^{-1} KCL (50) 250 kg ha^{-1} Ureum (46)	-	150 kg ha^{-1} MAP (33) 309 kg ha^{-1} LAN (28) 103 kg ha^{-1} KCL (50)
Total kg N ha^{-1}	222	225	-	104
Total kg P ha^{-1}	40	33	-	33
Total kg K ha^{-1}	50	50	-	52
Pest management	-	Eptam	-	Treflin – 1 L ha^{-1} Temik – 6 kg ha^{-1} Harnas – 1 L ha^{-1} Hammer – 0.3 L ha^{-1} Punch Duet Bio-buffer
Cultivation practices	Plough, tiller & plant	Bale residue, plough, disc, tiller & plant	Mower, disc plough	Disc, plough, tiller & plant - After harvest - Bale residue

5.2.3 Desktop assessment

All the simulations were done with the verified model (Chapter 4) SWAMP (Bennie et al., 1998) for the period 1980 to 1999. The following assumptions were made and inputs used.

5.2.3.1 Crop choices and rotation systems

Four popular crop rotation systems were simulated as indicated in Table 5.5, based on information obtained from the farmers (Section 5.2.2.1). The different dates for starting and ending the simulation periods (season lengths), which represents the number of days from planting until the crop is physiologically mature are also presented.

Table 5.5 Crop choices and rotation systems used in simulating the long-term effect of improved irrigation scheduling on water and salt management

Crop Rotation	Crop	Simulation period (days)		Date
cr1	Wheat	Growing Season	148	5 July – 30 November
	Maize	Growing Season	131	15 December – 24 April
		Drying Period	70	25 April – 4 July
cr2	Wheat	Growing Season	148	20 June – 15 November
	Maize	Growing Season	131	5 December – 15 April
		Drying Period	64	16 April – 19 June
	Wheat	Growing Season	148	20 June – 15 November
	Groundnuts	Growing Season	165	30 November – 14 May
		Drying Period	35	15 May – 19 June
cr3	Wheat	Growing Season	148	5 July – 30 November
	Maize	Growing Season	131	15 December – 24 April
		Drying Period	70	25 April – 4 July
	Peas	Growing Season	131	5 July – 13 November
		Drying Period	30	14 November – 14 December
	Maize	Growing Season	131	15 December – 24 April
		Drying Period	70	25 April – 4 July
cr4	Wheat	Growing Season	148	5 July – 30 November
	Maize	Growing Season	131	15 December – 24 April
		Drying Period	70	25 April – 4 July
	Fallow	Fallow Period	101	5 July – 14 October
	Cotton	Growing Season	180	15 October – 13 April
		Drying Period	81	14 April – 4 July

Crop rotation 1 (cr1) represents double cropping where two crops, wheat and maize, are planted alternately every year, which results in the system repeating itself every second year. With this rotation system wheat is planted in early July and harvested in early December, where after late maize is planted in mid-December. Although maize is physiologically mature by late April or early May, it is only harvested late in June (Drying period). The lack of crop diversity in crop rotation 1 can result in a severe infestation of the "Take-all" fungus (*Gaeumannomyces graminis var. Tritici*) during the wheat seasons.

To overcome this problem crop rotation 2 (cr2) was introduced, which applies the same double cropping principle, but with a bit of diversity. Here wheat and maize are planted in the first year followed by wheat and groundnuts in the second year, which results in the crop rotation system repeating itself every third year.

Crop rotation 3 (cr3) is essentially the same as cr2, the only difference being that here maize is planted more often as opposed to wheat. With this crop rotation wheat and maize are planted in the first year followed by peas and maize in the second year, which means that wheat, is substituted by peas in the second year.

Crop rotation system 4 (cr4) is a combination of double and fallow cropping, where two crops, wheat and maize, are grown during the first year followed by only one crop (cotton) in the second year. Here the crop rotation system repeats itself every third year, with a long fallow period during the second year.

The drying and subsequent harvest period of all the different crops, which is longer than 15 days, was simulated as a drying (fallow) period since salt leaching could occur during these periods. If these periods are shorter than 15 days no simulation occurred since long-term weather station data showed no significant rainfall events during these shorter periods.

5.2.3.2 Soil conditions

The Hutton soil form and Stella family of measuring point v6 and v7 were selected for all the simulations, as this type of soil is found extensively at both the Orange-Riet and Vaalharts Irrigation Schemes. Seven soil layers were selected with a total depth of 2000 mm. The silt-plus-clay content ranged from 11 to 13%. Volumetric soil water content for the seven soil layers at the start of each crop rotation system simulation was 0.083, 0.144, 0.287, 0.309, 0.326, 0.346 and 0.348 mm mm^{-1}, respectively, while the salt content was 57, 39, 64, 113, 154, 154 and 154 mS m^{-1}, respectively. These values represent the measured volumetric soil water contents and salt concentrations at the end of the maize season for measuring point v7.

A constant water table was selected at a depth of 1800 mm from the soil surface with an electrical conductivity of 165 mS m^{-1}, which is the mean value measured during the measuring period. The salt distribution coefficient (0.49) that was selected corresponded to the mean value determined in quantifying the water and salt balances of measuring point's v6 and v7, as explained in Chapter 4.

Salts added to the soil as a result of fertilizers were applied to the first soil layer only at the start (day 0) of each crop's growing season simulation. The amount of salts added was calculated as explained in Chapter 3 with Equation 3.7. For wheat, maize groundnuts, peas and cotton 686, 716, 381, 541 and 724 kg salts ha^{-1}, were added to the soil during each growing season, respectively.

5.2.3.3 Meteorological parameters

Weather data were obtained from the Agricultural Research Council's Institute Soil, Climate and Water (ARC-ISCW) in Pretoria for the period 1980 to 1999 for weather station Vaalharts (computer number 19847, latitude -27.95, longitude 24.833 and altitude 1175 m) located within Vaalharts Irrigation Scheme. Daily evaporative demand (ET_o) of the atmosphere was calculated according to Allen et al. (1998) from maximum and minimum temperature, maximum and minimum relative humidity, wind speed and actual sunshine hour data. This daily calculated evaporative atmospheric demand and rainfall data were imported into SWAMP for the 20 year period.

5.2.3.4 Irrigation

In order to ensure optimal water use by the different crops, irrigation was calculated by using the potential crop water requirement sub-routine of SWAMP. With this approach no provision was made for over-irrigation, thus optimizing the application of irrigation water. The transpiration requirement for maximum production was calculated with Equation 5.1:

$$T_m = ET_o(\frac{Y_m}{m}) \quad \textbf{5.1}$$

Where T_m = transpiration requirement for maximum biomass production (mm)
Y_m = maximum biomass production (kg ha^{-1})
m = crop specific factor
ET_o = mean evaporative demand for the growing season (mm day^{-1}).

The mean evaporative demand of the atmosphere during the growing season of the different crops was obtained from long-term data (22 years) of weather station Vaalharts, which together with the crop specific factor and maximum biomass production are shown in Table 5.6. Equation 5.2 was used subsequently to calculate the total seasonal crop water requirement given a specific target seed yield or biomass production. The target seed yields and harvest indices used to convert seed yield to total biomass production for the various crops, are shown in Table 5.6. The seed yields for the various crops represent regional mean values for which most of the farmers are aiming:

$$CWR = T_m - \left[T_m\left(1-\frac{Y_a}{Y_m}\right)\right] \quad \textbf{5.2}$$

Where CWR = total season crop water requirement (mm)
Y_a = specific target biomass production (kg ha^{-1})

Table 5.6 Mean evaporative demand of the atmosphere for the growing season (ET_o), maximum biomass production for the specific crop (Y_m), crop specific factor (m), transpiration requirement for maximum biomass production (T_m), specific target or actual biomass production (Y_a) and total season crop water requirement (CWR) used in calculating the irrigation requirement for the various crops used in the simulations

Crop	**Wheat**	**Maize**	**Peas**	**Groundnuts**	**Cotton**
Mean ET_o (mm day^{-1})	4.40	5.66	4.70	5.66	5.70
Y_m (kg ha^{-1})	20000	26300	9400	14450	18600
m	145	220	71	143	184
T_m (mm)	607	677	583	572	576
Target seed yield (kg ha^{-1})	6500	13000	4000	4000	5000
Harvest index	0.47	0.55	0.40	0.30	0.27
Y_a (kg ha^{-1})	13889	23636	10000	13333	18519
CWR (mm)	421	608	620	572	574

Daily crop water requirement for the various crops was calculated by distributing the total seasonal crop water requirement throughout the growing season with a generated growth curve equation (Bennie et al., 1998). The crop parameters that were used to represent the different stages of crop development are the same as in Table 4.1 (Chapter 4).

Irrigation was assumed to take place once a week, or every seven days, for all the various crop simulations. The daily crop water requirements for these seven day periods for all the crops were subsequently added in order to calculate the amount of irrigation for that specific irrigation event. If rain occurred during any of these seven day periods the irrigation amount was reduced accordingly. When more rain than crop transpiration occurred for any of the seven day periods, no irrigation would take place. The mathematical algorithms used to calculate the timing and amount of irrigation for the 20 year period were programmed separately in Microsoft Excel, which were then imported into SWAMP. An electrical conductivity of 2 mS m^{-1} for rainfall and 65 mS m^{-1} for irrigation water was used, which represents the mean values measured at the various measuring points within Vaalharts during the study period.

5.2.3.5 Simulation procedures

Basically, each crop rotation system was repeatedly simulated from 1980 to 1999. The same soil conditions, as discussed before, were used at the start (1980) of each crop rotation simulation, because wheat was the first crop in all the crop rotation systems. For the start of the next crop growing season, drying period or fallow period simulation, depending on the crop rotation systems, the volumetric soil water content and salt concentration at the end of the previous simulation was used. This process was repeated for the entire period (1980-1999) in order to generate a data set for continuous crop production under these conditions, for the different crop options.

5.3 Results and discussion

5.3.1 *In situ* assessment

Although there are many factors that influence the productivity of irrigation fields, water management often takes centre stage in achieving sustainable production levels. The discussion therefore is dedicated to the following focal points: irrigation and crop water stress, irrigation and water conservation, yield and water use efficiency, and peak water supply during the growing seasons.

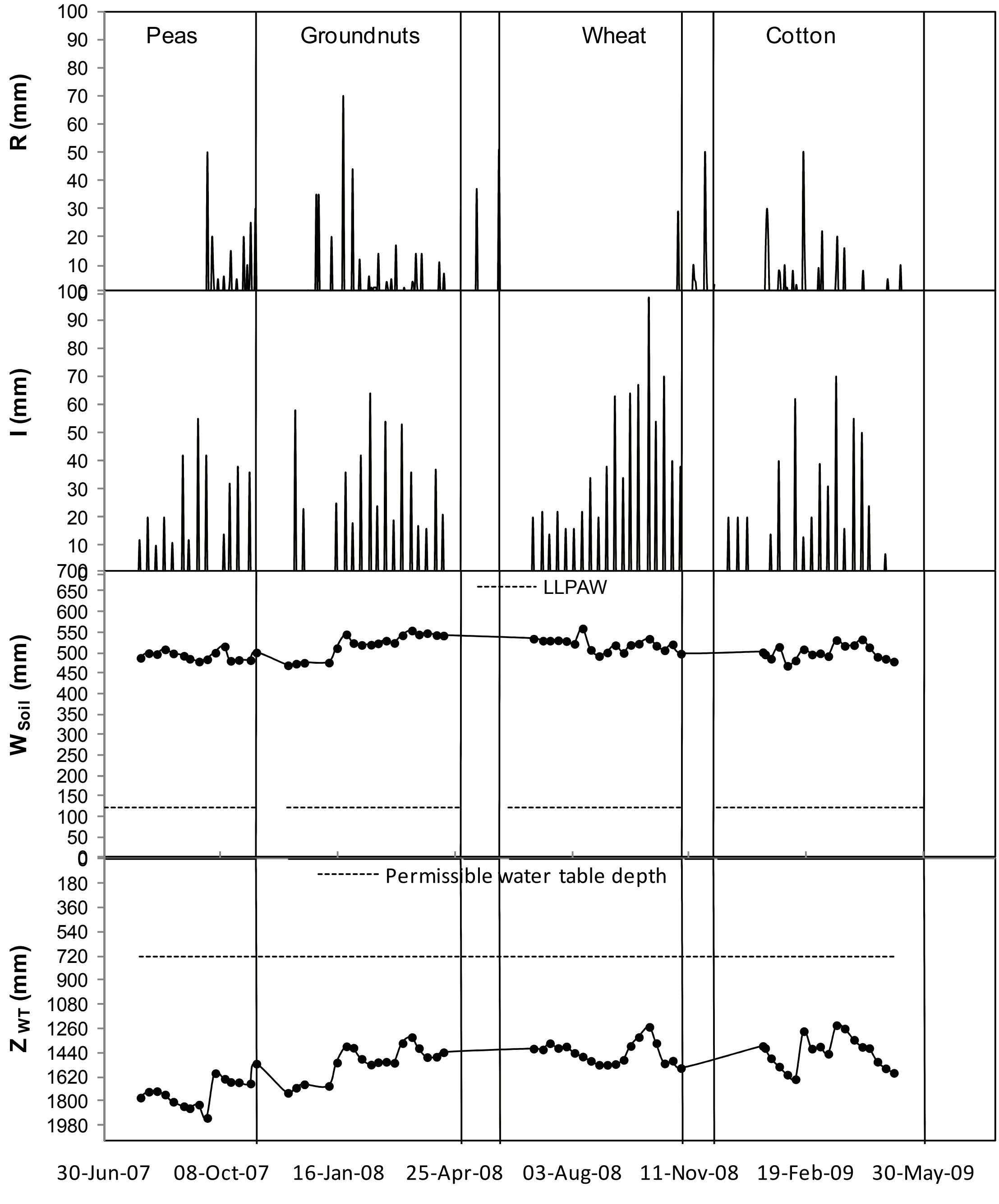
Details on water-related aspects during the seasons are depicted in Figure 5.2a for measuring point v6 and Figure 5.2b for measuring point v7. Results on the seasonal soil water balance are summarised in Table 5.7 for measuring point's v6 and v7.

5.3.1.1 Irrigation scheduling and crop water stress

The farmer did not use any irrigation scheduling services or engage in modern soil water monitoring equipment to facilitate his decision making about when and how much water to irrigate. Instead, he used the augur-and-feel method to estimate soil wetness. Soil samples were augured over a depth of about 1 m.

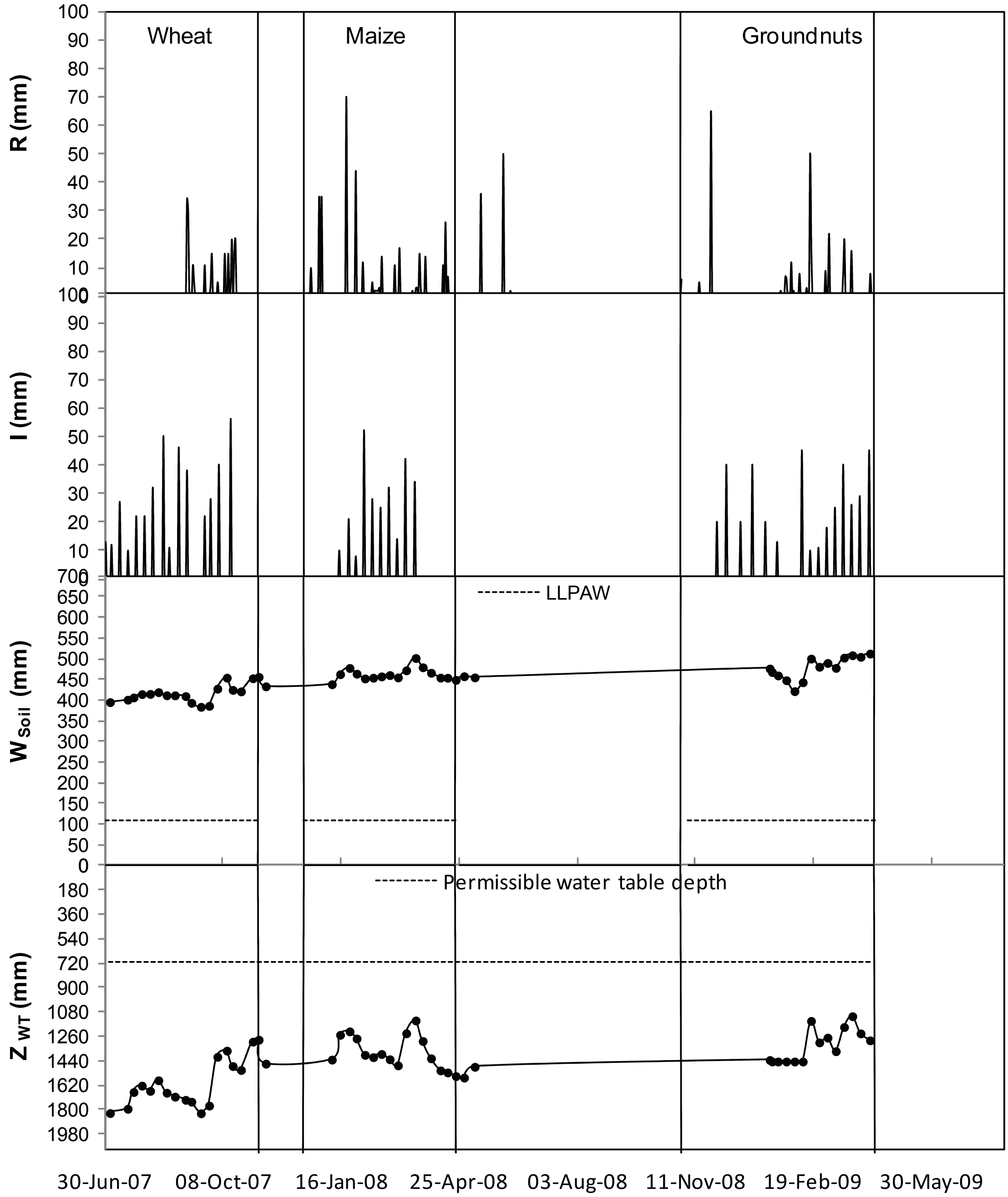
This method was probably effective for avoiding crop water stress as can be seen in Figure 5.2 when the soil water content is compared relative to the lower limit of plant available water level, estimated with SWAMP. The actual soil water contents were much higher than the lower limit in all the seasons, irrespective of the rotations. Consequently, there was no potential risk of crop water stress, due to a lack of water supply, during any of the growing seasons. The presence of an artificial drainage system is enough proof that waterlogging is a potential threat to crop production on this plot, especially in the light of the fact that the drainage system was blocked. In spite of the blockage, the water table remained deeper than the permissible water table depth norm of 720 mm, during the entire study (Figure 5.2).

Ehlers et al. (2003) observed that the soil pores within the capillary zone has a mean saturation of 85% which could result in oxygen deficient conditions. The max height of capillary rise of 720 mm for these soils as estimated by Ehlers et al. (2003) was used as the permissible water table depth. The graphs showed further that the water table fluctuated between 1000 and 1800 mm from the surface in the eastern half, and between 1200 and 1980 mm in the western half. From these results it can be concluded that the crops were not subjected to waterlogging during the study period.



(a)

Figure 5.2 Rainfall (R), irrigation (I), soil water content of a 2000 mm profile (W_{Soil}), water table depth (Z_{WT}), lower limit of plant available water (LLPAW) and permissible water table depth for measuring point v6 (a) and v7 (b).



(b)

Figure 5.2 continued.

5.3.1.2 Irrigation and water conservation

Despite the erratic nature of the rainfall, it has played a huge role in the supply of water during growing seasons. For example, the contribution of rain to the total evapotranspiration of the successive crops in the PGWC rotation amounted to 38, 71, 6 and 63%, respectively, and for the crops in the WMFG rotation the percentage were 36, 76 and 80%, respectively. Irrigation on the other hand contributed to 64, 116, 150 and 116% of the total evapotranspiration of the crops in the PGWC rotation, respectively, and 78, 58 and 124% in the WMFG rotation, respectively. From this it is clear that there was a gross over irrigation in most seasons, especially for the broadleaf crops.

Table 5.7 Net gain (+D) or loss (-D) of water from the potential root zone (2000 mm) through upward or downward drainage for measuring points v6 and v7 as calculated from the change in soil water content (ΔW_{Soil}), rainfall (R), irrigation (I), evaporation (E), transpiration (T) and artificial drainage (AD) or calculated from water table uptake (WTU) and percolation towards the water table (P)

Measuring point	Crop	ΔW_{Soil}	R	I	E	T	ET	AD	± D	WTU	P
		mm									
v6 (PGWC)	**Peas**	13	202	344	-41	-496	-537	0	**4**	169	-165
	Groundnuts	72	334	543	-34	-436	-470	0	**-335**	222	-557
	Fallow	-8	91	0	-24	0	-24	0	**-74**	0	-74
	Wheat	-36	29	752	-68	-435	-502	0	**-315**	278	-594
	Fallow	3	94	0	-29	0	-29	0	**-61**	0	-61
	Cotton	-23	273	501	-70	362	-432	0	**-365**	233	-597
v7 (WMFG)	**Wheat**	61	204	441	66	497	563	0	**-21**	209	230
	Maize	11	350	266	41	417	459	0	**-147**	264	411
	Fallow	21	121	0	46	0	46	0	**-54**	0	54
	Groundnuts	36	260	402	43	281	324	0	**-302**	179	481

5.3.1.3 Yield and water use efficiency

The commodity (C) and above-ground total dry matter (TDM) yields for both the actual harvested products and potential maximum achievable yields for the area were summarised for the two crop rotation systems in Table 5.8. The difference between the potential maximum yield and the actual yield gives the potential yield deficit. Yield deficits were large in both the PGWC and WMFG rotations; they varied from between 14 and 100% for the PGWC rotation and between 32 and 42% for the WMFG rotation. Based on the observations made in the previous section that water or oxygen stress in the crops are omissible, a conclusion can be made that the yield deficiencies were caused by stress factors other than water and oxygen.

Stress factors are complex to analyse and require in most cases detailed weather, soil and crop measurements before reliable conclusions can be made. However, optimum planting dates and therefore crop selection within crop rotations are simple indicators that might explain some of the yield deficits experienced at the measuring point. Optimum planting dates for winter crops (peas, wheat and barley) are from mid-June until mid-July. It is clear that the winter crops in the case study were planted in the required period, but this was not always the case for the summer crops (cotton, maize and groundnuts). The best planting dates are known to be October, which implies that a winter fallow cropping rotation is essential. Those farmers who use double cropping are forced to prepare the soil after harvesting the winter crops, which means that the summer crops could only be planted from mid-November if peas were cultivated, and from the first week in December if wheat was grown. Projecting these principles on the measuring point, it is clear that the wheat-cotton double cropping rotation in v6 (PGWC rotation) was a costly mistake, because cotton requires a relatively long and warm growing season. The planting date of cotton was 5 December 2008, after harvesting wheat on 1 December 2008. It will often fail to achieve economic yields in areas where the growing season duration is made marginally adequate due to planting delays, as in this study, where the buds did not receive sufficient heat units to reach full maturity. The result was a total crop failure. In retrospect, a smarter crop selection should have been to plant the cotton on the eastern side (v7) after the winter fallow in October 2008 and thus replacing groundnuts in the WMFG rotation. The additional two months should have been sufficient for the crop to proceed through all the growth stages.

Table 5.8 Commodity (C) yield and above-ground total dry matter (TDM) yield, transpiration (T) and water use efficiency (WUE) for the PGWC and WMFG cropping rotation systems (actual is subscript a and potential or maximum is subscript max)

Field	Crop	Commodity yield (kg ha^{-1})		Total dry matter yield (kg ha^{-1})		T (kg ha^{-1})	*WUE$_C$ (g kg^{-1})	*WUE$_{TDM}$ (g kg^{-1})
		C_a	#C_{max}	TDM_a	#TDM_{max}			
PGWC (v6)	**Peas**	3428	4000	7617	9500	4960000	0.689	1.533
	Groundnuts	3971	4500	11346	14500	4360000	0.911	2.602
	Total year 1	-	-	18963	24000	9320000	-	2.035
	Wheat	5845	8000	14256	16000	4350000	1.344	3.277
	Cotton	0 **	6500	14084	18500	3620000	-	3.891
	Total year 2	-	-	28340	34500	7970000	-	3.556
	Total year 1&2	-	-	47303	58600	17290000	-	2.73
WMFG (v7)	**Wheat**	5432	8000	15520	20000	4970000	1.093	3.123
	Maize	9896	14500	17062	26500	4170000	2.373	4.092
	Total year 1	-	-	32582	46500	9140000	-	3.565
	Groundnuts	2619	4500	7483	14500	2810000	0.93	2.662
	Total year 2	-	-	7483	14500	2810000	-	2.663
	Total year 1&2	-	-	40065	61000	11950000	-	3.353

\# Default values obtained from the SWAMP model.

* WUE was calculated as the mass (g) of the C or TDM per ha divided by the mass (kg) of water transpired per ha

** Planted too late resulting in delayed maturity.

Maize should have been planted on the western side (v6) instead of cotton, because maize has a wider planting period than cotton, especially with the short seasonal high maize yielding cultivars available. Despite the technology, postponing maize planting dates until after November will result in a yield loss of 153 kg ha^{-1} day^{-1}. This guideline was derived from linear regression analysis using data from all the Vaalharts measuring points (a = 63537, b = -153 and R^2 = 0.5). Comparing the results of the regression equation with the maize planted on 15 December (Julian Day 349 = x) in the WMFG rotation, revealed that the actual yield (9896 kg ha^{-1}) was close to the estimated maximum yield of 10 100 kg ha^{-1}. Apart from cotton, the planting dates of the other crops were all in the optimum or practical range for fitting into the crop rotation systems.

Environmental induced stress that leads to a reduction in dry matter will modify the transpired water (T) or the water use efficiency of the crop as indicated in Table 5.8. The water use efficiency (WUE) was calculated as the mass (g ha^{-1}) of C or TDM divided by mass (kg ha^{-1}) of water transpired. Comparing the PGWC and the WMFG rotations with respect to their water use efficiency on an annual basis, revealed that, over the first year, the WUE_{TDM} of the wheat-maize crop selection was about 50% higher than that of the corresponding peas-groundnut selection (WUE_{TDM} = 2.035). The main reason for this can be attributed to the metabolic pathway of fixing carbon within the two rotations. In the peas-groundnut sequence there are two successive C_3 crops *versus* the C_3-C_4 combinations of the wheat-maize selection. Generally, C_4 crops are more efficient in producing dry matter from transpired water than C_3 crops. These results explain from a water conservation view point why the wheat-maize combination is so popular amongst farmers. Crop types utilized in the second year were of the C_3 metabolic type, *viz.* wheat-cotton *versus* winter fallow-groundnuts. As expected, there were huge differences in the cumulative total dry matter between the rotations due to the winter fallow; 28 340 kg ha^{-1} for wheat-cotton sequence *versus* 7 483 kg ha^{-1} for the winter fallow-groundnuts sequence. The corresponding mean WUE_{TDM} values were 3.556 and 2.663 g kg^{-1}, respectively.

The WUE values differ widely amongst the C_3 crops used in the case study. Accordingly, cotton has the best water use efficiency (WUE_{TDM} = 3.891 g kg^{-1}), followed by wheat (mean of 3.2 g kg^{-1}), groundnuts (mean of 2.632 g kg^{-1}) and then peas (1.533 g kg^{-1}). Water use efficiency based on the economic or commodity yield is of great importance. The commodity based WUE ratio reflected the same trend as the WUE_{TDM}, except for cotton with its zero yield harvested. Future research should focus on the economic sustainability of crop rotation systems in order to guide and assist farmers on selecting best sequences within long-term crop rotations.

5.3.1.4 Peak irrigation demand-supply period

This section focuses on the water demand-supply management during the peak growth period of the crops. The hypothesis focussed on whether the adopted dual cropping system helped the farmer to overcome apparent difficulties in supplying water to the crops during the peak water demand period. Dual cropping was employed on three of the four production seasons; peas and wheat in the first season, followed by groundnuts and maize in the second season and cotton and groundnuts during the fourth season. The peak growth period was taken as the reproductive growth stage of the crops. The relevant mean crop water demand and required water application rates were calculated by dividing the cumulative amounts by the length of the reproductive season.

With regard to the peas-wheat combination, it emerged that both crops have a relatively short peak period (50-40 days) of high water demand, which resulted in a high mean ET rate of 6.2 and 5.8 mm day^{-1}, respectively. Rain was a significant contributor during the period and supplied 43 and 60% of the total demand (ET), which required mean irrigation rates of just below 4 mm day^{-1} for both crops. Rain helped in reducing the irrigation requirement during the following summer with the cultivation of groundnuts and maize under the centre pivot. Rain supplied 51 and 34% of the total water demand, respectively, reducing the need for irrigation to 4.9 and 3.3 mm day^{-1}, respectively. The length of the growing season and rainfall played a significant role in the demand and supply of water during the fourth season. Groundnuts have a very long reproductive period (90 days) compared to cotton (50 days), but fortunately groundnuts received 182 mm of rain which reduced the irrigation requirements to 2.3 mm day^{-1} compared to 4.5 mm day^{-1} for the cotton. Rainfall was markedly lower during the cotton season and resulted in a required mean irrigation rate of 4.5 mm day^{-1}.

From the previous discussion it is clear that the crop peak water demand varied among the cropping seasons and that the maximum demand was 6.2 mm day^{-1} during the peak season. On the other hand, the soil water contents were very high during all seasons due to the presence of the water tables, and calculations showed that the upward flux from the water table could supply at least 4 mm day^{-1} during any of the seasons. In some cases the potential profile water supplies amounted to almost 11 mm day^{-1}. In the light of the above discussion, and the fact that the centre pivot had a capacity of applying 12 mm day^{-1}, there is ample evidence that the irrigation system is capable of supplying the required peak water demand, irrespective of whether one or two crops are being grown under the centre pivot.

5.3.1.5 Salt additions and removals

The aim of this section was to compare the measured salt regimes of the two rotations (PGWC and WMFG). The results of specific salinity indicators, such as the electrical conductivity of the irrigation water (EC_i), electrical conductivity of the water table (EC_{WT}) and electrical conductivity of the soil (EC_e), are presented in Figure 5.3a and b for the PGWC (v6) and WMFG (v7) crop rotations, respectively. Note that EC_i and EC_{WT} were measured weekly, while EC_e were measured seasonally (five times during the study). Figure 5.4a and b presents detailed graphs on the EC_e distribution in the profile for the five sampling events of measuring point's v6 and v7, respectively. The results on the salt balance components are summarized in Table 5.9 for measuring point's v6 and v7.

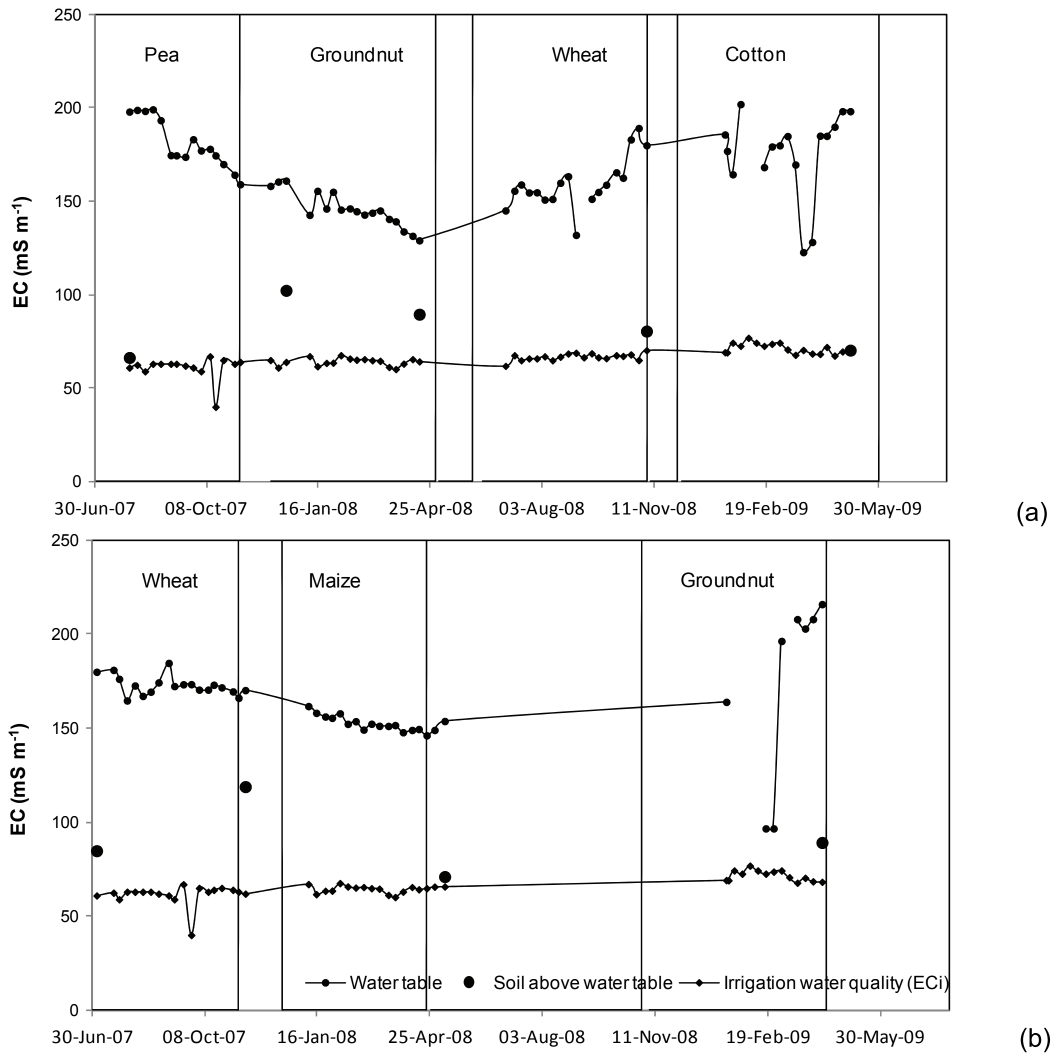


Figure 5.3 The electrical conductivity (EC) of the water table and the soil above the water table for measuring points v6 (a) and v7 (b).

Salt was directly and indirectly added to the field. Direct application was introduced through fertilizers (S_F), irrigations (S_I) and rain (S_R) and indirectly through hydraulic processes associated with the water table (S_{WTU}). The direct application of salt during the PGWC rotation resulted in a total addition of 11516 kg salt ha^{-1} compared to the 6548 kg salt ha^{-1} measured on the WMFG rotation. It is clear that the higher salt addition in the PGWC rotation was caused by the water and nutrients required by the fourth crop (cotton), compared to the WMFG rotation which comprised three crops.

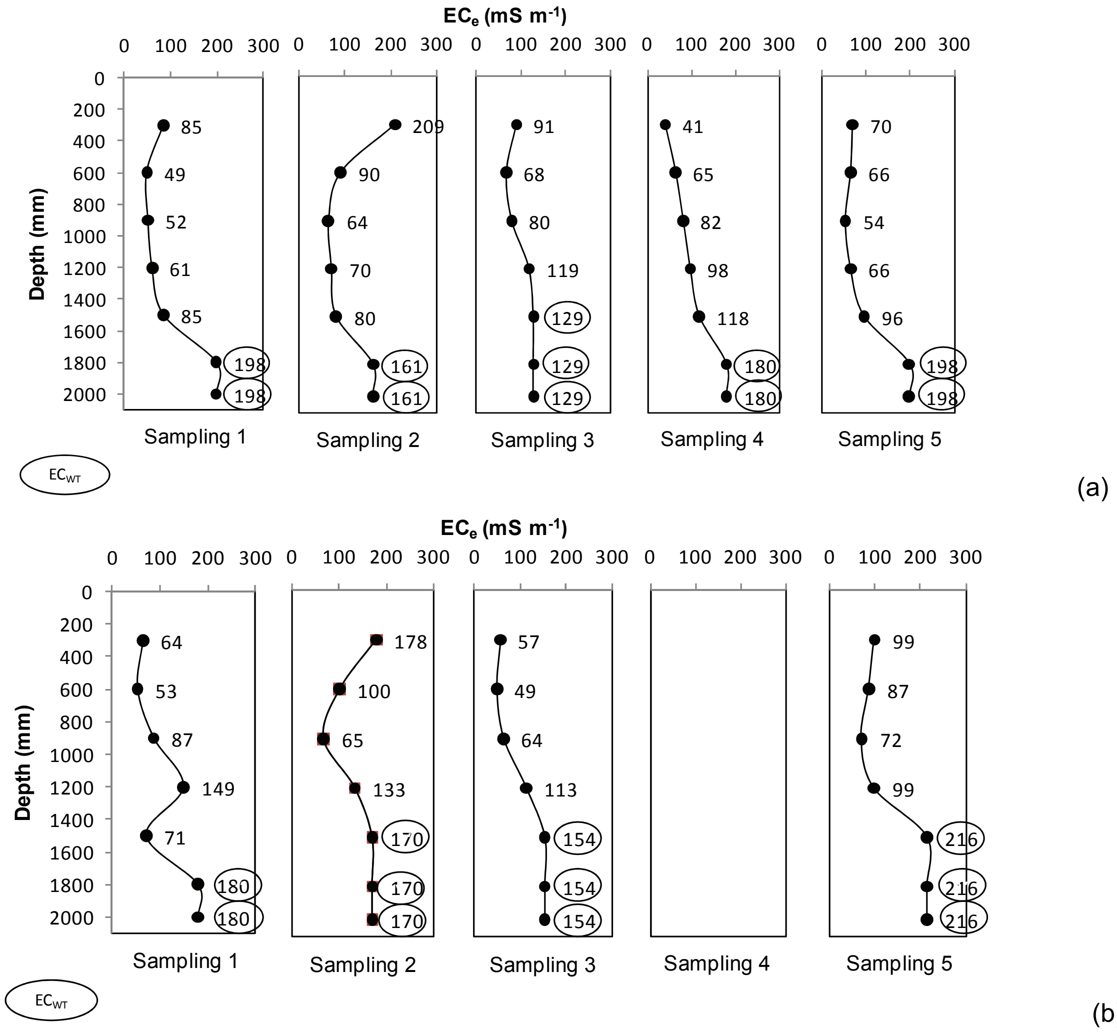


Figure 5.4 Salt distribution in the soil profile, expressed as the electrical conductivity of a saturated extract (EC_e), and electrical conductivity of the water table (EC_{WT}) of measuring points v6 (a) and v7 (b), for five sampling events (July 2007, December 2007, April 2008, November 2008 and May 2009) taken during the measuring period (sampling dates is provided in Figure 5.3).

An increase in irrigation amounts will directly lead to an increase in the amount of salt added to the field, especially when the EC_i is stable as indicated by the results in Figure 5.3. Conversely, an increase in rainfall will lead to lower irrigation amounts and eventually, to lower salt additions.

This phenomenon is clearly illustrated during the wet maize season (WMFG rotation) versus the dry wheat season of the PGWC rotation. Rainfall contributed less than 1.6% of the total direct salt additions to the field. The contribution of fertilizers towards the total salt which was applied directly, differed markedly between the two rotation systems; it was 9% in the PGWC rotation and 14% in the WMFG rotation. The salt which was added indirectly to the root zone through water table uptake varied between 2293 and 3340 kg ha^{-1} in the PGWC rotation and between 2342 and 3032 kg ha^{-1} in the WMFG rotation.

Due to the blockage of the drainage system, salt could only be removed from the root zone via deep drainage. The S_p-values in Table 5.9 indicate that vast amounts of salt percolated into the water table, between 3212 and 6913 kg ha^{-1} season^{-1} during the PGWC rotation, and between 2345 and 6556 kg ha^{-1} season^{-1} during the WMFG rotation. Significant amounts also leached into the water table during the fallow periods as a result of the wet soil, due to the presence of the shallow water table (Figure 5.2). Under these conditions, irrigation and rain will result in wetting the soil above the DUL leaching excess salts downward in the root zone. Salt tends to concentrate in the water table as the process of removal through ground water movement or artificial drainage is slow and they can be returned into the root zone via the upward capillary flux resulting from water table uptake.

Estimations with the SWAMP model indicated that a substantial amount of the salt was redistributed in the profile as a result of the transpiration stream (S_{WTU}), apparently between 2293 and 3340 kg salt ha^{-1} season^{-1} during the PGWC rotation and between 2520 and 6907 kg salt ha^{-1} season^{-1} during the WMFG rotation. Fortunately there was a net removal of salt from the potential root zone due to drainage ($-S_D$) in all the seasons, irrespective of crop rotations. The variation in leaching was high; for the PGWC rotation the variation was very high (> 3000 kg salt ha^{-1} season^{-1}) during the two summer cropping periods as well as during the second winter season when wheat was cultivated. Fallow periods resulted in huge amounts of salt being removed as indicated in (Table 5.9). During the fallow period, the leaching efficiency varied from 1 kg salt ha^{-1} mm^{-1} in the WMFG rotation to about 6 kg salt ha^{-1} mm^{-1} in the PGWC rotation.

Table 5.9 Net gain ($+S_D$) or loss ($-S_D$) of salt from the potential root zone (2000 mm) through upward or downward drainage for measuring points v6 and v7 as calculated from the change in salt content of the soil (ΔS_{Soil}), net addition of salt through fertilizers (S_F), addition through rainfall (S_R), irrigation (S_I) and capillary rise (S_{WTU}), as well as movement of salt into the water table through percolation (S_P) and out of the potential root zone through the artificial drainage system (S_{AD})

Measuring points	**Crop**	**ΔS_{Soil}**	**S_F**	**S_R**	**S_I**	**S_{AD}**	**$\pm S_D$**	**S_{WTU}**	**S_P**
		kg ha^{-1}							
v6 (PGWC)	**Peas**	899	214	30	1574	0	**-919**	2293	3212
	Groundnuts	99	237	50	2606	0	**-2794**	2434	5228
	Fallow	-456	0	14	0	0	**-470**	0	470
	Wheat	477	267	4	3779	0	**-3573**	3340	6913
	Fallow	-345	0	14	0	0	**-359**	0	359
	Cotton	-90	281	41	2405	0	**-2817**	2792	5607
v7 (WMFG)	**Wheat**	1596	415	31	2018	0	**-867**	2717	3583
	Maize	-1843	351	53	1277	0	**-3524**	3032	6556
	Fallow	-675	0	18	0	0	**-694**	0	694
	Groundnuts	2381	175	39	2171	0	**-4**	2342	2345

5.3.1.6 Salt changes in profile

The mean EC of the soil samples suggested a slight build-up of salt during the first winter season, irrespective of the rotations (Figure 5.4). According to the salt distribution profiles, the salt accumulated mainly in the upper part (0-600 mm) of the profiles indicating that ET had played a significant role in salt transportation. Irrigation and rain leached the salt from these zones in the subsequent summer seasons in both rotations (sample 3 in Figure 5.4). In the process, salt was also leached from the bottom part (1800-2000 mm) of the respective profiles. In the subsequent winter and summer seasons of the PGWC rotation, net downward water movement resulted in the percolation of salt towards the water table as can be deduced from the EC_e in the bottom part of the profile. Unfortunately soil samples were not taken at the end of the fallow period in the WMFG rotation. However, the end result was that percolation resulted in the transportation of salt towards the water table, which caused the EC_{WT} to be between 2 and 3 times higher than the EC_i.

In summary, a total of 11516 and 6548 kg salt ha^{-1} was added through rain, irrigation and fertilizers during the PGWC and WMFG rotations, respectively. Most of the salt, 95% in the PGWC rotation, and 78% of the WMFG rotation, was fortunately removed from the potential root zone through leaching. Thus only 584 and 1459 kg salt ha^{-1} respectively, remained in the profiles.

The assessment showed therefore that the crops were grossly over-irrigated which ensured almost no build-up of salt in the profiles. Irrigation scheduling can thus be improved by the farmer in order to conserve water and ensure optimal water use. This is true especially since these crops were not subjected to water stress or waterlogging conditions as shown in the previous section. Optimal irrigation scheduling where only crop water requirements (transpiration) are applied can however lead to salt accumulation in the root zone, which reduces crop growth and yield. Assessing the effect of optimal irrigation scheduling on soil salinity and crop yield, and therefore long-term crop selection will be invaluable.

5.3.2 Desktop simulation assessments

The aim of the desktop simulations were to determine what crops or crop rotation system would achieve the best results, with regard to soil salinity and yield, when optimally irrigated for 20 years. In order to accomplish this the inputs and assumptions described in Section 5.2.3 were used. It was decided to use wheat, maize, groundnuts, peas and cotton as crops with a double and fallow cropping system, given that these crops and rotation systems were the most popular at Orange-Riet and Vaalharts.

5.3.2.1 Rainfall

The amount and distribution of rainfall will play a significant role in salt accumulation or soil salinity, which in turn will determine yield and therefore crop choices and rotation systems. This is because rainfall can only be optimised and incorporated into irrigation scheduling for a specific period when it rained less than the crop water requirement for that specific period. Figure 5.5 shows the evaporative demand (ETo) and rainfall per day for the period 1980 to 1999, over which the simulation study was conducted. As can be seen during this period, there were two distinct rain events where it rained in excess of 100 mm. The first occurred during February 1988 and the second during August 1999. Three rain events where it rained in excess of 60 mm were also identified. The first event of more than 60 mm occurred during November 1983, while the second and third occurred close to the two rain events of more than 100 mm (February 1988 and June 1999). From this it is evident that rainfall distribution can be classified according to three phases or periods. The first was from January 1980 to November 1983, the second from November 1983 to February 1988 and the third from February 1988 to June 1999. From February 1988 to January 1994 there was a distinct pattern of rainfall distribution with four rain events where the rainfall was between 40 and 60 mm. From January 1994 until June 1999 the number of rain events of between 40 and 60 mm increased significantly (10 events above 40 mm). In light of this it was decided to divide the rainfall distribution pattern from 1980 to 1999 into four phases or periods. It is anticipated that these periods determined by significant rainfall events and distribution, would have the most influence on soil salinity and yield as simulated for the various crop rotation systems.

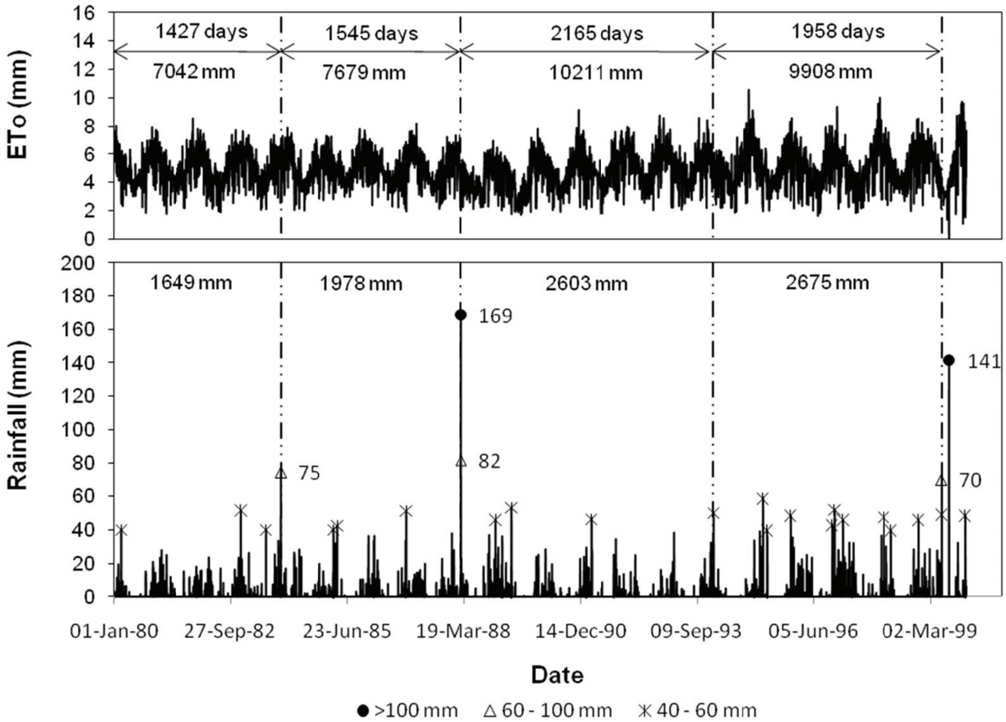


Figure 5.5 Amount of evaporative demand and rainfall per day for the period 1980 to 1999 as used in simulating soil salinity for the different crop rotation systems.

Since the four periods were not of the same length, the potential impact of rainfall on soil salinity for the specific period were expressed in terms of the aridity index (cumulative rainfall, mm / cumulative ET_o, mm) and the number of rainfall events above 40 mm. During the first period (January 1980 to November 1983) it rained the least with three rain events of between 40 and 60 mm and was the driest period with an aridity index of 0.23. The second period (November 1983 to February 1988) had the same number of rain events of between 40 and 60 mm, but was a bit wetter with an aridity index of 0.26. The third period was the longest and had approximately the same aridity index (0.25) as the second period, with four rain events of between 40 and 60 mm. The last period recorded the highest rainfall with 10 rain events of between 40 and 60 mm with an aridity index of 0.27. It is anticipated that these four distinct periods in rainfall distribution will also be reflected in the amount of salt that accumulated in the soil.

5.3.2.2 Irrigation

It must be emphasised that the weekly irrigation amounts were calculated as the crop water demand (transpiration) for that week, minus the rainfall during the week, which was explained in Section 5.2.3.3. No provision was made for over-irrigation to accommodate leaching of salts.

5.3.2.3 Soil salinity

Figure 5.6 illustrates the mean electrical conductivity of the soil for the different crop rotations as simulated during the period 1980 to 1999. The four rainfall distribution periods, as described above, are also presented. For all the crop rotation systems, the mean salinity of the soil at the start of the simulations (1980) was at the same value.

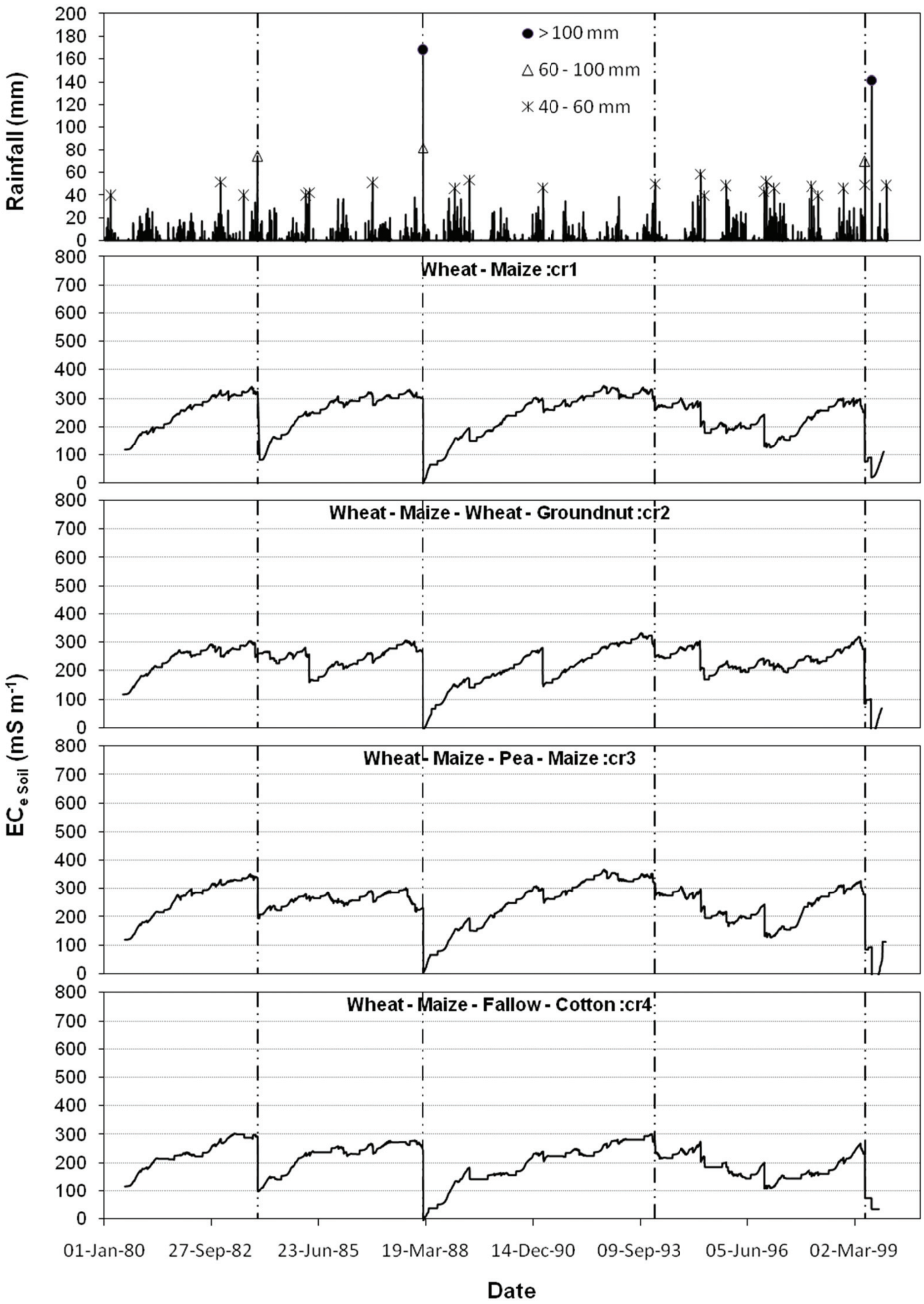


Figure 5.6 Mean electrical conductivity of the soil, expressed as a saturated extract (EC_e), for all the crop rotation systems as simulated during the period 1980 to 1999.

During the first period, or from the inception of the simulations until the first rain event of more than 60 mm, the mean salinity of the soil showed a steady increase for all the crop rotation systems. The mean salinity of the soil increased from approximately 100 to 300 mS m^{-1} for all the crop rotation systems.

At the start of the second period, just after the first rain event of more than 60 mm, the mean salinity of the soil for crop rotation 1, 3 and 4 showed a sharp decrease. The mean salinity of the soil for crop rotation 1 and 4 decreased to 100 mS m^{-1} from where it increased back to 300 mS m^{-1} during the second period. For crop rotation 3 the mean salinity of the soil decreased to 200 mS m^{-1} from where it remained relatively constant as it reached a value of approximately 220 mS m^{-1} just before the second rain event of more than 60 mm.

Crop rotation 3 showed no significant decline in mean soil salinity as it fluctuated between 200 and 300 mS m^{-1}, with an end value of 300 mS m^{-1} prior to the second rain event of more than 60 mm.

During the start of the third period just after the second rain event of between 60 and 100 mm, and the first when the rainfall exceeded 100 mm, the mean salinity of the soil for all the crop rotation systems decreased significantly. Almost all of the salts were leached from the soil by the 80 and 170 mm rainfall events for all the crop rotation systems.

After these two significant rain events, the mean salinity of the soil again increased and reached a maximum during January 1994. The mean salinity of the soil reached a maximum of roughly 300 mS m^{-1} for all the crop rotation systems.

From the start of the fourth period (January 1994) until June 1999 the mean salinity of the soil for all the crop rotations showed a slight decline followed by an increase which ended again at 300 mS m^{-1}. The mean salinity of the soil for all the crop rotations remained therefore relatively constant from just before the third rain event of between 60 and 100 mm.

In general, as can be expected for all the different crop rotation systems, the mean salinity of the soil showed periods of salt accumulation. A single high rainfall event or a combination of rainfall events close together, however, leached a considerable amount of salt from the soil. The mean salinity of the soil for this twenty year period never rose above 350 mS m^{-1} for all the crop rotation systems. Seed yields of the maize-wheat rotation (cr1) should therefore not be significantly decreased by soil salinity since the threshold salinity level as reported by Ehlers et al. (2007) for wheat and maize is 600 and 350 mS m^{-1}, respectively. This should also be true for the wheat-maize-wheat-groundnuts rotation (cr2) since groundnuts has a threshold salinity level of 320 mS m^{-1} (Maas, 1990). For crop rotation 3, which is a wheat-maize-peas-maize rotation, care should be taken as peas have a threshold salinity level of only 105 mS m^{-1}. For crop rotation 4, which is the wheat-maize-fallow-cotton rotation, no significant reduction in seed yield is expected, since cotton has a threshold of 700 mS m^{-1}.

5.3.2.4 Seed yield

The expected reduction in seed yield due to soil salinity, for the five crops in the four crop rotation systems is provided in Table 5.10. Reduction in seed yield for the crops is expressed as a mean percentage of the maximum potential seed yield simulated during the specific period. Basically wheat and maize are the primary crops used in the four crop rotation systems. With crop rotation 1 wheat and maize were alternately planted for the entire period, resulting in 20 and 19 simulations of each, respectively. For crop rotation 2 and 3, groundnuts and peas were used every second year as an alternative crop for maize and wheat, respectively. During crop rotation 2, groundnuts were simulated 9 times, with maize simulated 10 times and wheat 20 times. With crop rotation 3, the opposite was done with 19 simulations of maize and 10 each for wheat and peas. For crop rotation 4, a fallow period was included and cotton used as a third crop with 10 simulations each of wheat and maize, 9 simulations of cotton and 10 fallow simulations.

During the first period from June 1980 to November 1983, increases in soil salinity resulted in no significant reduction in seed yield for wheat, maize and cotton irrespective of crop rotation systems. Peas of crop rotation 3 showed a 38% reduction in mean seed yield due to soil salinity, while groundnuts showed only a slight reduction (10%) in seed yield.

After the first rain event of between 60 and 100 mm at the beginning of the second period, soil salinity decreased in the presence of a water table as explained in Section 5.3.2.3. During the remainder of the period as soil salinity increased again no reduction in mean seed yield for all the crops used in the different crop rotation systems was observed, except in the case of peas.

Table 5.10 Mean seed yield, expressed as a percentage of the maximum obtainable seed yield in a saline stress free environment, for the different crop rotation systems and conditions during the four rainfall periods

Period	Crop	cr1	cr2	cr3	cr4
1 Jun-80 to Nov-83	**Wheat**	0.96	0.97	0.97	0.98
	Maize	0.95	0.96	0.95	0.96
	Groundnuts	-	***0.85***	-	-
	Peas	-	-	***0.62***	-
	Cotton	-	-	-	0.97
2 Nov-83 to Feb-88	**Wheat**	0.94	0.95	0.95	0.96
	Maize	0.96	0.96	0.96	0.96
	Groundnuts	-	***0.86***	-	-
	Peas	-	-	***0.49***	-
	Cotton	-	-	-	0.98
3 Feb-88 to Jan-94	**Wheat**	0.95	0.97	0.94	0.96
	Maize	0.95	0.96	0.95	0.96
	Groundnuts	-	***0.86***	-	-
	Peas	-	-	***0.66***	-
	Cotton	-	-	-	0.94
4 Jan-94 to Jun-99	**Wheat**	0.91	0.95	0.89	0.92
	Maize	0.96	0.96	0.96	0.97
	Groundnuts	-	***0.86***	-	-
	Peas	-	-	***0.66***	-
	Cotton	-	-	-	0.91

The salinity of the soil was not influenced by this rain event, and steadily increased during the remainder of the period. However, crop rotation 3 showed clearly that salt sensitive crops like peas, demand additional management inputs. Severe peas yield losses occurred with a recorded loss in seed yield of 49%.

During the third period none of the crops for all the crop rotation systems was affected by soil salinity again, except peas. This is mainly because soil salinity decreased dramatically at the start of this period due to the two big rain events. The seed yield of peas was again reduced, mainly because wheat and maize are grown beforehand, resulting in enough time for salt accumulation as pea is a salt sensitive crop. A slight reduction in groundnut seed yield due to excessive soil salinity can be expected. Soil salinity during the fourth period remained relatively constant resulting again in a significant reduction in the seed yield of peas.

In general with crop rotation 3, or where a salt sensitive crop like peas was used as an alternate crop, it will be difficult to maintain maximum yield for a period of 20 years. Increases in soil salinity resulting from optimal irrigation scheduling, caused significant reduction in seed yield of peas for this crop rotation system under these soil conditions. Seed yields of wheat, maize, groundnuts and cotton were not significantly reduced under these soil salinity conditions when irrigation scheduling was optimised. The accumulation of salt in the root zone due to irrigation could however be more significant for different soil types. This aspect will be investigated in Chapter 6.

5.4 Conclusions

In situ assessment using measured data

The *in situ* assessment of two measuring points which included popular crop choices and rotation systems, under centre pivot irrigation, provided valuable water and salt management information. From a water management point of view, it was concluded that no convincing evidence was provided to support the argument that dual cropping is a valid strategy for overcoming water supply constraints in the presence of a shallow water table and an irrigation system designed to apply 10 mm day^{-1}. Instead, the results rather suggest that the centre pivot is probably over-designed. Conversely, situations can change where a shallow water table is absent and with different combinations of soil, crop, atmospheric demand and capacity of irrigation systems, which might make dual cropping a viable option. From the three double cropping rotations that were analysed valuable lessons emerged. Firstly, crop selection and hence optimum planting dates are of the utmost importance to ensure economic yields. Cotton cannot be used in a double crop rotation following a wheat crop because it requires a relatively long and warm growing season and therefore demands a winter fallow. Secondly, modern maize cultivars with short or ultra-short growing seasons are of immense value to increase land productivity through double cropping with wheat or peas. Thirdly, the analysis of water use efficiency confirmed why wheat-maize is a popular double crop rotation amongst irrigation farmers. The water use efficiency differed markedly amongst the C_3 crops; cotton has the highest efficiency, followed by wheat, groundnuts and then peas. Fourthly, farmers need to evaluate their long-term strategy on crop selection, not only from an economical view point, but also for pest control purposes. For example, the peas-groundnut rotation, which is a legume-based rotation, should rather be substituted by a grass such as wheat or maize. The same principle holds where a grass-based rotation is applied, such as wheat-maize. Although the analysis shows that the crops were not subjected to water stress or waterlogging, there is ample room to improve water conservation and ensure optimal water use through better irrigation scheduling. It was clear that the crops were grossly over-irrigated, which ensured that there was almost no build-up of salt in the profiles. The question that needs to be answered is what is the effect of optimal water management on soil salinity and crop yield, and therefore on long-term crop selection?

Desktop assessment using simulated data

A desktop study was done where the effect of optimal irrigation of four crop rotation systems on soil salinity and yield were investigated. The desktop assessment revealed that when optimal irrigation is applied, rainfall played a profound role in salt accumulation or soil salinity.

The general effect of rainfall distributions and amounts on soil salinity, for all the crop rotation systems can be described as follows: Gradual increases in soil salinity, due to salt accumulation, occurred with all the crop rotation systems. Abrupt decreases in soil salinity due to salt removal from the potential root zone occurred on three occasions during the 20 year period, which corresponded with the described significant high rainfall events. Crop rotation 1, 2 and 4 seems viable and the maximum potential seed yield of wheat, maize, groundnuts and cotton should be obtainable, since the mean salinity of the soil never rose above 350 mS m^{-1}. Care should however be taken with crop rotation 3, especially with peas, as they are a salt sensitive crop. In the analysis of seed yield data for all the crops, during the entire simulation period, it was concluded that it would be difficult to maintain a maximum yield where peas are used in a crop rotation system. Yield losses, as a result of soil salinity exceeding the threshold value of the crop, can be prevented by increasing salt leaching through the carefully planned over-irrigation of salt sensitive crops. Soils will however respond differently to irrigation management in terms of unproductive water losses and salt accumulation, which will be assessed in Chapter 6.

CHAPTER 6
ASSESSING SOIL RESPONSE TO IRRIGATION MANAGEMENT

6.1 Introduction

Water and salt management will be significantly influenced by the different pedological, physical, and chemical properties of the 400 soil types in South Africa (Soil Classification Working Group, 1991). Procedures or criteria have been developed whereby soil properties can be evaluated for irrigation (Louw, 1967; Verster & Stofberg, 1974; Schoeman, 1987; MacVicar; 1976; Irrigation Planning Staff, 1980; Hensley & Laker, 1980; Bester & Liengwe, 1989).

These criteria are based on a principle whereby, the more difficult it is to manage a soil in terms of its properties, the less suitable it is for irrigation. Matching soil properties to irrigation management in terms of on-farm management of unproductive water losses and salt accumulation remains, however, a challenge. This is because the evaluation of soil for irrigation and the response of the soil to irrigation is a complex process. The process encompasses extensive and intensive soil, terrain, climate and water quality surveys, i.e. inventorising and mapping of natural land and soil features (Hensley & Laker, 1980). In addition there is the exchange of information between technical experts, such as those from the soil, crop, climate, engineering and agricultural economic sciences. Poor communication and understanding amongst specialists often leads to an inequality between soil properties and agronomic requirements (Turner & Scotney, 1993). Other factors of importance are associated with the personal preferences of the targeted farmers, *viz.* social, religious and cultural aspects (Tapson et al., 1986). These factors are the main drivers of a positive attitude towards irrigation, which is frequently ignored, often with devastating consequences.

In the first part of this chapter an assessment in terms of water and salt management, of the different soils at the various measuring points located within Orange-Riet and Vaalharts was done through an examination of their pedological, physical and chemical properties. These soil properties combined with irrigation management determines the response of soil to irrigation, with regard to water and salt movement. During the second part, an *in situ* assessment of two contrasting soils (sandy and clayey) was done, which incorporates the degree of unproductive water losses as well as yield reductions and soil degradation due to salt accumulation. Finally, a desktop study through simulations with SWAMP was included in order to assess the long-term response of four soils to irrigation where unproductive water losses were minimised by taking into account rainfall and the contribution of the water table when irrigating according to crop water requirements.

6.2 Methodology

The data needs and methods used in order to accomplish the objectives of this chapter were grouped as follows: Firstly, the *in situ* measurements that were done at the various measuring points, as explained in Chapter 3, were used to assess the different soil qualities at Orange-Riet and Vaalharts. Secondly, the *in situ* measurements (Chapter 3) and water and salt balance results (Chapter 4) of four measuring points were used to assess the agronomic performance of two contrasting soils. To accomplish the third objective, the approach was to conduct a desktop study using the SWAMP model in order to assess the long-term response of soils to irrigation where drainage (leaching) was minimised. For this purpose, four different soils were selected. Their *in situ* measured properties were used as inputs in the model.

6.2.1 Soil salinity assessment

Pedological, drainage, sodicity and salinity information of all the measuring points listed in Table 3.2, was used in the assessment. Based on the measured mean silt, clay and sand percentages of the A and B horizons, each measuring point's textural class was determined with the texture triangle (Soil Classification Working Group, 1991). From these different texture classes the measuring points were grouped into sandy, loamy and clayey soils, which will be discussed accordingly.

6.2.2 *In situ* case study assessment

6.2.2.1 Location and description

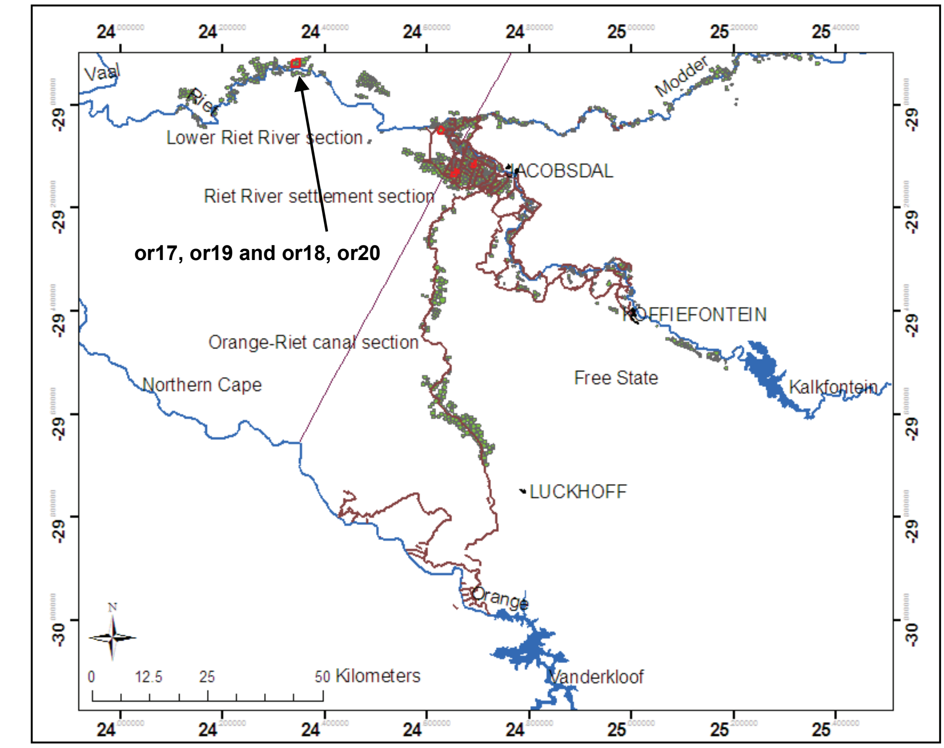
For this case study, four measuring points (or17, or18, or19 and or20) situated on a farm in the Lower Riet River section of the Orange-Riet Irrigation Scheme were selected (Figure 6.1a). Two of the measuring points were located on the crest (or17 and or19) and the other two in the valley bottom of the farm. One of the measuring points on the crest was located in a 32 ha centre pivot irrigation system (or17), and the other (or19) on a 35 ha centre pivot irrigation system just west of or17 (Figure 6.1b). Both the measuring points in the valley bottom were positioned on the 42 ha centre pivot irrigation system and served as replicates as shown in Figure 6.1b.

The soils on the crest are aeolian sandy deposits of lime and belong to the Hutton form and Ventersdorp family (Soil Classification Working Group, 1991). The profile has four diagnostic horizons; Orthic A with 4% clay (0-300 mm), red apedal B1 with 4% clay (300-600 mm), red apedal B2 with 7% clay (600-1500 mm) and an unspecified C with 6% clay (1500-1750 mm). All horizons fall into the fine sandy textural class with an apedal massive structure. A very prominent feature is the cementation of the C horizon at a depth of 1750 mm, forming an impermeable continuous strong calcrete pisolitic pan.

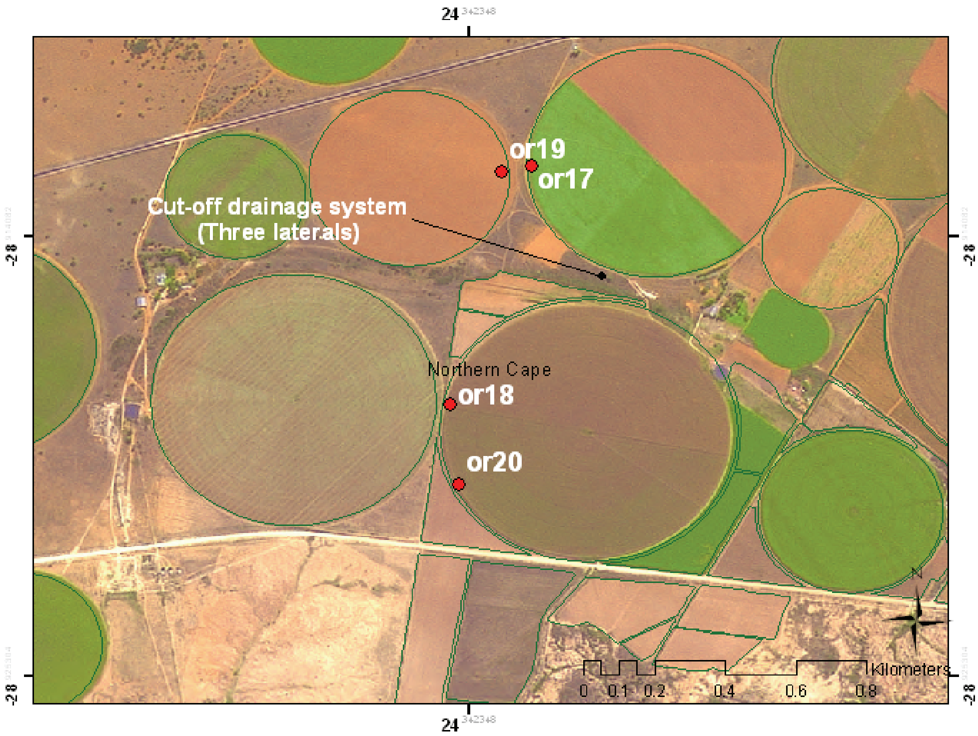
The soil in the valley bottom has its origin in alluvium clay deposits and was classified as Valsrivier Aliwal (Soil Classification Working Group, 1991). The profile has four diagnostic horizons; Dark brown Orthic A with 41% clay (0-300 mm), dark brown B1 with 43% clay (300-900 mm), dark brown B2 with 46% clay (900-1200 mm) and an unspecified C with 50% clay (+1500 mm). All the horizons have a strong coarse angular blocky structure with many clay cutans, slickensides and lime concretions. Of note is the presence of blue, black, brown, red and white mottles in both the B2 and C horizons. These mottles were more prominent and common in the C compared to the B2. Roots were absent in both these horizons, as emerged in the soil description.

A uniformity coefficient, distribution uniformity, application efficiency and system efficiency of 93, 91, 99 and 89% for the centre pivot at or17, respectively, and 93, 91 97 and 88% at or19, respectively, suggests that the irrigation systems on the sandy soils are in a good condition. The same was true for the centre pivot where measuring points or18 and or20 were located, with values of 93, 92, 97 and 88%, respectively.

At none of the four measuring points was an artificial drainage system installed. However, the waterlogging problem that occurred was solved by the farmers with a drainage system installed on the border between the sand and clay soils in between the crop fields at or19 and or18, or20. Figure 6.1b shows the location of the drainage system. The flow rate and electrical conductivity of the drainage water from these three laterals, which flows into a drainage pit, were measured weekly as explained in Chapter 3. Drainage water from the drainage pit is then discharged into a storage dam, where it was blended with Lower Riet River water and re-used as irrigation water on the measuring sites.



(a)



(b)

Figure 6.1 Geographical positions of measuring points or17, or18, or19 and or20 within the Lower Riet section of the Orange-Riet Irrigation Schemes (a) and location of the measuring points on the irrigated fields (b).

6.2.2.2 Agronomic practices

For the duration of the two year study period, the centre pivot on the Hutton soil was used to produce groundnuts, barley, wheat and oats, while the Valsrivier soil was planted with maize, wheat and sunflower (Table 6.1). Crop rotations differed in relation to the three centre pivots. The two centre pivots on the Hutton soil (or17 and or19) used a single crop rotation during the first year, but the crop type differed. In the case at or17 a winter fallow-groundnuts rotation was used, while a wheat-summer fallow rotation was used at or19. During the second year a single crop rotation (barley-fallow rotation) was introduced at or17, while a double cropping rotation (oats-groundnuts) was used at or19.

Table 6.1 Summary of the agronomic practices followed during the four crop seasons at measuring points or17, or19 and or18, or20

Measuring point or17				
Crop rotation	**Fallow**	**Groundnuts**	**Barley**	**Fallow**
Cultivar	-	Aqua	Puma	-
Planting date	-	November 2007	July 2008	-
Harvesting date	-	May 2008	November 2008	-
Planting density	-	300 000 seeds ha^{-1}	73 kg ha^{-1}	-
Fertilizer	-	350 kg ha^{-1} 2:3:4 (30) 250 kg ha^{-1} LAN (28) 300 kg ha^{-1} ANO_3 (21)	250 kg ha^{-1} 2:3:2 (22) 292 kg ha^{-1} ANO (21) 694 kg ha^{-1} 3:1:2 (20) 1.5 kg ha^{-1} Zinc pholate 1.5 kg ha^{-1} Tripholate 1 L Marinure DS	-
Total kg N ha^{-1}	-	156	147	-
Total kg P ha^{-1}	-	35	47	-
Total kg K ha^{-1}	-	47	62	-
Pest management	-	-	Bromoxinyl – 1 L ha^{-1}	-
Cultivation practices	Maize residue was left on the field	Residue was incorporated with a disc, plough, tiller & plant	Disc, rip, power harrow & plant	Residue incorporated with a disc
Measuring point or19				
Crop rotation	**Wheat**	**Fallow**	**Oats/Grazing**	**Groundnuts**
Cultivar	Kariga	-	-	Aqua
Planting date	July 2007	-	-	November 2008
Harvesting date	December 2007	-	-	May 2009
Planting density	78 kg ha^{-1}	-	-	300 000 seeds ha^{-1}
Fertilizer	260 kg ha^{-1} 2:3:2 (22) 430 kg ha^{-1} 3:1:2 (20) 100 kg ha^{-1} Ureum (46) 530 kg ha^{-1} ANO_3 (21)	-	-	300 kg ha^{-1} Supers (10.5) 300 kg ha^{-1} ANO_3 (21) 400 kg ha^{-1} 10:1:6 (20)
Total kg N ha^{-1}	217	-	-	110
Total kg P ha^{-1}	39	-	-	38
Total kg K ha^{-1}	45	-	-	29
Pest management	Granstar – 1 L ha^{-1}	-	-	-
Cultivation practices	Burn, rip, power harrow & plant	Residue was left on the field	Residue was incorporated with a disc	Rip, power harrow & plant - After harvest – Rip & power harrow

Table 6.1 continue

Measuring point or18 and or20				
Crop rotation	**Fallow**	**Maize**	**Wheat**	**Seed Sunflower**
Cultivar	-	Pannar 6236	Duzzie	-
Planting date	-	20/10/2007	02/07/2008	22/12/2008
Harvesting date	-	26/05/2008	10/12/2008	18/05/2009
Planting density	-	85 000 plants ha^{-1}	75 kg ha^{-1}	50 000 plants ha^{-1}
Type of fertilizer applied (kg ha^{-1})	-	250 kg ha^{-1} 2:3:4 (30) 625 kg ha^{-1} UAN (32)	250 kg ha^{-1} 2:3:2 (22) 595 kg ha^{-1}3:1:2 (20) 100 kg ha^{-1} Urea (46) 437 kg ha^{-1} ANO_3 (21) 1.5 kg ha^{-1} Zinc pholate 1.5 kg ha^{-1} Tri pholate 1 L Marinure DS	200 kg ha^{-1} 2:3:2 (22) 450 kg ha^{-1} ANO_3 (21) 300 kg ha^{-1} 10:1:6 (20)
Total kg N ha^{-1}	-	217	213	143
Total kg P ha^{-1}	-	25	44	23
Total kg K ha^{-1}	-	34	56	34
Pest management	-	Atrazine – 1 L ha^{-1}	Bromoxinyl – 1 L ha^{-1}	-
Cultivation practices	Maize residue was left on the field & farmer allowed cattle to graze on the field	Disc & plant	Burn, disc, power harrow & plant	Wonder till, power harrow & plant - After harvest - Disc & rip

The Valsrivier soil had a single crop rotation (winter fallow-maize) during the first year and a double crop rotation (wheat-sunflower) in the second year. Details of the other agronomical practices are summarised in Table 6.1. Conventional land preparation equipment (disc ploughs, mouldboard ploughs, rippers, power harrows and wonder tillers) were used to manage specific situations. For example, where a maize-fallow rotation was used, the maize residues were left on the field to decompose during the fallow period, or were used for grazing. At the end of the fallow period the remaining residue was incorporated with a disc plough, irrespective of the soil type. After disc-ing, the clay soil was harrowed before planting, while the sandy soil was traditionally ploughed with a mouldboard plough to create a temporal structure for planting. The sandy soil was also ripped during double crop rotations, prior to the planting of the second crop. The farmer burned the wheat residue during double crop rotations.

6.2.3 Desktop case study assessment

All the simulations were done with the verified model SWAMP (Chapter 4). It was decided to use measuring point's or17, or18, v5 and v11 to represent a range of Soil Forms with different texture classes and conditions*, viz.* Hutton, Valsrivier, Bainsvlei and Bloemdal, respectively. I*n situ* environmental conditions, rainfall patterns and soil water qualities were used. Two soils were located at Orange-Riet (Hutton and Valsrivier) and two at Vaalharts (Bainsvlei and Bloemdal). Ideally the four soils should have been located in the same region, but this was unfortunately not possible, because the model required an in situ determined salt distribution coefficient. More detail on these coefficients will be given in the next section.

6.2.3.1 Soil conditions

The soil inputs for the model consist of silt-plus-clay content and volumetric soil water content at the start of the simulation corresponding to the drained upper limit. The electrical conductivity of a saturated extract at the end of the measuring period and the mean water table depth and electrical conductivity over the measuring period were also included. The selected salt distribution coefficient corresponded to the value determined in quantifying the water and salt balance of the specific measuring point, as explained in Chapter 4. In essence, this value describes the drainage conditions of the measuring point as measured during the measuring period. Table 6.2 summarises the soil conditions represented by the Hutton (Hu), Valsrivier (Va), Bainsvlei (Bv) and Bloemdal (Bd) soil forms.

Table 6.2 Soil properties [silt-plus-clay content, volumetric soil water content (θ), and electrical conductivity of a saturated extract (EC_e)] representing the Hutton (Hu), Valsrivier (Va), Bainsvlei (Bv) and Bloemdal (Bd) soils that were used in simulating their long term response where drainage or leaching was minimized

Depth (mm)	**Thickness (mm)**	**Hu**	**Va**	**Bv**	**Bd**	**Hu**	**Va**	**Bv**	**Bd**	**Hu**	**Va**	**Bv**	**Bd**
		Silt-plus-clay (%)				**θ (mm mm^{-1})**				**$EC_{e\ Start}$ (mS m^{-1})**			
300	**300**	9	50	16	10	0.080	0.333	0.317	0.135	87	141	143	49
600	**300**	9	50	15	11	0.080	0.333	0.319	0.149	166	176	520	60
900	**300**	9	50	15	12	0.080	0.333	0.333	0.302	165	179	400	54
1200	**300**	9	50	16	12	0.080	0.333	0.356	0.311	61	171	189	85
1500	**300**	9	50	16	14	0.080	0.333	0.362	0.331	210	137	189	141
1800	**300**	11	50	16	14	0.098	0.333	0.362	0.357	222	154	189	141
2000	**200**	11	50	16	14	0.098	0.333	0.362	0.357	87	141	189	141
Mean		***10***	***50***	***17***	***12***	***0.085***	***0.333***	***0.344***	***0.273***	***150***	***165***	***273***	***101***

For the Hutton and Valsrivier soil forms, no water table was present, while both the Bainsvlei and Bloemdal soils had a constant water table at a depth of 1056 and 1503 mm from the soil surface, respectively. During the measuring period it was clear that the water table at measuring point's v5 (Bainsvlei) and v11 (Bloemdal) were continuously recharged from higher lying fields and, hence a constant water table was assumed. The electrical conductivity of the water table was kept constant at a value of 222 and 132 mS m^{-1}, respectively. The salt distribution coefficient for the measuring points was 0.95 for the Hutton, 1 for the Valsrivier, 0.36 for the Bainsvlei and 0.70 for the Bloemdal. As explained in Chapter 5, the amount of salt added to the soil as a result of fertilizer application was added only to the first soil layer at the start of each simulation. For wheat and maize, a total of 686 and 716 kg salts ha^{-1}, respectively, were added through fertilizer application during every crop growth simulation.

6.2.3.2 Crop choices and rotation system

A double cropping rotation system where two crops, wheat and maize, were planted alternately every year was chosen (Table 5.6). With this crop rotation method the system repeats itself every second year. For wheat the simulation started on 5 July and ended on 29 November, while for maize the process began on 1 December and ended on 10 April. A maize drying and harvest period, which was basically a simulation of a fallow period from 11 April to 4 July, was also included. The selection of the crop rotation system was based on the results from Chapter 5, which showed that it was popular in both irrigation schemes. It should be kept in mind that wheat is a salt tolerant crop, while maize is a medium salt sensitive crop.

6.2.3.3 Meteorological parameters

Climate data for a 20 year period, from 1982 to 2001 for Orange-Riet and from 1980 to 1999 for Vaalharts were used in the simulation study. Daily evaporative demand (ET_o) was calculated from maximum and minimum temperatures, maximum and minimum relative humidity, wind speed and actual sunshine hour data. The weather data was obtained from the Agricultural Research Council's Institute for Soil, Climate and Water (ARC-ISCW) in Pretoria for the 20 year period. Data were used from weather station "Rietrivier: Sandpersele" (Nu: 19892, Lat: -29.07, Long: 24.62 and Alt: 1140) and Jan Kempdorp: Vaalharts (Nu: 19847, Lat: -27.95, Long: 24.83 and Alt: 1175) located within the Orange-Riet and Vaalharts Irrigation Scheme, respectively. This daily calculated evaporative demand and rainfall data for the 20 year period of Orange-Riet and Vaalharts were imported into SWAMP.

6.2.3.4 Irrigation

The mathematical algorithms that were used to calculate the timing and amount of irrigation during a growing season were programmed into SWAMP. In an attempt to ensure as little drainage and leaching as possible on each soil during the 20 year simulation period at Orange-Riet and Vaalharts irrigation was dynamically calculated as follows:

Irrigation took place once a week. Summation of the daily evapotranspiration, simulated by SWAMP, for the previous seven days minus the rainfall during this period provided the amount of irrigation that was applied every seventh day. This would imply that irrigation is extremely efficient, because as the crop stresses and uses less water, less irrigation will be applied, minimising drainage.

When the rainfall exceeded the simulated evapotranspiration during the seven day period, no irrigation took place. When a water table was present the contribution of the water table to evapotranspiration for the previous seven days was subtracted as proposed by Ehlers et al. (2003). Uptake from the water table was assumed to be recharged via lateral movement of the groundwater and/or percolation from the top of the soil profile, hence the existence of a constant water table. This was done to accommodate root accessible water tables in an attempt to minimise drainage.

An electrical conductivity of 2 mS m^{-1} for rainfall was used, while the mean electrical conductivity of the irrigation water, measured at the measuring point, which represents the specific soil condition, was used. For the Hutton and Valsrivier soils, drainage water blended with Lower Riet River water with a value of 102 mS m^{-1} were used, while for the Bainsvlei and Bloemdal soils, Vaal River water with a value of 65 mS m^{-1}.

6.3 Results and discussion

6.3.1 Soil salinity assessment

6.3.1.1 Sandy soils

The results on the pedological and soil physical properties, such as soil form and family, terrain unit and slope, structure, silt-plus-clay content, saturated hydraulic conductivity and bulk density were summarized in Table 6.3 for all the measuring points grouped as sandy (Hereafter called sandy soils). Table 6.4 shows the mean sodium adsorption ratio of a saturated extract and electrical conductivity of a saturated extract of five samples taken during the measuring period. The pH_w measured at the start of the project was also included.

Pedological assessment: The sandy soils were classified as Hutton Ventersdorp (or4 – or6, or8 – or11, or17, or19, v6, v7 and v9) and Bloemdal Roodeplaat (or13, v11 and v12). Despite the different soil forms, these soils have strong similarities with respect to their pedological features. Amongst these were the following: (i) the eolian fine sandy deposits that served as parent material, (ii) the calcrete pisolitic pan that under-lies the solum, except v11 and v12 which have a siliceous sandstone layer, (iii) the terrain unit which is either located on the crest, upper or lower footslope and (iv) the gentle slopes, which vary from

0-1% over the fields. Conversely, the profiles revealed differences in the pedological features. A good example is the slope shape of the terrain and the morphological signs of wetness at or17/19, which differed from the rest of the sandy profiles. The terrain at or17/19 has a convex, compared to either a concave or straight slope shape of the others. The profile at or17/19 has no signs of wetness, while the rest have signs of wetness in at least the C horizon. Coincidentally, all the fields with concave or straight slope shapes combined with signs of wetness had water tables. Another factor which contributed towards the formation of the water tables is the sandy texture of the profiles. It is known that these soils have poor water retention properties (Chimungo, 2010), low water holding capacities (Bennie et al., 1988) and high hydraulic conductivities as can be derived from the saturated hydraulic conductivity summarised in Table 6.3. These restrictive properties demand additional managerial inputs, for instance careful estimations of when and how much to irrigate, to prevent under and over irrigation. Under irrigation can lead to crop water stress and yield losses, while over irrigation and periods of high rainfall will enhance drainage and the rise of water tables.

Table 6.3 Pedological and physical properties such as soil form and family, terrain unit and slope, structure, silt-plus-clay content, saturated hydraulic conductivity (K_s) and bulk density (ρ_b) of all the measuring points (MP) that were grouped as sandy

MP	**Soil type**	**Terrain**		**Structure**			**Silt-plus-clay (%)**			**K_S (mm h^{-1})**			**ρ_b (kg m^{-3})**		
		Unit	**Slope (%)**	**Horizon**											
				A	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
or4	Hutton Ventersdorp	1	0	ap	ap	ap	7.4	11.6	12.8	50	31	23	1594	1629	1671
or5	Hutton Ventersdorp	1	0	ap	ap	ap	10.6	12.6	14.6	50	31	23	1594	1629	1671
or6	Hutton Ventersdorp	1	0	ap	ap	ap	11.6	12.2	12.6	50	31	23	1574	1629	1671
or8	Hutton Ventersdorp	1	0	ap	ap	ap	9.9	12.1	13.3	50	31	23	1574	1629	1671
or9	Hutton Ventersdorp	1	0	ap	ap	ap	9.9	12.1	13.3	50	31	23	1574	1629	1671
or10	Hutton Ventersdorp	1	0	ap	ap	ap	9.9	12.1	13.3	50	31	23	1574	1629	1671
or11	Hutton Ventersdorp	1	0	ap	ap	ap	9.9	12.1	13.3	50	31	23	1574	1629	1671
or17	Hutton Ventersdorp	1	1	ap	ap	ap	8.9	9.0	10.8	67	54	41	1617	1607	1613
or19	Hutton Ventersdorp	1	1	ap	ap	ap	7.6	8.6	9.5	67	54	41	1617	1607	1613
v6	Hutton Ventersdorp	4	0.5	ap	ap	ap	9.6	11.2	13.9	16	11	-	1776	1768	-
v7	Hutton Ventersdorp	4	0.5	ap	ap	ap	10.8	10.9	10.9	16	11	-	1776	1768	-
v9	Hutton Ventersdorp	4	0.5	ap	ap	ap	10.1	12.8	14.6	16	11	-	1776	1768	-
or13	Bloemdal Roodeplaat	1	1	ap	ap	ap	11.2	12.3	12.8	32	23	-	1584	1688	-
v11	Bloemdal Roodeplaat	3	1	ap	ap	ap	9.7	12.7	13.6	40	35	24	1605	1640	1656
v12	Bloemdal Roodeplaat	3	1	ap	ap	ap	9.6	12.1	12.7	40	35	24	1605	1640	1656
Mean							***9.8***	***11.6***	***12.8***	***43***	***30***	***26***	***1628***	***1659***	***1658***

ap = Apedal massive

Uncontrolled rise of the water table can lead to waterlogging, which can reduce yields. Therefore, sandy soils with gentle, concave slope shape terrain and impermeable underlying material poses great irrigation risks and demands additional resources for efficient management thereof. Proof of this is the fact that all the profiles (fields) with the above mentioned qualities have artificial drainage systems, while the latter were absent where the terrain has a convex slope shape (or17 and or19). In this case, the water moves laterally on top of the impermeable calcrete layer. However, uncontrolled lateral water flow may cause waterlogging problems on the down slope side as was the case at measuring point’s or18 and or20.

These measuring points were grouped as clayey and are located to the south of measuring point's or17 and or19.

Drainage assessment: Although no artificial drainage system was installed within the crop fields of measuring point's or17 and or19, a cut-off drain was present outside the crop fields. This cut-off drain was located at the border between the sand (or17 and or19) and clay (or18 and or20) soils in between the sandy and clayey crop fields as discussed in Section 6.2.2.1. Drainage systems of the crop fields with measuring points or4, or5, or6, or8, or9, or10 and or11 had only one lateral directly underneath or less than 70 m away from the measuring point. The crop fields of measuring points or13, v6 and v7 had drainage systems with more than one lateral, while v9, v11 and v12 covered the entire field. Nevertheless, not all the systems were efficiently managed. For instance, the drainage system used at v6 and v7 was blocked over the entire measuring period, rendering it inadequate as a drain, when compared to the neighbouring farm (v9) that constantly discharged the effluent into a drainage canal. Results of the chemical analysis of the soils can provide some insight onto the sustainability of these practices.

Sodicity assessment: The mean sodium absorption ratio of a saturated extract for sandy soil was 1.0, 1.7 and 1.8 for the A, B and C horizons, respectively (Table 6.4). The mean pH of the soils was 7.0 for the A horizon, 7.7 for the B horizon and 8.1 for the C horizon. According to the sodic norms (sodium adsorption ratio of a saturated extract > 15 and pH > 8.5), the results suggested that none of the soils of the measuring points grouped as sandy are sodic.

Table 6.4 pH_{Water} measured at the start of the measuring period together with the mean sodium adsorption ratio of a saturated extract (SAR_e) and electrical conductivity of a saturated extract (EC_e) of five samplings taken during the measuring period, with reference to all the measuring points that were grouped as sandy

Measuring points	**pH_{Water}**			**SAR_e**			**EC_e ($mS\ m^{-1}$)**		
	Horizon								
	A	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
or4	6.7	7.4	8.2	0.4	0.8	1.0	40	42	64
or5	6.7	7.3	7.6	0.5	0.7	0.8	48	32	55
or6	6.4	7.0	8.5	0.5	0.7	1.2	78	50	63
or8	6.8	7.4	7.8	0.4	0.7	0.8	37	50	78
or9	6.3	7.3	7.9	0.5	1.0	1.3	33	68	74
or10	6.4	7.0	8.2	0.5	0.7	0.8	32	27	52
or11	5.9	7.1	8.3	0.5	1.0	1.1	40	71	72
or17	7.9	8.3	8.3	1.4	2.2	3.0	61	77	119
or19	7.6	7.7	7.6	1.3	2.5	2.3	63	66	78
v6	7.2	7.9	7.8	1.3	2.0	2.4	99	80	100
v7	6.6	7.7	8.0	1.5	2.4	2.7	100	97	118
v9	8.2	8.6	8.7	1.5	2.4	2.6	109	148	155
or13	8.7	8.7	8.3	1.5	4.2	3.3	105	94	103
v11	6.9	8.1	8.2	1.1	1.8	1.8	61	78	79
v12	7.0	7.8	7.9	1.4	1.9	2.3	91	94	96
Mean	***7.0***	***7.7***	***8.1***	***1.0***	***1.7***	***1.8***	***66***	***71***	***87***

Salinity assessment: Salinity is associated with total concentration of salt and is indirectly measured with the electrical conductivity of a saturation extract (EC_e) in relation to crop specific lower limits. From the EC_e results of the sandy soils (Table 6.4), several observations/generalizations were made. Firstly, the EC_e of the B and C horizons was generally higher than the A horizon. This phenomenon is to be expected and can be attributed to normal irrigation and rainfall that leached the salt from the A into the B and C horizon. Another source of salt is the upward capillary flux from the water table into the B horizon. Secondly, the mean EC_e of the profiles was almost 3 times greater than the long-term electrical conductivity of the irrigation water (implying long term leaching fraction of 0.3), which was 19 mS m^{-1} for Orange Riet and 47 mS m^{-1} for Vaalharts, as determined by measuring gauges in the rivers as explained in Chapter 3. Thirdly, the mean EC_e of the A, B and C horizons of all the measuring points grouped as sandy were 66, 71 and 87 mS m^{-1}, respectively, compared to the salinity threshold of 105 mS m^{-1} for peas, 320 mS m^{-1} for groundnuts, 350 mS m^{-1} for maize, 600 mS m^{-1} for wheat and 700 mS m^{-1} for cotton (Chapter 5). In conclusion, firstly, it seems that the removal of salt due to excessive water applications and the ability of natural and artificial drains to cope with these excessive amounts generally result in soil salinities being lower than the salinity threshold of most of the popular field crops, except peas. Secondly, the mean EC_e, for the A, B and C horizons of the sandy soils were all lower than the norm of 400 mS m^{-1} and are far from saline.

6.3.1.2 Loamy soils

Table 6.5 shows the soil form and family, terrain unit and slope, structure, silt-plus-clay content, saturated hydraulic conductivity and bulk density of all the measuring points grouped as loamy (Hereafter called loamy soils). The pH_w measured at the start of the project for all the loamy soils are provided in Table 6.6, while the mean sodium adsorption ratio of a saturated extract and electrical conductivity of a saturated extract of five samplings taken during the measuring period is also included.

Pedological assessment: From the 10 measuring points, four soil types were identified, namely: Hutton Ventersdorp (or7, or15, v3, v4, v8), Plooysburg Rietrivier (or14), Bainsvlei Amalia (v5) and Bloemdal Roodeplaat (or12, v1, v2). Despite the different soil forms many pedological features appear to be similar, such as the eolian fine sand deposits that served as parent material and the calcrete pisolitic pan that under lies the solum. These soils were located either on the crest, upper foot slope or lower foot slope with gentle (0.5 and 1%) slopes. A fluctuating water table was present in all the Hutton and Bloemdal soils, except or15. The only difference between these two soils is the fact that the signs of wetness in the Hutton soils occurred deeper than the classification depth of 1500 mm. Although the Hutton soil of measuring point or15 has a hard pan carbonate at a depth of 1950 mm, the convex slope probably explains the absence of a water table, as explained in Section 6.3.1.1. At measuring point or14 the hard pan carbonate is much shallower (1200 mm) and the soil was subsequently classified as Plooysburg. Again no water table was present despite of the concave slope at this measuring point, which was probably due to the artificial drainage system that was installed on top of the very shallow hard pan carbonate layer. The Bainsvlei soil at measuring point v5 was probably also initially a Hutton. The area was, however, for decades continuously troubled by waterlogging and drainage problems because of the concave slope and tar road that blocks the natural drainage process on the downhill side of the area. The fluctuating water table and poor drainage conditions thus resulted in the formation of the soft plinthic horizon. Like the measuring points grouped as sandy, the texture, poor water retention properties, low water holding capacities and high hydraulic conductivities of the loamy soils, are factors contributing to the formation of water tables (Table 6.5).

Compared to the sandy soils, the mean silt-plus-clay contents for all the loamy soils of 12.8, 15.7 and 18.8% were 24, 26 and 32% higher in the A, B and C horizons, respectively. The mean saturated hydraulic conductivity and bulk density of the sandy and loamy soils were very similar, as shown in Tables 6.3 and 6.5, respectively. Because of this similarity with the sandy soils, it was concluded that the loamy soils also pose a great salinization risk and therefore demand additional resources for efficient management thereof. Not all the crop fields of the measuring points grouped as loamy were artificially drained.

Table 6.5 Pedological and physical properties such as soil form and family, terrain unit and slope, structure, silt-plus-clay content, saturated hydraulic conductivity (K_s) and bulk density (ρ_b) of all the measuring points (MP) that were grouped as loamy

MP	Soil type	Terrain		Structure			Silt-plus-clay (%)			K_S (mm h^{-1})			ρ_b (kg m^{-3})		
		Unit	Slope (%)	Horizon											
				A	B	C	A	B	C	A	B	C	A	B	C
or7	Hutton Ventersdorp	1	0	ap	ap	ap	9.0	13.4	14.6	50	31	23	1574	1629	1671
or15	Hutton Ventersdorp	3	1	ap	ap	ap	11.9	13.6	32.3	42	37	31	1568	1624	1644
v3	Hutton Ventersdorp	3	1	ap	ap	ap	12.6	13.9	13.0	67	54	41	1617	1607	1613
v4	Hutton Ventersdorp	3	1	ap	ap	ap	14.9	14.0	12.3	67	54	41	1617	1607	1613
v8	Hutton Ventersdorp	4	0.5	ap	ap	ap	12.7	12.8	13.1	16	11	-	1776	1768	-
or12	Bloemdal Roodeplaat	1	1	ap	ap	ap	10.8	15.0	15.4	32	23	-	1584	1688	-
v1	Bloemdal Roodeplaat	3	1	ap	ap	ap	-	-	-	9	16	6	1679	1647	1710
v2	Bloemdal Roodeplaat	3	1	ap	ap	ap	16.7	25.3	33.4	9	16	6	1768	1647	1710
or14	Plooysburg Rietrivier	3	1	ap	ap	ap	11.4	17.4	-	42	37	31	1568	1626	1644
v5	Bainsvlei Amalia	3	1	ap	ap	ap	15.6	15.5	16.1	-	-	-	-	-	-
Mean							***12.8***	***15.7***	***18.8***	***37***	***31***	***26***	***1639***	***1649***	***1658***

ap = Apedal massive

Drainage assessment: The soils of measuring points or15, v3 and v2 were not artificially drained as no artificial drainage systems were present within 70 m. The crop fields of or7, v4, v8, or12, v1, or14 and v5 had drainage systems that contained one drainage lateral, directly beneath the measuring point or 70 m from it. The fields of v4 and v5 did not have a drainage disposal canal. Drainage water was recycled via a drainage pit from where it was pumped back to the irrigation dam, which contained Vaal River water extracted from the irrigation canal. The water was then re-used on the same fields. This practice was intended to control the water table and was stopped as soon as the measurements commenced at the measuring point and it was realised that the salt in the drainage water was also recycled.

Sodicity assessment: For the A, B and C horizons the mean sodium adsorption ratio of a saturated extract were 1.1, 2.5 and 2.7, respectively, while the mean pH_w amounted to 7.0, 7.7 and 7.9, respectively. Thus the soil can be regarded as non-sodic.

Salinity assessment: Although the mean EC_e of the B (163 mS m^{-1}) and C (183 mS m^{-1}) horizons for the measuring points grouped as loamy are higher when compared to the sandy soils, the soils are still not saline (<400 mS m^{-1}). When compared to the results obtained in Chapter 5 it is evident that the production of peas with a threshold salinity level of 105 mS m^{-1} could be problematic. The standard deviation of the A, B and C horizons for all the loamy soils were 38, 124 and 133 mS m^{-1}, respectively, compared to 28, 31 and 28 mS m^{-1}, respectively, for the sandy soils. Since the pedological, physical and most of the chemical properties of the sandy and loamy soils are similar the explanation for this variation in salt content involves differences in irrigation water quality, irrigation management and natural or artificial drainage conditions. The results suggest therefore that potentially hazardous fields with respect to salinity problems could develop in sandy and loamy soils with poor irrigation water quality, irrigation management practices and drainage conditions.

Table 6.6 pH_{Water} measured at the start of the measuring period together with the mean sodium adsorption ratio of a saturated extract (SAR_e) and electrical conductivity of a saturated extract (EC_e) of five samplings taken during the measuring period, for all the measuring points that were grouped as loamy

Measuring points	**pH_{Water}**			**SAR_e**			**EC_e ($mS\ m^{-1}$)**		
	A	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
or7	6.7	7.1	7.1	0.5	0.6	1.1	71	51	71
or15	7.2	7.7	8.4	0.7	1.0	1.3	32	41	65
v3	7.1	8.1	8.1	1.3	5.6	5.1	74	293	247
v4	6.9	7.9	7.9	1.9	4.4	3.3	123	319	228
v8	6.9	7.7	7.9	1.5	2.0	2.2	97	96	83
or12	6.4	7.6	8.2	0.5	0.6	1.1	55	41	42
v1	6.8	7.8	8.0	1.3	2.0	3.1	89	142	233
v2	6.9	7.4	8.1	1.1	3.2	4.3	62	280	458
or14	6.8	7.8	-	0.7	1.1	-	58	54	-
v5	7.9	7.8	7.7	1.8	4.1	3.0	163	316	216
Mean	***7.0***	***7.7***	***7.9***	***1.1***	***2.5***	***2.7***	***82***	***163***	***183***

Potential hazardous fields: From all the measuring points grouped as loamy (Table 6.5), the soils of the fields at measuring points v3, v4, v1, v2 and v5 are potentially hazardous (EC_e > 200 mS m^{-1}). Since the soils at measuring point's v1, v2, and v3 are sufficiently natural or artificially drained, the high EC_e values are attributed to irrigation management where less over-irrigation and therefore leaching occurred. Coincidentally, at these measuring points lucerne was the prominent crop grown during the measuring period. Measuring points v4 and v5, as explained earlier, do not have sufficient artificial or natural drainage conditions. The combined consequence of this and irrigation management are reflected in the high EC_e (> 300 mS m^{-1}) of the B horizon at these measuring points.

6.3.1.3 Clayey soils

The pedological and physical properties, as listed above, of all the measuring points grouped as clayey (Hereafter called clayey soils) are provided in Table 6.7, while the soil salinity information is provided in Table 6.8.

Pedological assessment: Two soil types, namely Sepane Ramabesa and Valsrivier Aliwal were classified from the 5 measuring points that were grouped as clayey (Table 6.7). Pedological similarities between these soils are its alluvial parent material, terrain unit which is a valley bottom and slope of 0%. The main differences between these soils according to The Soil Classification Working Group (1991) is the fact that the Valsrivier has unconsolidated material without signs of wetness within the classification depth of 1500 mm, while the opposite is true of the Sepane soil, where periodic wetting and drying of the sub-soil is indicated. Although classified differently, all the measuring points grouped as clayey are actually similar since at both the Valsrivier and Sepane soils unconsolidated material with signs of wetness are present. For the Valsrivier soil the unconsolidated material with signs of wetness is just a little deeper than the classification depth, thereby also indicating periodic wetting and drying of the sub-soil. Despite these signs of wetness it is expected that no water tables would be present under normal conditions in clayey soils, mainly because these soils have good water retention properties, high water holding capacities and low hydraulic conductivities (Table 6.7). When compared to the mean of the loamy soils, the mean silt-plus-clay content of the clayey soils for the A, B and C horizon of 53, 57 and 55% were 75, 71 and 65% higher, respectively. Although, as indicated earlier, the saturated hydraulic conductivity and bulk density of the sandy and loamy soils were similar, the measuring points grouped as clayey showed much lower values. The saturated hydraulic conductivity of the clayey soils were 77, 75 and 80% lower in the A, B and C horizon, respectively, when compared to the loamy soils. The bulk density was 13, 3 and 3% lower, respectively, in the clayey soils when compared to the loamy soils. Despite the fact that the hydraulic properties of the measuring points grouped as clayey does not favour the formation of water tables, a water table was present at measuring points or1 and or2. The formation of a water table was attributed to the lateral influx of water from surrounding fields and poor natural and/or artificial drainage conditions.

Drainage assessment: Measuring points or1 and or2 were located in a depression and were historically part of a wetland, which explains the presence of a water table and the installation of an artificial drainage system. Measuring point or2 was located on one of the four drainage laterals that were installed on the south part of the field, where the depression is the most significant. Measuring point or1 was located on the same field, but on the opposite side where no drainage laterals were installed. Visual observations from man holes indicated however that the laterals were blocked.

Table 6.7 Pedological and physical properties such as soil form and family, terrain unit and slope, structure, silt-plus-clay content, saturated hydraulic conductivity (K_s) and bulk density (ρ_b) of all the measuring points (MP) that were grouped as clayey

MP	**Soil type**	**Terrain**		**Structure**			**Silt-plus-clay (%)**			**K_S (mm h^{-1})**			**ρ_b (kg m^{-3})**		
		Unit	**Slope (%)**	**Horizon**											
				A	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
or1	Sepane Ramabesa	5	0	*s	*s	*s	41	44	46	7	6	4	1455	1531	1614
or2	Sepane Ramabesa	5	0	*s	*s	*s	54	60	62	7	6	4	1455	1531	1614
v10	Sepane Ramabesa	5	0	**s	***s	***s	41	41	41	8	10	5	1212	1681	1667
or18	Valsrivier Aliwal	5	0	**s	**s	**s	61	68	60	10	8	6	1485	1628	1567
or20	Valsrivier Aliwal	5	0	**s	**s	**s	69	70	66	10	8	6	1485	1628	1567
Mean							***53***	***57***	***55***	***8***	***8***	***5***	***1418***	***1600***	***1606***

*s = strong medium angular blocky
**s = strong coarse angular blocky
***s = moderate coarse angular blocky

Since no drainage disposal canal is present in the vicinity, drainage water from adjacent fields is pumped from a drainage pit just to the side of this crop field over a railway into a natural depression. The presence of a natural slope indicates a high probability that the effluent drains back towards the crop field through subsurface lateral movement. However, this was unfortunately never tested. Obviously these unique conditions resulted in the presence of a water table. At none of the other measuring points was a water table detected, and no artificial drainage system was installed except the cut-off drain at measuring point or18 and or20 as explained in Sections 6.2.2.1.

Sodicity assessment: The mean sodium adsorption ratio of a saturated extract and pH_w for the measuring points grouped as sandy and loamy was slightly lower, when compared to the measuring points grouped as clayey. Despite this, the mean sodium adsorption ratio of a saturated extract for the A, B and C horizons of 2.1, 2.9 and 3.7, respectively, and pH_w of 8.2, 8.6 and 8.8, respectively, for the measuring points grouped as clayey, confirm that no sodic conditions prevailed during the study period.

Table 6.8 pH_{Water} measured at the start of the measuring period together with the mean sodium adsorption ratio of a saturated extract (SAR_e) and electrical conductivity of a saturated extract (EC_e) of five samplings taken during the measuring period, for all the measuring points that were grouped as clayey

Measuring points	**pH_{Water}**			**SAR_e**			**EC_e ($mS\ m^{-1}$)**		
	A	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
or1	8.0	8.8	9.0	1.9	2.2	4.2	163	129	164
or2	8.4	8.6	8.7	1.6	2.4	4.3	170	192	202
v10	9.0	8.4	8.5	2.5	3.1	2.5	136	388	325
or18	7.7	8.6	8.8	2.3	3.4	3.4	119	130	123
or20	8.1	8.7	9.1	2.4	3.3	4.3	113	130	127
Mean	***8.2***	***8.6***	***8.8***	***2.1***	***2.9***	***3.7***	***140***	***194***	***188***

Salinity assessment: None of the clayey soils can be classified as saline (EC_e > 400 $mS\ m^{-1}$). The mean EC_e of the clayey soils in the A, B and C horizon were 140, 194 and 188 $mS\ m^{-1}$, respectively. As with the mean EC_e of the loamy soils, the production of peas could be problematic with a threshold salinity level of 105 $mS\ m^{-1}$. Table 6.8 shows in general, that as in the case of the loamy soils, the EC_e of the clayey soils varied more than the sandy soils. The standard deviation of the A, B and C horizon for the clayey soils was 26, 112 and 83, $mS\ m^{-1}$, respectively. The standard deviation of the A horizon compares well to the A horizon of the sandy (28 $mS\ m^{-1}$) and loamy (38 $mS\ m^{-1}$) soils. For the B horizon, the standard deviation compares well to the B horizon of the loamy soils (124 $mS\ m^{-1}$). Although most of the pedological, physical and chemical properties of clayey soils suggest that they are more prone to salinity problems, the EC_e of the measuring points suggested otherwise. As with the sandy and loamy soils, the results do however suggest that potentially hazardous fields with respect to salinity problems could develop in clayey soils due to poor irrigation water quality, irrigation management practices and drainage conditions.

Potentially hazardous fields: Clayey soils may be even more prone to salinity problems as these soils are normally irrigated downstream with poorer quality water like measuring points or1, or2, or18 and or20 (Chapter 7). Higher EC_e values than those measured at these measuring points were expected. Only measuring points or2 and v10 had higher EC_e values than 200 $mS\ m^{-1}$ and were regarded as potentially hazardous. The generally poor drainage conditions and irrigation water quality of the measuring points grouped as clayey are not reflected in the EC_e. An *in situ* case study assessment of the agronomical performance of two contrasting soils (sandy and clayey) during the measuring period could provide some insight onto this aspect.

6.3.2 *In situ* case study assessment

From the discussed soil quality assessment clear differences in the response and suitability of soils to irrigation were observed at the various measuring points, with regard to irrigation-induced salinity. Understanding these differences or restrictions of soils is difficult without an assessment of their agronomical performance, which incorporates the degree of unproductive water losses that will lead to crop failure, yield reductions and land degradation due to salinity. It was decided to use measuring points or17, or19, or18 and or20 in the *in sit*u assessment of the agronomical performance of two of the soil types discussed in Section 6.2.3. Measuring points or17 and or19 represent the sandy soil (Hutton) and or18 and or20 the clayey soil (Valsrivier). These measuring points were selected because they were tended by the same manager or farmer with the same irrigation water quality.

6.3.2.1 Water management

An outstanding management feature at these measuring points is the use of fallow practices (Table 6.1). Historically, fallow periods are mainly introduced under irrigation to rest the soil, i.e. protecting the soil against the build-up of diseases and pests. From a water management point of view the question which arose was: Did the hydraulic properties of the soils influence the hydrological components, especially the unproductive losses (evaporation and drainage), during the fallow and growth seasons, without exposing the crop to mild or severe water stress?

The graphs in Figure 6.2 represent detailed results on rainfall, irrigation and soil water content during fallow and crop growth sequences under the centre pivots for the Hutton (or17 and or19) and Valsrivier (or18 and or20) soils. Measuring points or18 and or20 were treated as replicates, because similar agronomical practices were applied on the areas.

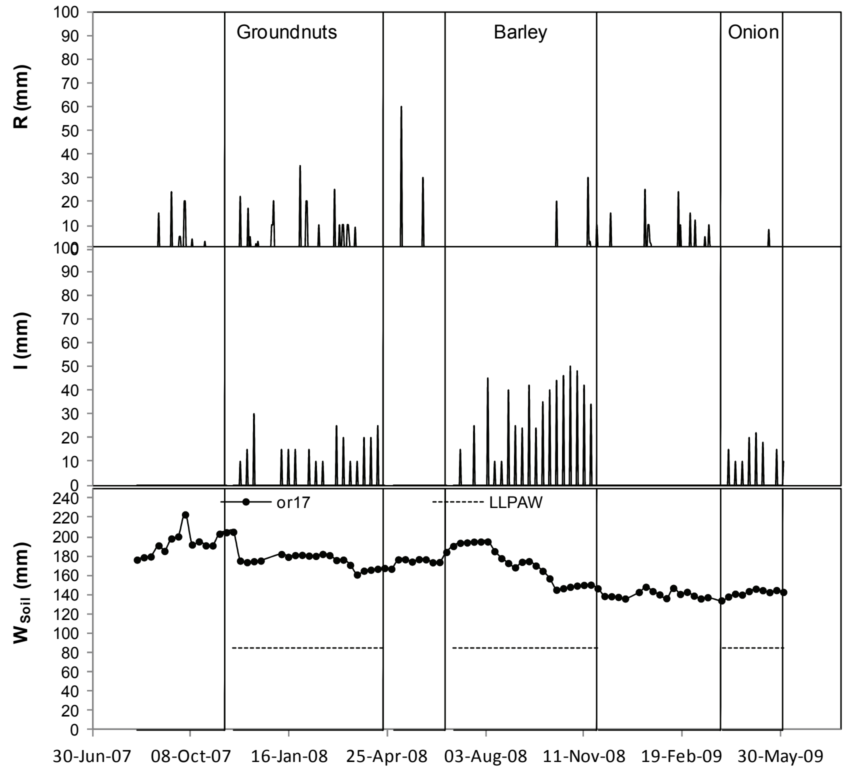
Date from measuring points or17 and or19 were kept separate, because the agronomical practices between the centre pivots differed. A summary of the soil water balance components for the fallow and growth periods of the Hutton and Valsrivier soils is presented in Table 6.9.

Rainfall storage efficiency (RSE, %), i.e. the amount of water stored in the soil (ΔW_{Soil}) per unit rain, is a good indicator of water conservation (Botha, 2006). RSE was calculated for each of the fallow periods and the results indicated that the RSE was generally low in both soils. The Hutton soil RSE was 14% in the first and 26% in the second fallow periods at measuring point or17. Negative RSE was obtained at or19, despite the 303 mm rain that was received.

Both the fallow periods of the Valsrivier soil resulted in negative RSE's, which means that none of the rain (54 mm rainfall during the first fallow and 178 mm in the second fallow) was stored and did not contribute to crop production in the succeeding seasons. Thus, irrespective of soil types, huge water losses occurred during the fallow periods. The main drivers or mechanisms of water loss during the fallow periods were evaporation and drainage.

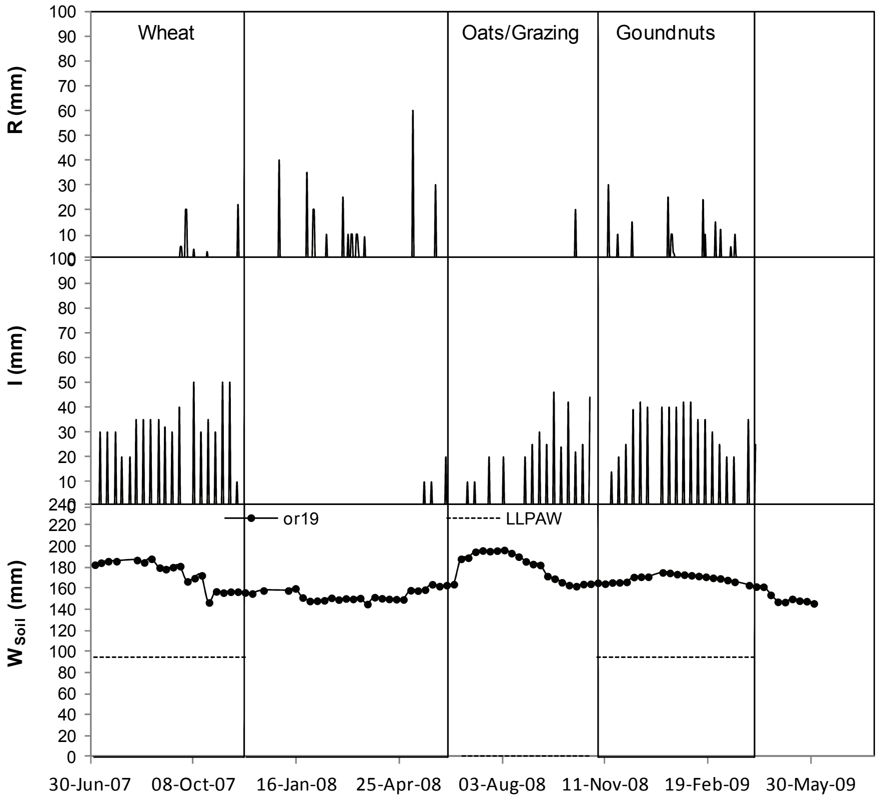
The results of the Hutton soil indicated that evaporation amounted to a total of 44 mm in the first and 25 mm in the second fallow periods at or17 and 94 mm at or19. For the Valsrivier, evaporation amounted to 56 and 148 mm during the first and second fallow periods, respectively. The mean daily evaporation rates, calculated for the total fallow period, were higher in the Valsriver soil (1.10 mm day^{-1}) than the Hutton soil (0.47 mm day^{-1}). These results were expected because of the inherent relationship between the hydraulic conductivity and soil water content of the two soils. The sandier Hutton soil has a high hydraulic conductivity in the wet range compared to the clayey Valsriver soil. The hydraulic conductivity, however, decreases rapidly in the Hutton soil as the water content decreases during drying cycles (Chimungu, 2009). This was not the case for the Valsrivier soil, which means that it can sustain high evaporation rates over longer periods when compared to the Hutton soil (Hillel, 2004). The above mentioned hydraulic properties of the two soils have huge implications for water loss through drainage. The Hutton has a very high saturated hydraulic conductivity (Table 6.3 and 6.7) and low water retention compared to the Valsrivier (Chimungu, 2009), which entails that the Hutton has a high risk of water loss through drainage. The drainage results obtained during the fallow periods of the soils, confirmed the theoretical explanation; 39 and 75 mm over the fallow periods at or17, and 256 mm at or19, compared to the 0 and 45 mm in the first and second fallow periods of the Valsriver.

The hydraulic properties of the soils have similar effects on water losses during the growing seasons. The mean soil water loss through evaporation during the growing season in the Valsriver was about twice as high as the Hutton; 101 mm per season compared to 40 mm per season at or17 and 52 mm per season at or19. The drainage situation turned around where the loss amounted to a mean of 30 mm per crop season in the Valsriver, compared to the 209 mm per season at or17 and 307 mm per season at or19. This high loss of water from the potential root zone occurred in spite of the presence of the impermeable hardpan carbonate layer in the Hutton, as explained in Section 6.2.3.1. The only explanation is that water drains laterally at a high rate on top of this layer, due to the convexity of the slope as discussed in Section 6.3.1.1.

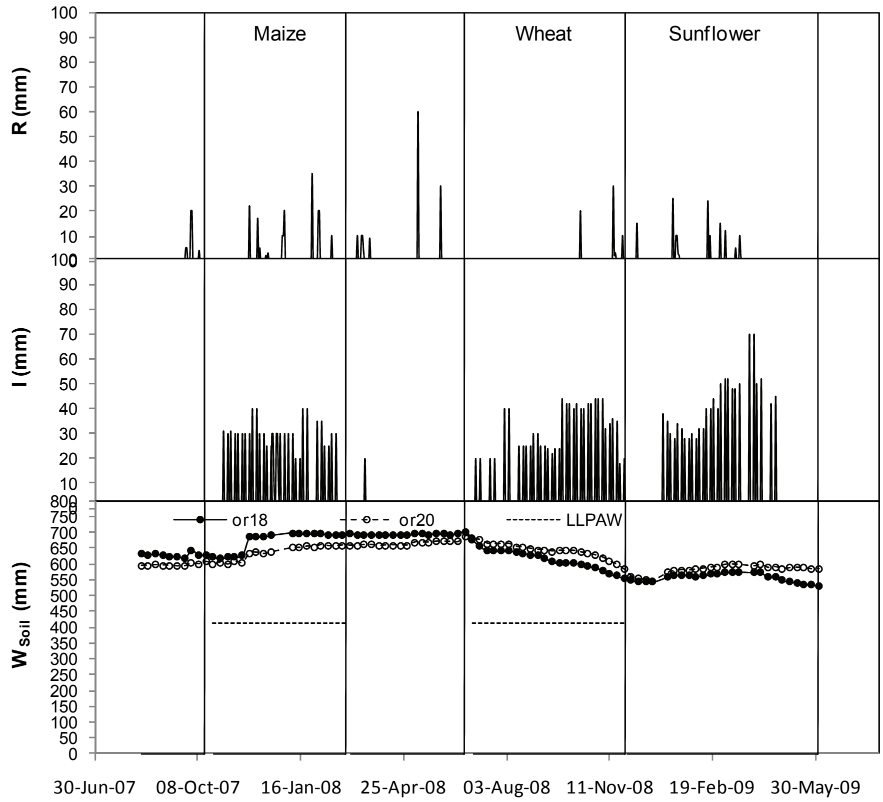


(a)

Figure 6.2 Rainfall (R), irrigation (I), soil water content (W_{Soil}) and lower limit of plant available water (LLPAW) for measuring points or17 (a), or19 (b) and or18, or20 (c).



(b)



(c)

Figure 6.2 continued

The fact that there was no water table present during the study period supports this explanation. The results also explain why the farmer had installed the cut-off drain between the border of the sandy and lower lying clay soils as indicated in Figure 6.1b. With this intervention the natural hydraulic process of discharging effluent on the clay soils was stopped, which improved water management of the clay soil. To support this statement the flow rate, expressed in litres per minute, and volume of water discharged by the three laterals (Figure 6.1b) were analysed.

Figure 6.3 shows the flow rate for all three laterals during the entire measuring period. Drainage laterals A and B stopped flowing for a short period from the middle July 2008 to the middle September 2008. Drainage lateral C only flowed for a short period from the end of June 2008 to the beginning of December 2008. The flow rate of drainage lateral B was the lowest and varied between 1 and 7 L min^{-1} with a mean of 3.4 L min^{-1} during the measuring period. Drainage lateral A varied between 10 and 20 L min^{-1} during the first year (July 2007 to July 2009) after which it increased to approximately 40 L min^{-1} during the second year, with a mean of 25.5 L min^{-1} during the measuring period. It was assumed that each drainage lateral drained an area 20 m on either side of it which, according to Hillel (2000), is the drain spacing for clay soils. The length of the three drainage laterals was obtained from the farmer, which resulted in a combined drainage area of 11 800 m^2. From this it was calculated that the three drainage laterals discharged 3029 mm of water in total or 35 744 m^3 at a mean combined rate during the measuring period of 4.6 mm day^{-1}. This confirms therefore that lateral water flow from the higher lying sandier irrigated fields towards the lower lying clay fields was controlled effectively by these three drainage laterals.

From a management point of view the question arises about how the water balance components can be managed to reduce the losses without harming the soil. The obvious management practice for restricting evaporation is mulching. From the descriptions of the agronomical practices in Table 6.1 at the measuring point (Table 6.1), it can be concluded that for most of the fallow periods the soil surface was covered with mulch.

Table 6.9 Net gain (+D) or loss (-D) of water from the potential root zone through upward or downward drainage for measuring points or17, or19 and or18, or20 as calculated from the change in soil water content (ΔW_{Soil}), rainfall (R), irrigation (I), evaporation (E) and transpiration (T)

Soil	Measuring point	Crop	ΔW_{Soil}	R	I	E	T	ET	± D
			mm						
Hutton	**or17**	**Fallow**	13	96	0	44	0	44	**-39**
		Groundnuts	-5	262	265	39	280	319	**-213**
		Fallow	35	135	0	25	0	25	**-75**
		Barley	-45	65	599	40	464	504	**-205**
	or19	**Wheat**	-62	79	627	49	500	548	**-219**
		Fallow	-7	303	40	94	0	94	**-256**
		Oats/grazing	-35	65	385	74	131	205	**-280**
		Groundnuts	-51	185	609	32	340	375	**-421**
Valsrivier	**or18, or20**	**Fallow**	-2	54	0	56	0	56	**0**
		Maize	31	199	496	82	507	589	**-75**
		Fallow	-5	178	10	148	0	148	**-45**
		Wheat	-89	65	572	124	589	712	**-14**
		Sunflower	-60	131	584	96	679	775	**0**

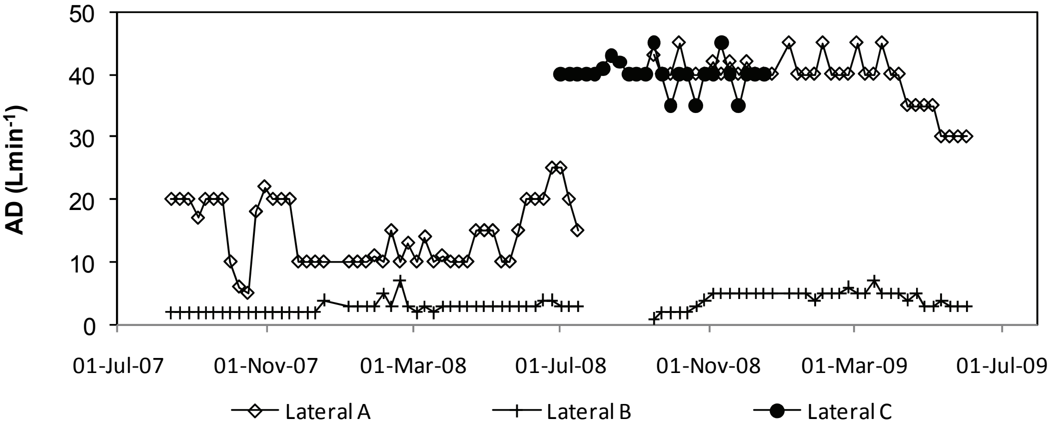


Figure 6.3 Measured flow rate (AD) from the three drainage laterals installed on the border of the sand and clay soils in between the crop fields at or17 and or18, or20 during the measuring period.

The mean evaporation rates over the fallow periods were 0.47 mm day^{-1} at or17 and or19 and 1.10 mm day^{-1} for the Valsriver. These evaporation rates compared well with the rates reported in other studies conducted in semi-arid conditions (Bennie et al., 1994; Van Rensburg, 2010). Thus, not much more can be done to restrict evaporation from both soils. However, this is not the case for drainage. Bennie (1995) showed that the profile available water capacity (PAWC) can be utilised to reduce drainage in two ways. Firstly, the long-term rainfall patterns need to be analysed and enough storage space should be reserved in the profile to accommodate rain events during the growing season. Secondly, the soil water content at the start of the fallow period needs to be near the lower limit of plant available water. This means that irrigation should be scheduled in such a way that the season ends with a dry profile. In retrospect, the soil water contents were in most cases very high at the start of the fallow periods. Hence, it is clear that if the above indicated principles are employed, a considerable amount of rainwater can be conserved during the fallow and growing seasons of these soils. The sandy nature of the Hutton soils, high hydraulic conductivity and low water holding capacity combined with the high soil water contents results in a lot of water loss through drainage during high rain events or high irrigations. The benefit of this is that poorer quality irrigation water can be utilized, since leaching can easily take place.

6.3.2.2 Salt management

The results of specific salinity indicators, such as the electrical conductivity of the irrigation water (EC_i) and electrical conductivity of the soil, measured as a saturated extract (EC_e), are presented in Figure 6.4. Note that EC_i was measured weekly, while EC_e was measured five times during the study period (seasonally). Figure 6.5 presents detailed graphs on the EC_e distribution in the profile for the five sampling events. The results of the soil water balance components and the associated salt concentrations are summarized in Table 6.10.

Salt addition: The amount and quality of irrigation water played a huge role in the total addition of salt to the soils compared to fertilizers and rainwater. For the Hutton soil, the total additions were 6975 kg ha^{-1} (or17) and 13381 kg ha^{-1} (or19) and for the Valsrivier 14901 kg ha^{-1}. Of these sources, the contribution through rain was the lowest, 1% of the total salts added in both soils. Salt dissolved from fertilizer application amounted to 12 and 7% of the total salt applied to the Hutton (or17 and or 19) and 8% to the Valsrivier. Irrigation was by far the principal source of salt and contributed 87, 93 and 91% of the total salt additions to the Hutton (or17, or19) and the Valsrivier, respectively. This was due to the poor quality of the irrigation water when compared to measuring points that utilized the Orange River (21 mS m^{-1}) as a source. The irrigation water was a blend of drainage water collected from the higher lying Hutton and water extracted from the Riet River. The results in Figure 6.4 showed that the EC_i was stable over the first year of the study; the values fluctuated between 65 and 97 mS m^{-1}. However, with the arrival of the dry winter season, the EC_i rose sharply from 75 to 130 mS m^{-1}, where after it gradually decreased to its original value at the end of that season. During the following summer the EC_i started to rise again, first gradually and then sharply from the middle of the season, reaching a peak of about 200 mS m^{-1} at the end of the season.

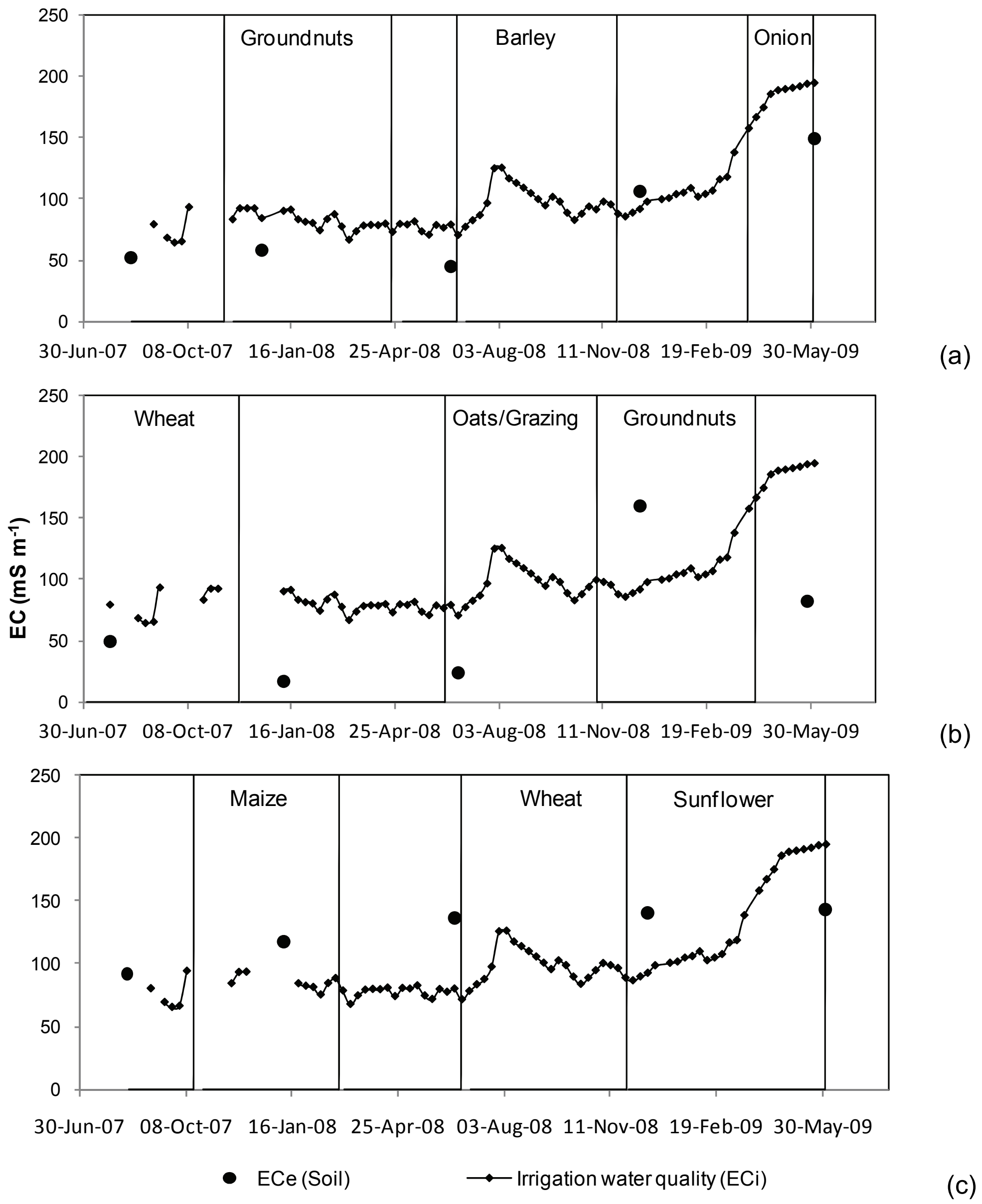


Figure 6.4 The electrical conductivity of the irrigation water (EC) and soil, measured as a saturated extract ($EC_{e\ Soil}$), at measuring points or17 (a), or19 (b) and or18, or20 (c) during the entire measuring period.

The sharp increase in the EC_i, coupled with the high water demand (679 mm), had a huge impact on the total salt additions to the Valsrivier during the sunflower seasons. More than 6000 kg salt ha^{-1}, which was almost half of the total amount applied over the two years of the study.

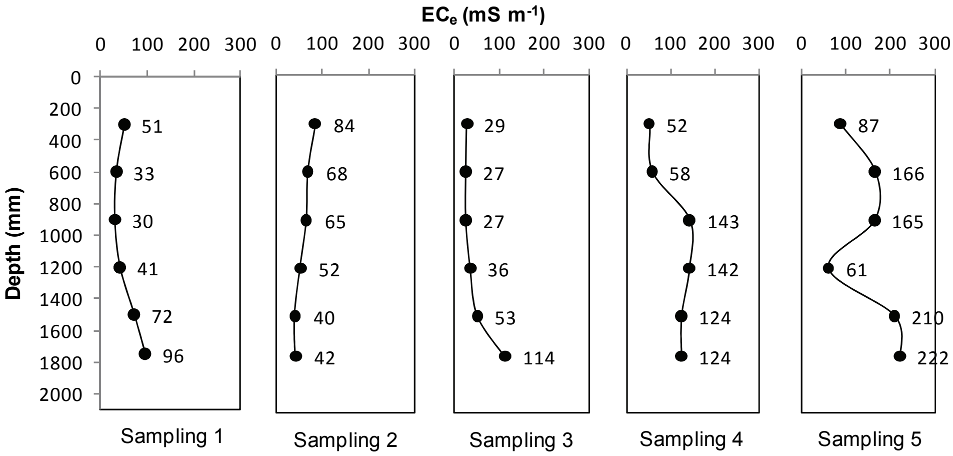
Salt removal and changes in the profile: Salt removal was estimated with the SWAMP model by combining field measurements and modelling to solve the salt balance numerically, as explained in Chapter 4. Unfortunately the limitation of the model is that it uses leaching as the sole remover of salt from the profile and does not take precipitation or dissolution of salts into account. Given this limitation, the model estimated that leaching removed 68% (4776 kg salt ha^{-1}) and 86% (11482 kg salt ha^{-1}) of the total salt added to the Hutton at or17 and or19, respectively (Table 6.10). For the Valsriver, the model estimated that only 7% (1038 kg salt ha^{-1}) of the total additions (14901 kg salt ha^{-1}) were removed via leaching. Leaching estimations for both soils seemed reasonable, especially when the soil wetness conditions and hydraulic properties are taken into account. The problem, however, was that the predicted EC_e values of particular wheat and sunflower periods at the Valsrivier were considerably higher than the measured EC_e values. This implied that salt was additionally removed via mechanisms other than leaching. It was assumed that the difference between salt addition and leaching was removed through precipitation. These calculated values are listed in Table 6.10.

The poor leaching in the Valsrivier can also be seen in the EC_e distribution over the profile (Figure 6.5). These results showed that the depth distribution of the EC_e profiles was relatively homogeneous. There was a slight build-up towards the last season, but not at the rate expected, given the high amount of salt applied. Another salient feature is that none of the EC_e depth interval measurements in the Valsrivier exceeded 200 mS m^{-1} during any of the five sampling events, despite the extremely high salt additions to the soil. As indicated earlier, the hydraulic properties of the Hutton enhanced leaching, but despite this there was a steep build-up of salts over the last three EC_e measurements at or17 and between the third and fourth sampling dates at or19. Over-irrigation during the last season at or19 leached most of the salts. Thus, it is clear that irrigation scheduling plays a more prominent role in the salt distribution of the sandy soil. The salt distribution was homogeneously distributed after the over-irrigation. It is interesting to note that the EC_e levels rose sometimes above 200 mS m^{-1} in the Hutton (sampling 5 at or17; sample 4 at or19).

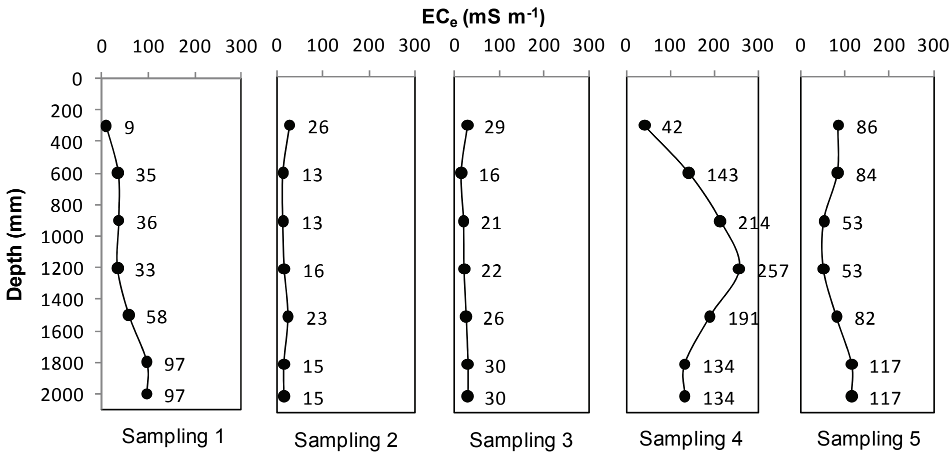
The poor quality irrigation water utilized by the farmer, and the high leaching fractions on the higher lying sandy soils, poor quality water is expected to flow from the three drainage laterals. Figure 6.6 shows the measured electrical conductivity of the drainage water from the three drainage laterals during the measuring period. At drainage lateral C the electrical conductivity was the lowest and varied between 251 and 269 mS m^{-1}, with a mean of 258 during the measuring period. During the first year of measurements the electrical conductivity at drainage lateral A and B remained constant at approximately 550 and 600 mS m^{-1}, respectively.

From September 2008 the electrical conductivity at both drainage laterals decreased to about 450 mS m^{-1}. Drainage lateral A remained relatively constant from there onwards, while drainage lateral B increased to a maximum of 688 mS m^{-1}. The mean electrical conductivity of drainage laterals A and B during the measuring period was 515 and 588 mS m^{-1}, respectively, while the mean for the three drainage laterals amounted to 513 mS m^{-1}. The combined total volume of water removed by the three drainage laterals and the high electrical conductivity of this water resulted in the removal of a total 115.8 ton or 9815 kg ha^{-1} of salt, during the measuring period, from the 11800 m^2 drainage area. Most of the salt that was removed by the three drainage laterals was recycled since the drainage water was blended with

Lower Riet River water and used as irrigation water (mean EC_i = 102 mS m^{-1}) on the sandy and clayey soils.



(a)



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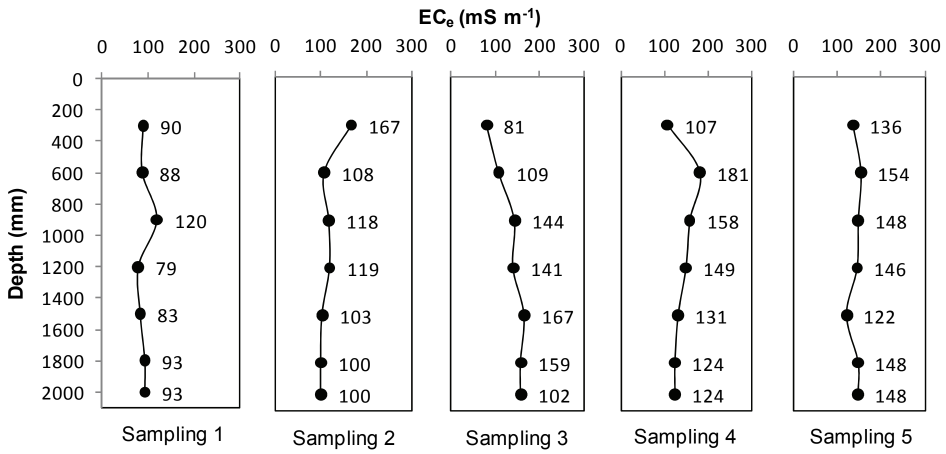


(c)

Figure 6.5 Salt distribution in the soil profile, expressed as the electrical conductivity of a saturated extract, for the five sampling events (July 2007, December 2007, June 2008, December 2008 and May 2009) taken during the measuring period at or17 (a), or19 (b) and or18,or20 (c).

Table 6.10 Net gain (+S_D) or loss (-S_D) of salt from the potential root zone through upward or downward drainage for measuring points or17, or19 and or18, or20 as calculated from the change in salt content of the soil (ΔS_{Soil}), salt from rainfall (S_R), salts from irrigation (S_I) and salt that precipitated (S_{Prec})

Soil	Measuring points	Crop	ΔS_{Soil}	S_F	S_R	S_I	S_{Prec}	± S_D
			kg ha^{-1}					
Hutton	**or17**	**Fallow**	-117	0	14	0	-	**-131**
		Groundnuts	511	343	39	1630	-	**-1501**
		Fallow	-802	0	20	0	-	**-822**
		Barley	2606	471	10	4448	-	**-2322**
	or19	**Wheat**	3188	503	12	3809	-	**-1136**
		Fallow	-1502	0	45	239	-	**-2550**
		Oats/grazing	2593	0	10	2830	-	**-246**
		Groundnuts	-1616	381	21	5531	-	**-7550**
Valsrivier	**or18, or20**	**Fallow**	8	0	8	0	-	**0**
		Maize	3106	334	30	3112	-	**-368**
		Fallow	-489	0	27	0	-	**-515**
		Wheat	684	527	10	4208	3905	**-155**
		Sunflower	239	362	20	6263	6406	**0**

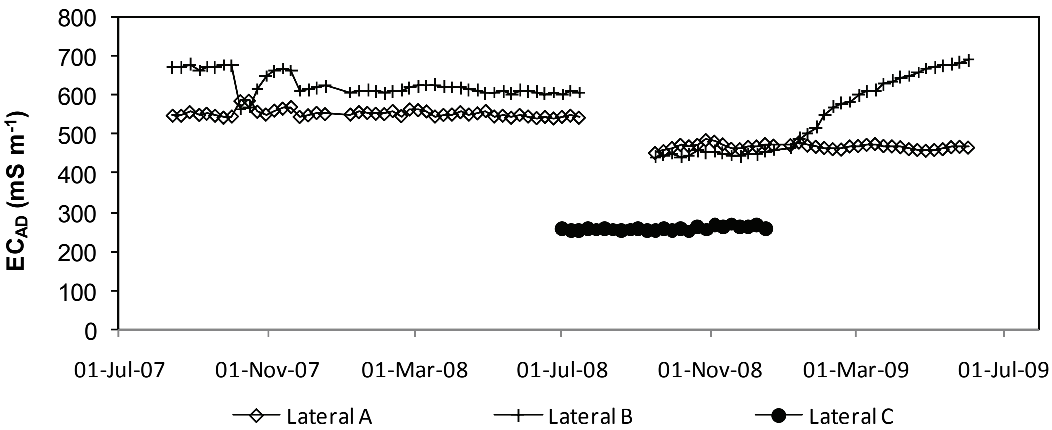


Figure 6.6 Measured electrical conductivity (EC_{AD}) from the three drainage laterals installed on the border between the sand and clay soils in between the crop fields at or17 and or18, or20 during the measuring period.

6.3.3 Desktop case study assessment

6.3.3.1 Results of water balance components

Table 6.11 provides a summary of the four soil's response with respect to the water balance components as affected by the 20 years of irrigation with a scheduling strategy of minimising drainage (Section 6.2.3). The total potential transpiration for wheat and maize grown at Orange-Riet in the Hutton and Valsrivier soils amounted to 8725 and 10812 mm, respectively, given the evaporative demand of the atmosphere for the 20 years. At Vaalharts the potential transpiration amounted to 8429 and 9835 mm for wheat and maize, respectively, that were planted in the Bainsvlei and Bloemdal soils. For the Hutton soil, the rainfall was 6831 mm and irrigation 9481 mm. With respect to the productive water losses it is clear that transpiration was suboptimal; transpiration of wheat and maize were only 75 and 58% of the total potential transpiration, respectively. Evaporation during the winter wheat seasons was 18% higher than during the maize seasons, which was in contrast to what was expected. The reason was mainly because 25% more water had been irrigated during the wheat seasons. Total evaporation during the wheat-maize crop rotation was however still low due to the sandy nature of the Hutton soil and efficient irrigation scheduling methods. In addition to these losses of water from the Hutton soil, 10% of rainfall-plus-irrigation drained beyond the potential root zone. This demonstrates the poor water retention properties of the soil, in terms of plant available water, which emphasises that these soils require special management in order to conserve water while maintaining good yields.

Although the Valsrivier soil received the same amount of rainfall as the Hutton soil, irrigation was higher. Irrigation contributed approximately 100% (8731 and 9297 mm for wheat and maize, respectively) towards the total potential transpiration. The higher amount of total evaporation (5177) of the Valsrivier soil compared to the Hutton soil was due to its high clay content. Given that irrigation contributed almost totally towards the total potential transpiration, approximately 76% of the rain that fell was evaporated (5177 mm). Rainfall was thus inefficient in causing drainage seeing that only 1.1% of the total rainfall-plus-irrigation drained beyond the potential root zone, which highlights the better water retention properties of the soil, when compared to those of the Hutton.

Regarding the Bainsvlei soil, irrigation was 13457 mm less than for the Valsrivier soil. This was due to the fact that the water table contributed approximately 100% towards evapotranspiration. The result was that approximately 92% of rainfall-plus-irrigation percolated through the potential root zone and recharged the water table. The difference between water table recharge (12525 mm) and uptake (24175 mm) was received via lateral drainage from higher lying fields.

Table 6.11 Net gain (+D) or loss (-D) of water from the potential root zone (2000 mm) through upward or downward drainage for the four soils during the wheat, maize and maize drying simulations, as calculated from the simulated change in soil water content (ΔW_{Soil}), rainfall (R), irrigation (I), evaporation (E), transpiration (T), runoff, water table uptake (WTU) and percolation towards the water table (P)

Soil	Simulated period	mm								
		ΔW_{Soil}	R	I	E	T	±D	WTU	P	Runoff
Hutton (or17)	Wheat	24	2106	5432	758	6519	-238	0	238	0
	Maize	-50	4069	4049	619	6310	-1239	0	1239	0
	Maize drying	12	656	0	484	0	-159	0	159	0
	Total	***-14***	***6831***	***9481***	***1861***	***12828***	***-1637***	***0***	***1637***	***0***
Valsrivier (or18)	Wheat	24	2106	8731	2088	8725	0	0	0	0
	Maize	355	4069	9297	1927	10812	-272	0	272	0
	Maize drying	-514	656	0	1162	0	-8	0	8	0
	Total	**-135**	**6831**	**18028**	**5177**	**19537**	**-280**	**0**	**280**	**0**
Bainsvlei (v5)	Wheat	0	2479	3552	3759	8355	6123	11916	5793	40
	Maize	0	5464	1018	1845	8813	4246	9938	5692	70
	Maize drying	0	1039	0	2321	0	1282	2321	1039	0
	Total	***0***	***8982***	***4571***	***7925***	***17168***	***11650***	***24175***	***12525***	***110***
Bloemdal (v11)	Wheat	365	2479	2323	888	8429	4960	5924	964	80
	Maize	-43	5464	2046	1007	9835	3453	6110	2657	165
	Maize drying	-335	1039	0	695	0	-680	0	680	0
	Total	***-14***	***8982***	***4369***	***2589***	***18264***	***7734***	***12034***	***4301***	***245***

Irrigation on the Bloemdal soil was similar to that of the Bainsvlei, while both soils received the same amount of rain. In contrast to the Bainsvlei soil, the water table of the Bloemdal soil contributed 12141 mm less towards evapotranspiration, because the capillary fringe was not in contact with the active evaporation zone and less of the root zone was within the capillary fringe. This also resulted in 5336 mm less water evaporating from the Bloemdal soil when compared to the Bainsvlei. Consequently more rainfall-plus-irrigation contributed towards evapotranspiration, which caused only 58% of rainfall-plus-irrigation to percolate and recharge the water table. Ultimately the Bloemdal received therefore 3916 mm less water, via lateral drainage from higher lying fields, in order to balance the difference between water table recharge and uptake.

6.3.3.2 Results of salt balance components

The results of the four soils in terms of the salt balance components for the 20 year period are shown in Table 6.12. The total salt added to the Hutton soil amounted to approximately 87 t ha^{-1}, of which rain contributed 1%, fertilization 16% and irrigation the rest (83%). Of these additions, 9347 kg ha^{-1} were stored in the soil profile. The rest of the salt was leached; 89% of the total additions. Despite the fact that in total a significant amount of salt was removed from the potential root zone, the potential transpiration was not obtained.

Table 6.12 Net gain (+S_D) or loss (-S_D) of salt from the potential root zone (2000 mm) through upward or downward drainage as calculated from the simulated change in salt content of the soil (ΔS_{Soil}), addition of salt through fertilizers (S_F), rainfall (S_R), irrigation (S_I) and capillary rise (S_{WTU}) as well as movement of salt into the water table through percolation (S_P) and salt precipitation (S_{Prec}) for the four soils during the wheat, maize and maize drying simulations

Soil	Simulated period	kg ha^{-1}							
		ΔS_{Soil}	S_F	S_R	S_I	S_{Prec}	$\pm S_D$	S_{WTU}	S_P
Hutton (or17)	Wheat	42726	13720	316	41556	0	-12865	0	12865
	Maize	-26705	13604	610	30976	0	-71895	0	71895
	Maize drying	-6675	0	98	0	0	-6773	0	6773
	Total	***9347***	***27324***	***1025***	***72532***	***0***	***-91534***	***0***	***91534***
Valsrivier (or18)	Wheat	11194	13720	316	66378	69220	0	0	0
	Maize	3990	13604	610	71121	65759	-15586	0	15586
	Maize drying	-319	0	98	0	0	-417	0	417
	Total	***14865***	***27324***	***1025***	***137498***	***134979***	***-16003***	***0***	***16003***
Bainsvlei (v5)	Wheat	18342	13720	372	17312	0	-13062	97234	110297
	Maize	3555	13604	820	4953	0	-15822	100873	116694
	Maize drying	-25242	0	156	0	0	-25398	0	25398
	Total	***-3346***	***27324***	***1347***	***22265***	***0***	***-54282***	***198107***	***252389***
Bloemdal (v11)	Wheat	40157	13720	372	11312	0	14753	72769	58015
	Maize	-17755	13604	820	9951	0	-42129	75325	117454
	Maize drying	-23480	0	156	0	0	-23633	0	23633
	Total	***-1077***	***27324***	***1347***	***21260***	***0***	***-51008***	***148094***	***199102***

The Valsrivier soil received the same amount of salt through fertilization and rainfall. However because 1.9 times more irrigation was applied, when compared to the Hutton, 64966 kg ha^{-1} of additional salt was added. Little of these salt additions were leached from the soil due to the small amount of drainage (Table 6.11). The difference between the amount of salt stored in the soil (14865 kg ha^{-1}) and the amount leached was assumed to precipitate, which amounted to 50 mS m^{-1} or 3461 kg ha^{-1} per cropping season.

Despite of the fact that more salt accumulated in this soil, when compared to the Hutton, no reduction in the potential transpiration was simulated. This aspect will be elaborated on in the next section.

For the Bainsvlei soil, salt additions through fertilization and rainfall were similar to those of the Valsrivier soil. Since less irrigation was applied due to the presence of a water table, 75% less salt was applied than for the Valsrivier soil. However, by utilizing the water table an additional 198107 kg ha^{-1} of salt was added to the soil through capillary rise. Of these total salt additions to the soil, 100% was leached into the water table. To balance the difference between these additions to the water table and the addition to the soil through capillary rise, a net of 40620 kg ha^{-1} was removed from the soil through lateral drainage to lower laying fields.

The Bloemdal soil, when compared to the Bainsvlei soil, received approximately the same amount of salt through fertilization, rainfall and irrigation. However, because the water table was 500 mm deeper, as opposed to the Bainsvlei soil, 25% less salt was applied to the potential root zone through capillary rise. Like the Bainsvlei soil, 100% of these total salt additions to the potential root zone were leached into the water table. Again, in order to balance the difference between these additions and the addition to the potential root zone through capillary rise, a net loss of 37347 kg ha^{-1} of salt to lower lying fields had to occur. The result was that the salt content of the soil decreased by 1077 kg ha^{-1} over 20 years. The fact that the total potential transpiration of wheat and maize was obtained in the Bloemdal soil and not the Bainsvlei soil needs further attention, and will be discussed in the next section.

6.3.3.3 Discussion on the impact of water and salt management on yield

The simulation results showed that the four soils responded uniquely to irrigation. This can be derived from the soil water content, drained upper limit and lower limit of plant available water results shown in Figure 6.7. The soil salinity over 20 years, expressed relative to the initial salinity and the relative seed yields for every season were also included in Figure 6.8.

Hutton

The first unique feature of the soil is its low evaporability. This can be seen from the long-term evaporation of the wheat-maize crop rotation results, which amounted to 11% of rainfall-plus-irrigation. The low evaporation is attributed to its sandy nature, which is associated with a high infiltration capacity and internal drainage. The second feature refers to the low profile available water capacity (PAWC) of the soil. The PAWC is the difference between the drained upper limit and the lower limit, amounting to a mean of 80 mm. During the simulation period the wheat-maize crop rotation never utilised more than 73% of the Hutton's plant available water, when the osmotic effect on plant available water was neglected. However, the salt accumulation plays a critical role in lowering the PAWC by adjusting the lower limit, as shown in Figure 6.7. The long-term mean results showed that 29% of the PAWC was reduced due to the osmotic potential induced by a mean electrical conductivity of 320 mS m^{-1}. This had a significant impact on the seed yield of wheat and maize as shown in Figure 6.8. The results show that during periods where soil salinity increased with a factor of three (474 mS m^{-1}) only 60% of the potential seed yield of wheat and maize was obtained. When soil salinity was decreased due to leaching by excess rain, more than 80% of the potential seed yield for wheat and maize was obtained. The third feature of the soil is associated with its deep drainage. Deep drainage amounted to a mean of 82 mm per year, which is high, considering the fact that irrigation scheduling was adopted to minimise drainage. This illustrates the difficulty of managing PAWC, especially its upper limit. Bennie (1995) recommended that a fraction of the PAWC must be reserved for rain. In retrospect, it is clear that the PAWC of sandy soils must be managed carefully. This is especially true where an irrigation schedule method of minimising drainage is applied. Under these conditions there is a tendency toward salt accumulation, which will reduce the PAWC further. The results therefore confirm the general opinion that sandy soil is a class two irrigation soil, due to the additional management that it requires.

Valsrivier

When the features of the Vaslrivier soil are compared to the Hutton soil the opposite was observed. This soil has a high evaporability (Section 6.3.3.1); the long term evaporation of the wheat-maize crop rotation was 21% of rainfall-plus-irrigation, i.e. 2.7 times higher than the Hutton. The high evaporation of the soil is attributed to its high unsaturated hydraulic conductivity under moderate to low soil water contents in the A-horizon. The second feature of the soil is its high PAWC, which amounted to 272 mm. Fortunately, the soil water content never decreased below 78% of the PAWC in the wheat-maize crop rotation. When considering that the osmotic effect, the PAWC was reduced by a mean of 4% or 12 mm (Figure 6.7).

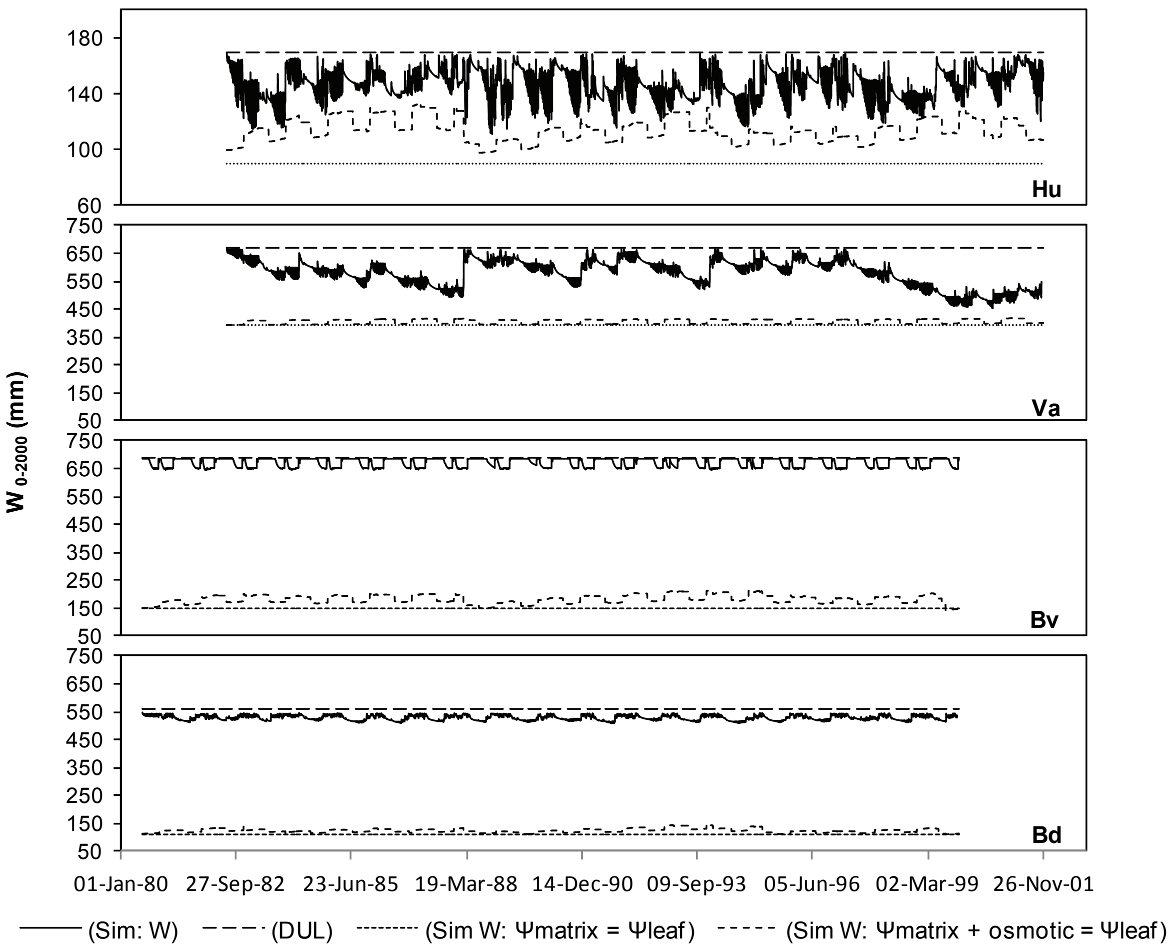


Figure 6.7 Simulated (Sim:) soil water content (W), drained upper limit, soil water content where matrix potential is equal to critical leaf water potential (Ψ_{matrix} = Ψ_{leaf}) and soil water content where matrix-plus-osmotic potential is equal to critical leaf water potential ($\Psi_{matrix + osmotic}$ = Ψ_{leaf}) for the Hutton (Hu), Valsrivier (Va), Bainsvlei (Bv) and Bloemdal (Bd) soils during the 20 year simulation period.

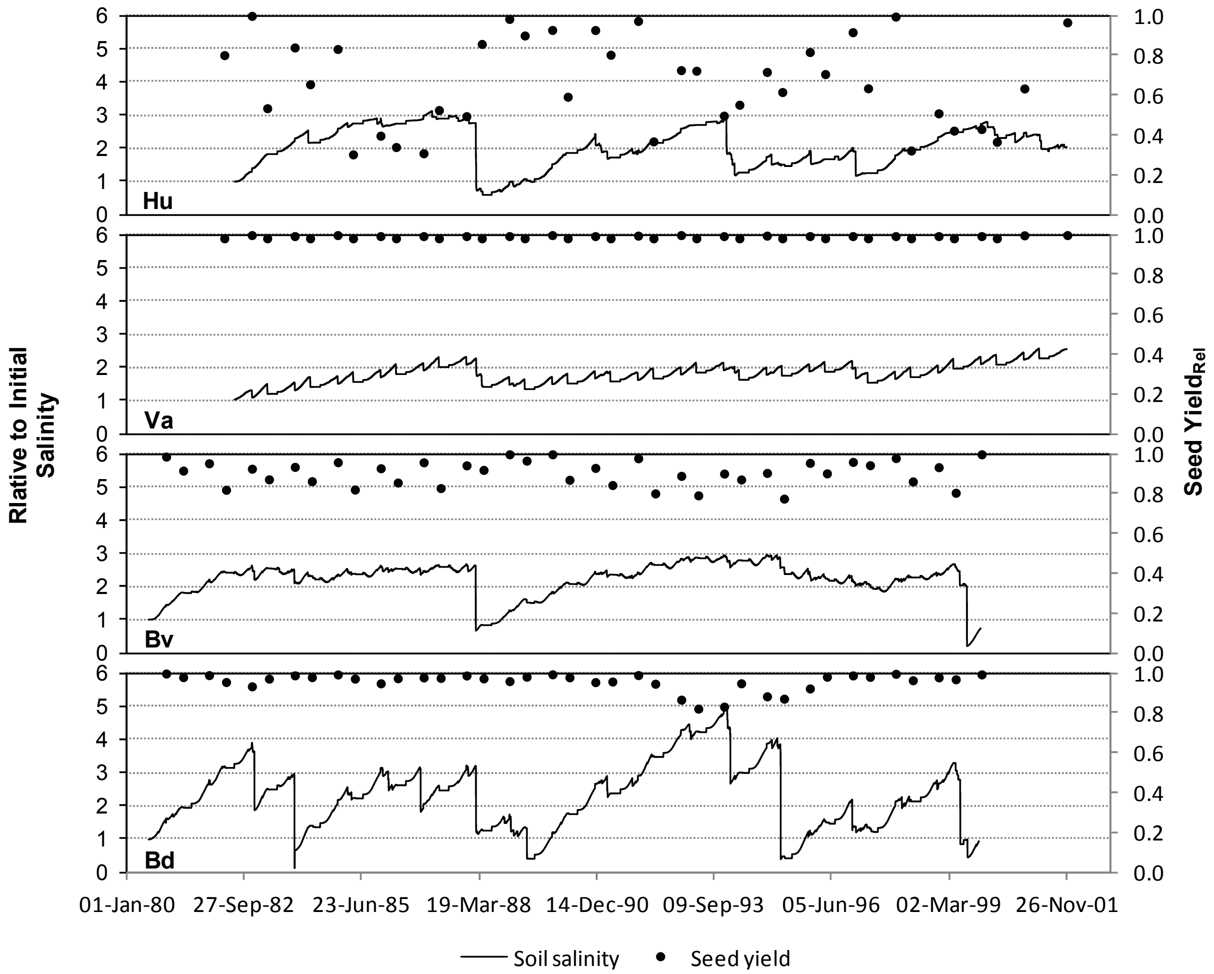


Figure 6.8 Simulated salt accumulation in the root zone expressed as a factor of the initial soil salinity at the start of the simulation for the Hutton (Hu), Valsrivier (Va), Bainsvlei (Bv) and Bloemdal (Bd) soils during the 20 year simulation period.

This was induced by a mean electrical conductivity of 295 mS m^{-1}. Understandably the osmotic effect had no impact on the seed yield of wheat and maize as shown in Figure 6.8 due to the high plant available water and relative low salinity. At no time during the 20 years did the seed yield of wheat and maize decrease below 95% of the target yields. The third feature of the soil is its low drainage, which amounted to 14 mm per annum. Leaching was responsible for removing only 800 kg salt ha^{-1} per annum, while a total of about 8300 kg salt ha^{-1} were added annually. In the model it was assumed that the balance precipitated in the soil. This aspect demands further research. However, if the assumption of salt precipitation is valid, the Valsrivier soil will be suitable for irrigation, which was also confirmed by Le Roux et al. (2007). These authors found that the soil quality of the Valsrivier at Vaalharts, for example, improved over five years of irrigation. The low soil salinity hazard and the high PAWC, makes this soil manageable and therefore justifies the soil being deemed suitable for irrigation (Class 3 soil).

Bainsvlei

The textural and structural properties of the Bainsvlei are similar to the Hutton. Hence total evaporation should have been similar at the very least, but was augmented by the presence of a shallow water table near 1000 mm from the surface. The SWAMP model estimated that the total evaporation was 4.2 times higher than the Hutton, confirming that the capillary fringe was near the surface. Another feature of the Bainsvlei is its high PAWC, which amounted to 540 mm. This was due to the underlying lime layer, which caused water to accumulate, forming a water table by filling the pores to field saturation. The capillary fringe also increased the soil water content further due to the capillary forces, consequently increasing the PAWC. As shown with the previous two soils, the osmotic potential lowered the PAWC, which in this case amounted to 6% or 34 mm of water. The long-term mean electrical conductivity of the wheat and maize seasons was 583 and 631 mS m^{-1}, respectively, against the initial value of 273 mS m^{-1}. Applying the relative yield reduction equation of Ehlers et al. (2007) under these conditions, yield losses of 21% were revealed. This salinity effect can also be seen in the seasonal yield distribution of wheat and maize in Figure 6.8, estimated with the SWAMP model. The relative seed yields show the alternating yield reduction in the crop rotation, with wheat (salinity threshold of 600 mS m^{-1}; Ehlers et al., 2007) largely unaffected, and maize (salinity threshold of 350 mS m^{-1}; Ehlers et al., 2007) decreasing to 80% of the target seed yield. A different feature of this soil when compared to the others, is the recycling of salts between the water table and the unsaturated root zone. During evapotranspiration, salts are transported from the water table to the root zone through capillary rise and vice versa during rain and/or irrigation events where it recharges the water table. Fortunately, a portion of this salt (2700 kg ha^{-1} per annum) in the water table drained laterally, away from the field (1% slope), making this soil suitable for irrigation. This study clearly shows that soils with water tables and suitable topography features, such as the Bainsvlei, require additional management and are therefore rightfully grouped as Class 2 irrigation soil.

Bloemdal

The physical, chemical and pedological properties of the Bloemdal are similar to those of the Bainsvlei, except for the C-Horizon that was classified as unspecified in the case of the Bloemdal, and soft plinthic in the case of the Bainsvlei. The main physical difference between these soils is the depth of the water table; the Bainsvlei was taken at 1000 mm and the Bloemdal at 1500 mm. This effected evaporation and the PAWC. With respect to evaporation, the capillary fringe was not connected with the active evaporation zone (top 300 mm; Bennie et al., 1994), which explained the lower total evaporation compared to the Bainsvlei soil. The total evaporation was 2589 mm over the simulation period, compared to the Bainsvlei 5336 mm. Water conserved this way helped to reduce the salt application via irrigation. The PAWC, on the other hand, was lower than the Bainsvlei due to the deeper water table; the thickness of the saturated zone was 500 mm less than the Bloemdal. This implies that there was more pore space available above the capillary fringe for managing water and salts in the Bloemdal soil. This zone acts as a sink for salts to accumulate as indicated in the relative salinity response in Figure 6.8 of the Bloemdal compared to the Bainsvlei. There were periods of salt accumulation that peaked between 4 and 5 times the initial salinity (101 mS m^{-1}), causing yield reduction, as can be derived from the relative yield response in Figure 6.8. There was no yield reduction during the other seasons, due to the high PAWC (446 mm) and the low osmotic potential (11 mm water became unavailable); the long term mean electrical conductivity was 243 mS m^{-1}. As in the case of the Bainsvlei, salts were removed through lateral drainage from the water table at approximately similar rates.

6.4 Conclusions

Soil quality assessment

From the soil quality assessment at Orange-Riet and Vaalharts, the following conclusions can be drawn: After decades of irrigation, the quality, as reflected by mainly the sodicity and salinity levels of the soils is generally good. The mean sodium adsorption ratio of the profile generally increased with an increase in clay content, but was never higher than 4 in any of the soils. Similar trends were observed for the electrical conductivity of the saturated extract. In this case the electrical conductivity increased from 75 mS m^{-1} for sandy soils to 143 mS m^{-1} for loamy soils to 174 mS m^{-1} for clayey soils. The maximum electrical conductivity measured was 283 mS m^{-1}, which confirms that none of these soils were saline. However, this does not imply that poor water and salt management did not occur.

In situ case study assessment

Two soils (sandy versus clay, without water tables) at Orange-Riet Irrigation Scheme were compared with regard to their response to irrigation. The assessment revealed that huge water losses occurred in the sandy and clayey soil through evaporation and drainage. Managers should take note that water loss through evaporation was about twice as high in the clay than the sandy soil. The opposite was true for drainage with a mean of 30 mm per crop season for the clay soil, compared to the 258 mm for the sandy soil. The high drainage results were related to the type and topography of the underlying parent material, which plays a pivotal role in the removal of water and salts in the soils at Orange-Riet and Vaalharts. Farmers can enhance sustainability by installing cut-off drains at strategic points along the topography as illustrated by this case study at Orange-Riet.

Desktop case study assessment

The results of the simulations done with the SWAMP model, in order to determine the long-term response of soils to irrigation where drainage and leaching were minimised, provided valuable information. The response of soils to this irrigation strategy can be concluded from the soil features such as profile available water capacity, presence of a water table and the depth of a water table as well their drainage conditions. Firstly the importance of profile available water capacity. Soils with a low profile available water capacity (lower than 80 mm), such as sandy soils, need to be managed carefully. The osmotic potential induced by salt tends to decrease the plant available water to levels that can harm the crop. On the other hand, in soils with a high profile water capacity, such as the Valsrivier, the effects of salt are masked. Secondly, the presence of water tables in or near the root zone. In general a water table increases the profile water capacity significantly, which also masks the osmotic effects of salts. Thirdly, the depth of the water table is of paramount importance in controlling salt. In shallow water tables where the capillary fringe is in contact with the active evaporation zone, a considerable amount of soil water can evaporate. This implies that additional water should be irrigated to meet the potential evapotranspiration, consequently additional salt will be applied. When the capillary fringe is below the active evaporation zone (deep water tables), an additional sink for water and salt storage is created. This zone plays a pivotal role in controlling salts. During low rainfall periods, where irrigation scheduling is adopted to minimise drainage, salt will accumulate at a higher rate as oppose to where a water table is absent. When rainfall exceeds the capacity of the sink, leaching was more efficient compared to soils lacking a water table. Salt leaching was attributed to lateral drainage of the water table, which is a prerequisite for the management of water table soils. Lastly, for Orange-Riet and Vaalharts Irrigation Schemes it was clear that the occurrence of high rainfall events helped unintentionally to control salinity in these soils.

It is clear that the degradation of irrigated soils to the point where this affects crop production are the result of a combination of factors such as crop selection (Chapter 5), soils and drainage conditions (Chapter 6) and irrigation water quality. These factors essentially determine the most suitable scheduling method (Chapter 8), which is required to optimise production and control off-site degradation of soil and water resources. However, the total salt content and chemical composition of the water at Orange-Riet and Vaalharts first needs attention, which will be given in Chapter 7.

CHAPTER 7
ASSESSING THE EFFECT OF IRRIGATION WATER SALINITY ON CROP PRODUCTION

7.1 Introduction

The risk of crops suffering salt-induced stress and soil salinization, resulting from the quality of irrigation water, depends on crop species and variety, soil and drainage conditions, and the amount and frequency of irrigation applied. The interaction of these factors therefore constitutes a water quality classification system, which is basically a summary of knowledge concerning the interaction of these factors.

Obviously, assessing the suitability of water sources for irrigation is a complex process, which must be performed for each region individually. Despite this, various general water quality classification methods have been developed and agree reasonably well with respect to criteria and limits (Thorne & Thorne, 1954; United States Salinity Laboratory Staff, 1969; Doneen, 1967; Rhoades & Bernestein, 1971; Rhoades, 1972; Rhoades & Merrill, 1976; Ayers & Westcott, 1976). The problem with almost all of the proposed criteria, however, is the fact that the emphasis is placed on what the quality of the water is, rather than what can be done with the water.

A given water source may therefore be classified as unsuitable, while it is in fact utilizable under specific conditions and *vice versa*. Theoretically, even water classified as extremely saline can be used for irrigation if the crop type and soil properties do not require complicated management practices in order to optimize production.

In the early years of salinity research, the focus was on how the increased salinity of irrigated lands affects soil structure and crop yields. This was through an improved understanding of soil chemistry and soil physics. Undeniably, some of the most striking advances achieved in the fields of irrigation-induced salinization, have been concerned with the status and movement of water and salt in the soil-plant-atmosphere continuum. Hence it was proposed and confirmed that even brackish water can be used safely and even advantageously to irrigate certain crop species and varieties for specific soil and climatic conditions with specific scheduling practices (Chapter 2).

The first objective of this chapter focuses on assessing the quality of water utilized at Orange-Riet and Vaalharts, which includes irrigation, water table and water from drainage systems. This was done in order to determine the range of water qualities that farmers at Orange-Riet and Vaalharts have at their disposal for irrigation. The second objective is an assessment of the long-term impact of these various irrigation water qualities on soil salinity and seed yield under an irrigation scheduling strategy of minimizing drainage and leaching. Crop choices as well as soil and climatic conditions represented the intrinsic conditions found at Orange-Riet and Vaalharts. The second objective will therefore test whether these farmers can produce sustainably when they utilize poorer quality water.

7.2 Materials and procedures for assessing water quality

The experimental approach consisted firstly of using *in situ* measurements that were conducted at the various measuring points, as discussed in Chapter 3, to assess the different water qualities at Orange-Riet and Vaalharts. Secondly a desktop study was done through simulations with SWAMP to assess the long-term effect of different qualities of irrigation water on the seed yield of two crops, and the salinity of two soils when irrigation scheduling was aimed at minimising drainage and leaching.

7.2.1 *In situ* assessment of water quality

Calcium, potassium, magnesium and sodium concentration measurements of the irrigation water, water table and water from drainage systems for all the measuring points listed in Table 3.2 were used in the water quality assessment. These measurements were taken five times during the measuring period as explained in Section 3.3.2. The electrical conductivity of the irrigation water, water table and water from the drainage systems that were measured weekly at each measuring point was also included in the assessment. The irrigation source of each measuring point was determined, from where each measuring point was grouped into Orange River, Vaal River or blended water. The blended water comprised mainly of a blend between Orange River, Riet River, Modder River, Lower Riet River water and water from artificial drainage systems.

7.2.2 Desktop

As with the previous chapters, all the simulations were done with the verified SWAMP model (Chapter 4) (Bennie et al., 1998). Climate data for a 20 year period, from 1982 to 2001 for Orange-Riet and from 1980 to 1999 for Vaalharts were used in the simulation study. From the results obtained in Chapter 6, it was decided to simulate conditions where two different soils were irrigated with four different qualities of water.

7.2.2.1 Soil conditions

Measuring points or17 and v11 were used to represent the different soil conditions. Natural or artificial drainage conditions that were used in the simulations were discussed in Section 6.2.3.1. The two soil conditions represent a Hutton (or17), without a water table and a Bloemdal (v11) with a water table. These soils were selected because they represent the majority of soils irrigated at Orange-Riet and Vaalharts, *viz.* sandy to sandy loam with or without a water table. The inputs required by the model represent the *in situ* soil conditions as listed in Tables 6.2 and discussed in Section 6.2.3.1. The water table were kept constant at a depth of 1500 mm from the soil surface with an electrical conductivity of 132 mS m^{-1}.

The salt distribution coefficient for the Hutton and Bloemdal were 0.95 and 0.70, respectively, which as explained in Chapter 4, represent the intrinsic soil and drainage conditions found at the two measuring points. The amount of salt added to the soil as a result of fertilizer application was the same as explained in Table 6.12.

7.2.2.2 Crop choices and rotation system

The same double crop rotation system, of wheat and maize planted alternately every year, as discussed in Section 6.2.3.2, was used. A maize drying and harvest period, which was basically a simulation of a fallow period, was included.

7.2.2.3 Meteorological parameters

The daily calculated evaporative demand and rainfall data for the 20 year simulation period at Orange-Riet and Vaalharts were calculated, as explained in Section 6.2.3.3, and imported into SWAMP.

7.2.2.4 Irrigation

The same irrigation scheduling strategy of minimising drainage and leaching, as discussed in Section 6.2.3.4, was applied again. Irrigation took place every seven days by irrigating an amount equal to the crop water used during the previous seven days, minus rainfall and minus the contribution of the water table, when present. An electrical conductivity of 2 mS m^{-1} for rainfall was used, while the electrical conductivity of the irrigation water, which was used as treatments on both soils, was 21, 65, 102 and 225 mS m^{-1}.

7.3 Results and discussion

7.3.1 *In situ* assessment

7.3.1.1 Irrigation water

Table 7.1 shows the mean calcium, potassium, magnesium, sodium and salt concentrations, expressed as the electrical conductivity (EC), of the measuring points that used Orange River, Vaal River and blended water as an irrigation source. The standard deviation was also included.

Table 7.1 Mean calcium (Ca), potassium (K), magnesium (M), sodium (Na) concentrations and the electrical conductivity (EC) of the irrigation water for measuring points that used Orange, Vaal and blended water as an irrigation source together with the standard deviation and mean sodium adsorption ratio (SAR)

Water source	mg L^{-1}								SAR	EC (mS m^{-1})	
	Ca		K		Mg		Na				
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	Mean	SD
Orange River	21	5	1.1	1.8	7	2	7	3	0.35	21	3
Vaal River	53	10	8.0	1.9	20	4	46	5	1.37	68	10
Blended	53	27	6.8	6.8	32	23	71	44	1.82	84	27

SD = Standard deviation

Calcium was the dominant cation on a mass concentration basis in all three of the water sources, followed by sodium, magnesium and potassium. The variation in calcium, potassium, magnesium and sodium concentrations was the lowest for the measuring points that used Orange River water followed by Vaal River water. Since the quality of blended water is a function of the quality of the water sources and blending ratio, the variation was the highest. The measured calcium, potassium, magnesium and sodium concentrations of the Orange River water compare well with the long-term mean of 16, 2, 7 and 6 mg L^{-1}, respectively, as reported by Du Preez et al. (2000). This was also true for the measuring points that used Vaal River water as an irrigation source with long-term mean values of 39, 8, 19 and 37 mg L^{-1}, respectively. Since farmers do not know their blending ratios and because the blended water comprises mainly a blend between Orange River, Riet River, Modder River, Lower Riet River and water from drainage systems, no long-term comparison can be made. From these cation concentrations it can be concluded that none of the measuring points utilized a source of water that is regarded as sodic because the sodium adsorption ratio was less than 15.

Orange River irrigated measuring points received water that had the lowest salt concentration, *viz*. 21 mS m^{-1}, followed by Vaal River irrigated measuring points (68 mS m^{-1}). These results compare well with the long-term mean values of the Orange and Vaal River as reported by Du Preez et al. (2000), *viz*. 19 and 52 mS m^{-1}, respectively. Blended irrigated measuring points received a mixed quality of irrigation water. The large variation in EC shows that some farmers received water of a better quality than Vaal River water, but worse than Orange River water, while some received water with an EC higher than 100 mS m^{-1}. From the results it can therefore be concluded that Orange River irrigation water has a low salinity hazard, while Vaal River irrigation water has a medium salinity hazard. Blended irrigation water at Orange-Riet and Vaalharts can however pose a low, medium or high salinity hazard depending on the blending ratio and the source of the water.

7.3.1.2 Water table

The mean calcium, potassium, magnesium, sodium and salt concentrations of the water table for all the measuring points, are summarised in Table 7.2. For the Orange River, irrigated measuring points, the mean calcium concentration in the water table was 3.2 times higher than the irrigation water. This same trend was observed for potassium, magnesium and sodium. The increase in cation concentration was however more pronounced for potassium (9.5 times), magnesium (8.7 times) and sodium (11.2 times). Generally much higher cation concentrations were observed at the measuring points irrigated with Vaal River water.

Table 7.2 Mean calcium (Ca), potassium (K), magnesium (Mg), sodium (Na) concentrations and the electrical conductivity (EC) of the water table for measuring points that used Orange, Vaal and blended water as an irrigation source together with the standard deviation and mean sodium adsorption ratio (SAR)

Water source	Measuring point	mg L^{-1}				SAR	EC (mS m^{-1})	
		Ca	K	Mg	Na		Mean	SD
Orange River	or4	68	8.1	62	60	1.3	112	15
	or5	75	6.0	64	41	0.8	114	16
	or6	64	6.9	68	103	2.1	148	23
	or7	59	6.1	83	106	2.1	201	51
	or8	72	4.9	63	44	0.9	114	13
	or9	79	12.8	62	71	1.5	127	12
	or10	60	7.0	60	54	1.2	110	20
	or11	72	20.8	61	50	1.0	120	16
	or12	67	7.9	47	158	3.6	181	27
	or13	61	13.7	40	99	2.4	120	19
	or14	-	-	-	-	-	-	-
	or15	-	-	-	-	-	-	-
	Mean	**68**	**9.5**	**61**	**79**	**1.7**	**135**	**21**
Vaal River	v1	167	13.1	103	296	4.4	291	88
	v2	196	16.8	109	374	5.3	398	44
	v3	174	13.4	112	170	2.5	222	52
	v4 *	351	40.5	120	279	3.3	381	27
	v5 *	174	14.6	75	167	2.7	222	27
	v6	108	5.8	71	112	2.1	163	23
	v7	135	6.4	58	153	2.8	164	23
	v8	106	4.7	59	144	2.8	152	28
	v9	158	5.8	91	171	2.7	205	55
	v10	112	9.0	133	142	2.1	227	112
	v11	94	4.4	50	100	2.1	132	10
	v12	122	6.4	66	127	2.3	158	29
	Mean	**158**	**11.7**	**87**	**186**	**2.9**	**226**	**43**
Blended	or1	68	4.1	27	259	6.7	215	27
	or2	101	18.3	69	386	7.3	612	130
	or17	-	-	-	-	-	-	-
	or18	-	-	-	-	-	-	-
	or19	-	-	-	-	-	-	-
	or20	-	-	-	-	-	-	-
	Mean	**85**	**11.0**	**48**	**323**	**7.0**	**414**	**79**

SD = Standard deviation

The mean calcium, potassium, magnesium and sodium concentrations of the water table were 3, 1.5, 4.4 and 4 times higher than the irrigation water, respectively. The increase in cation concentrations from the irrigation water to the water table were therefore not as pronounced as for Orange River irrigated measuring points. At none of the measuring points irrigated with Orange River, Vaal River or blended water, can the water table be classified as sodic. Deterioration in water quality, with regard to sodicity, was observed from the irrigation water to the water table*, viz.* 0.35 to 0.9 for Orange River measuring points and 1.4 to 2.6 for Vaal River measuring points. In general, the mean salt concentration of the Orange River water measuring points was 6.4 times higher than the salt concentration of the irrigation water (21 mS m^{-1}). Vaal River irrigated measuring points showed a more noticeable variation in water table EC with a maximum standard deviation of 112 and minimum of 23 mS m^{-1}. The mean water table salt concentration of these measuring points was however only 3.3 times higher than the irrigation water (68 mS m^{-1}). Given these ECs, none of the measuring points irrigated with Orange and Vaal River water can be classified as saline. However this was not the case with the water table that developed under irrigation with blended water. With regard to the mean EC of the soil (53 mS m^{-1}) above the water table for Orange River irrigated measuring points (Chapter 6), the mean EC of the water table was 2.5 times higher. For Vaal River irrigated measuring points the mean EC of the water table was 1.3 times higher than the mean EC of the soil above the water table.

Unlike irrigation water, the continued monitoring of salt concentration in water tables at Orange-Riet and Vaalharts was neglected in the past. Only one study at Orange-Riet (Van Dyk et al., 1997) and two at Vaalharts (Herold & Bailey, 1996; Ellington et al., 2004) included measurement of the salt concentration of the water table. At Orange-Riet Van Dyk et al. (1997) noted a variation of 60 to 180 mS m^{-1} from samples taken during 1982 in the Settlement section of the scheme. Measurements were repeated during 1996, which showed the same variation in salinity. Ellington et al. (2004) found during their investigations at Vaalharts that the mean salt concentration measured by Herold & Bailey (1996) increased by 35%, and varied between 100 and 270 mS m^{-1}, while Verwey & Vermeulen (2011) recorded a mean of 191 mS m^{-1} during August 2008 and May 2009. These results together with measurements taken during this study provide a general trend of water table salinity at Orange-Riet and Vaalharts. Comprehensive measurement strategies, where specific locations throughout the two schemes are monitored continuously are, however, needed. This is especially true before any conclusions regarding salt build-up in the water table can be drawn.

7.3.1.3 Artificial drainage water

Table 7.3 shows the mean calcium, potassium, magnesium, sodium and salt concentrations of all the measurements taken from drainage water that came from Orange River, Vaal River and blended irrigated fields. The mean calcium, potassium, magnesium and sodium concentrations, of the water flowing from drainage systems, where Orange River was the irrigation source were 3.4, 5.8, 14.7 and 16.7 times higher, respectively, than the irrigation water. For Vaal River irrigated fields the mean concentrations of cations in the drainage water were 2.4, 0.8, 3.3 and 2.8 times higher, respectively, than the irrigation water, while for blended water the concentration were 2.4, 3.5, 4.2 and 8.2 times higher, respectively. None of the water flowing from the drainage systems at Orange-Riet and Vaalharts Irrigation Schemes was however classified as sodic, *viz*. mean sodium adsorption ratio of drainage water where Orange River, Vaal River and blended water was the source amounted to 2.1, 2.3 and 8.1, respectively.

The mean EC (167 mS m^{-1}) of water from the artificial drainage systems, where Orange River water was the irrigation source, was slightly higher than the mean EC of the water table (135 mS m^{-1}), which was also true with regard to the standard deviation. Where Vaal River water was the irrigation source the mean EC of the water from the drainage systems (221 mS m^{-1}) was basically in equilibrium with the mean EC of the water table (226 mS m^{-1}). This was expected because all of the measuring points that utilise Vaal River water are located in Vaalharts, which has an extensive artificial drainage network.

Table 7.3 Mean calcium (Ca), potassium (K), magnesium (Mg), sodium (Na) concentrations and the electrical conductivity (EC) of the water table for measuring points that used Orange, Vaal and blended water as an irrigation source together with the standard deviation and mean sodium adsorption ratio (SAR)

Water source	Ca		K		Mg		Na		SAR	EC (mS m^{-1})	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	Mean	SD
Orange River	72	7	6.4	4.3	103	39	117	45	2.1	167	38
Vaal River	125	39	6.7	2.0	66	26	129	44	2.3	221	27
Blended	125	65	23.7	37.1	133	35	580	556	8.1	-	-

SD = Standard deviation

It can be concluded that the range of water qualities at Orange-Riet and Vaalharts, in terms of irrigation water, groundwater and artificial drainage water that are available varies between 21 and 225 mS m^{-1}. In light of this, the question arises as to what degree poorer quality water can be used as an irrigation source and how much leaching will be required? Simulating the long-term effect of these water qualities on soil salinity and seed yield of wheat and maize, when irrigation is scheduled to minimise drainage and leaching on two different soils, could provide some insight into these aspects.

7.3.2 Desktop assessment

7.3.2.1 Salt accumulation

The addition of salt through irrigation to the potential root zone and removal through drainage from the potential root zone of the Hutton and Bloemdal soils respectively, for each of the 20 wheat and 19 maize seasons during the simulation period of 20 years when irrigated with 21, 65, 102 and 225 mS m^{-1} water, is illustrated in Figures 7.1 and 7.2. The response of the soils with these water qualities to irrigation, in terms of their salinity, expressed relative to the initial soil salinity was also included.

The results in Figure 7.1 showed that a mean total of 359, 335, 243 and 204 mm of water per season were added to the potential root zone of the Hutton soil through irrigation with 21, 65, 102 and 225 mS m^{-1} water, respectively, which added a mean total of 565, 1632, 1860 and 3447 kg salt ha^{-1} of salt per season, respectively. This resulted in an increase in soil salinity from the start of the season to the end during 27 of the 39 crop seasons at a mean rate of 20, 35, 42 and 61 mS m^{-1} per season for the different water qualities, respectively, with a standard deviation of 7, 16, 23 and 45 mS m^{-1} per season, respectively. As a consequence the mean soil salinity of the potential root zone for the various irrigation water qualities reached a maximum of 1.6, 2.6, 3.1 and 3.8 times the initial soil salinity, (150 mS m^{-1}), respectively.

For the Bloemdal soil much less irrigation was applied because of the presence of a water table*, viz.* a mean total of 120, 112,106 and 91 mm per season, respectively, which resulted in the addition of a mean total 188, 545, 809 and 1529 kg ha^{-1} of salt per season, respectively. The result was an increase in soil salinity from the start of the season to the end during 29 of the 39 crop seasons at a mean rate of 54, 60, 63 and 75 mS m^{-1} per season, respectively, with a standard deviation of 22, 27, 27 and 31 mS m^{-1} per season, respectively. The mean soil salinity of the potential root zone for the various irrigation water qualities reached a maximum of 4.6, 5.0, 5.2 and 5.6 times the initial soil salinity (101 mS m^{-1}), respectively.

In order to minimize drainage and leaching, irrigation scheduling was adapted to apply less water, when evapotranspiration declined due to water stress as the salinity increased. This effectively means that less salt was added to the potential root zone when evapotranspiration declined. From the results it is clear that there was a decline in evapotranspiration with an increase in the salt concentration of the irrigation water, which will be discussed later, since the amount of irrigation applied decreased. The increasing standard deviation in salt accumulation per season with an increase in irrigation water salinity of the Hutton soil also suggests that evapotranspiration declined when poorer quality irrigation water was used resulting in a significant variation in salt addition through irrigation. For the Bloemdal soil there was no significant increase in standard deviation of accumulated salts per season with an increase in irrigation water salinity. This suggests no real reduction in evapotranspiration with a steady addition of salt through irrigation.

Salt accumulated at a much faster rate in the Bloemdal soil when compared to the Hutton despite the fact that approximately twice as much salt was applied through irrigation on the Hutton for all the different irrigation water qualities that were simulated. This was due to the upward movement of salt through capillary rise due to water table uptake from the water table that was present in the Bloemdal soil. Figures 7.1 and 7.2 show that the relative soil salinity increased with an increase in irrigation water salinity. The mean salinity of the Hutton soil during the 20 years, when 65, 102 and 225 mS m^{-1} irrigation water was used, increased by a mean of 118, 174 and 307 mS m^{-1}, respectively, to the reference salinity (21 mS m^{-1}). For the Bloemdal soil the mean salinity during the 20 years increased by only 21, 35 and 73 mS m^{-1}, respectively. In terms of salt accumulation, care should therefore be taken when irrigating a Hutton soil, without a water table and with poorer quality water.

7.3.2.2 Salt removal

From the given results it was clear that the relative increase compared to the initial soil salinity, with increasing irrigation water salinity levels, was less in the Bloemdal (Figure 7.2) than the Hutton (Figure 7.1). The reason for the lower accumulation of salts in the Bloemdal soil with an increase in irrigation water salinity was because salt removal through leaching was much more efficient when compared to the Hutton for all the different irrigation water qualities. The scheduling strategy that was employed resulted in drainage and leaching of the potential root zone only when rainfall exceeded evapotranspiration for a specific period. Salt accumulated generally during the drier wheat seasons irrespective of the quality of irrigation water, and was leached during the wetter maize seasons, especially while the maize was drying and evapotranspiration was low (Figures 7.1 and 7.2).

For the Hutton soil 100, 93, 91 and 89% of salts added through fertilization, rainfall and irrigation were removed from the potential root zone during the 20 years when 21, 65, 102 and 225 mS m^{-1} irrigation water was used, respectively. Soil salinity subsequently decreased by 24 mS m^{-1} when 21 mS m^{-1} irrigation water was used, while it increased by 112, 175 and 328 mS m^{-1} when 65, 102 and 225 mS m^{-1} irrigation water was used. During 12 of the 39 simulated crop seasons, the mean decrease in salinity from the start to the end of the season was 33, 62, 90 and 83 mS m^{-1} per season, respectively, for the different irrigation water qualities. Soil salinity decreased to minimum values of 0.3, 0.5, 0.6 and 1 times the initial soil salinity, respectively, for the irrigation water qualities. The mean value for the 20 years was 0.9, 1.7, 2.0 and 2.9 the initial soil salinity, respectively, for the irrigation water qualities.

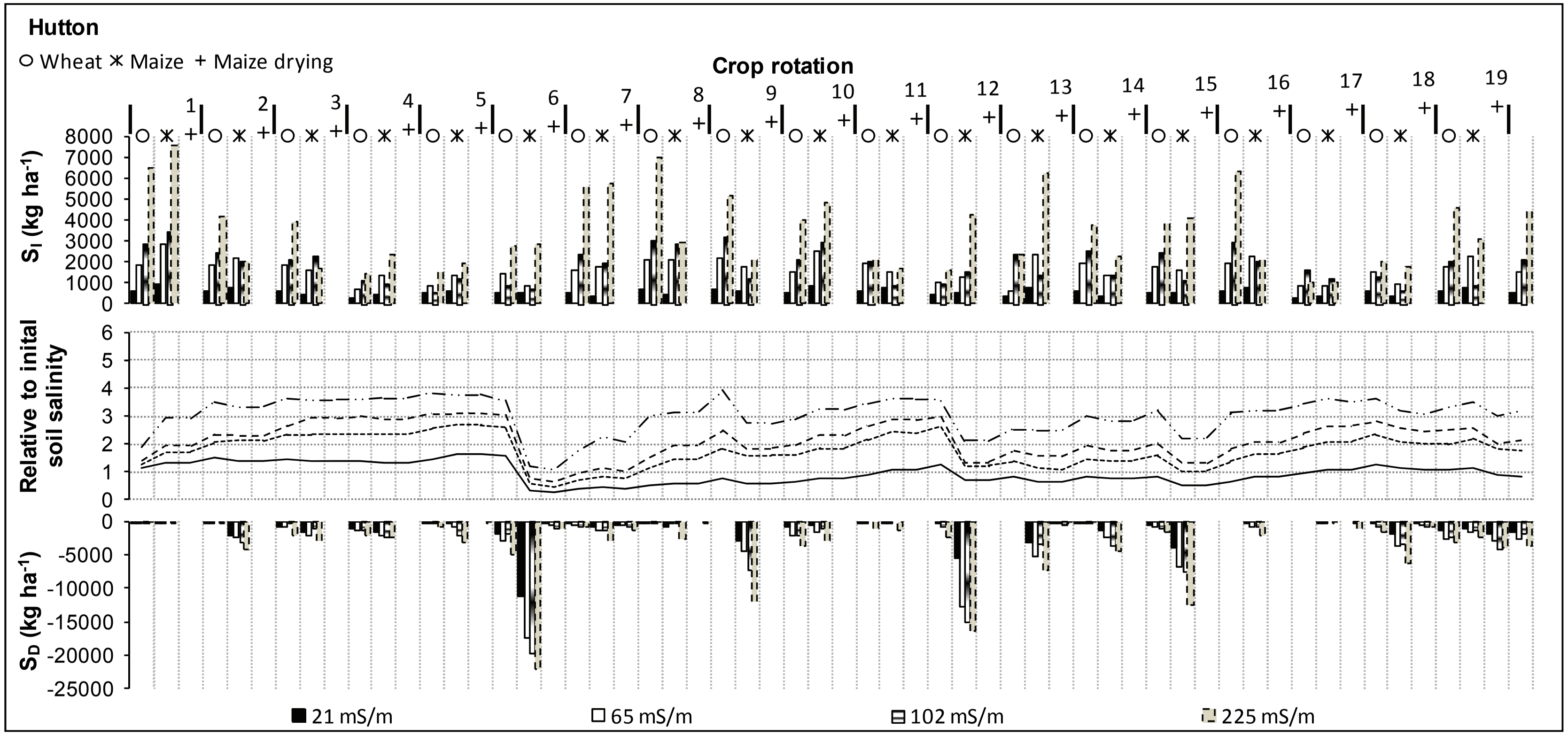


Figure 7.1 Salt addition through irrigation (S_I) and removal through drainage (S_D) from the potential root zone (2000 mm) of the Hutton soil for every wheat and maize season during the 20 year simulation period together with the soil salinity, expressed relative to the initial salinity.

10.5

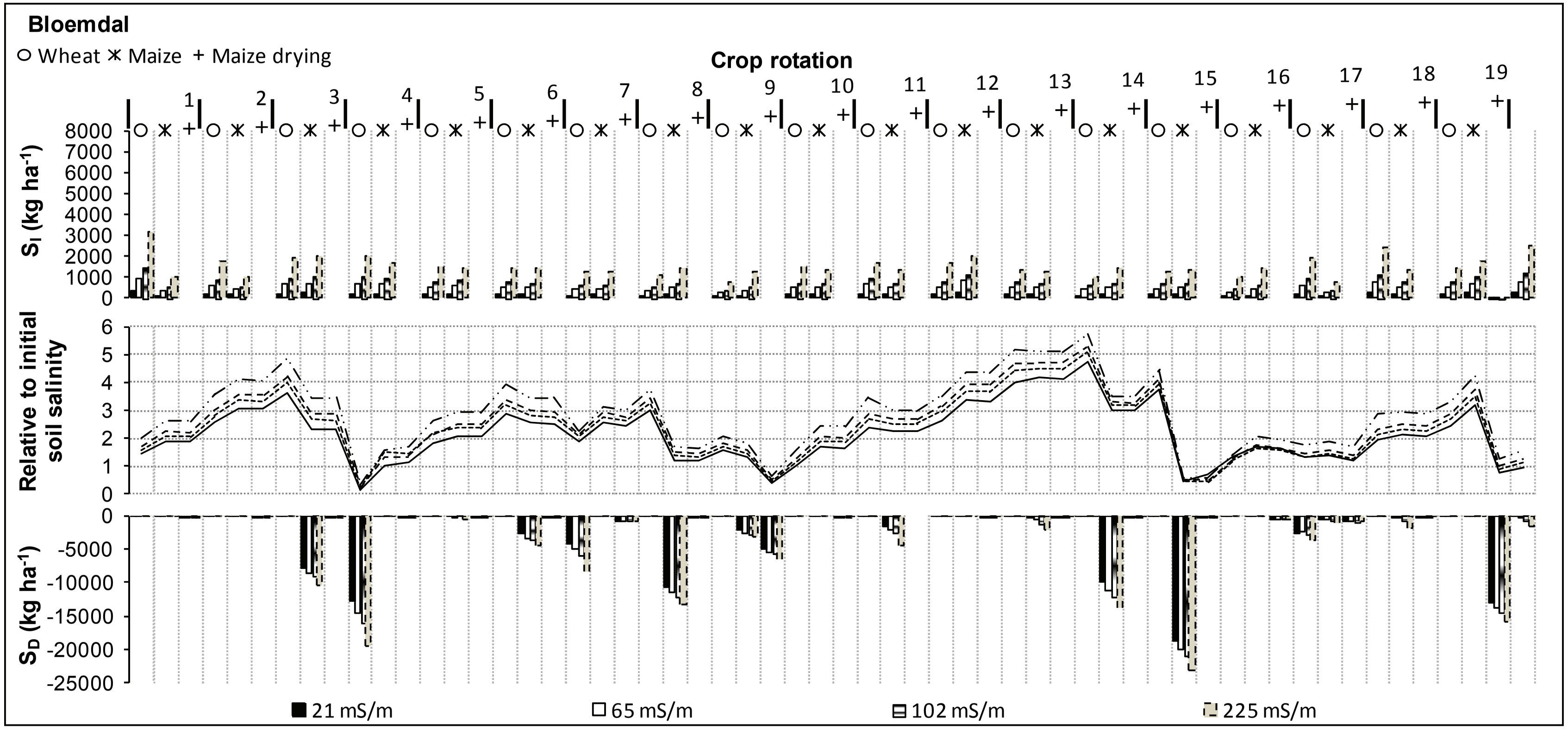


Figure 7.2 Salt addition through irrigation (S_I) and removal through drainage (S_D) from the potential root zone (2000 mm) of the Bloemdal soil for every wheat and maize season during the 20 year simulation period together with the soil salinity, expressed relative to the initial salinity.

For the Bloemdal soil approximately 100% of the salts added through fertilization, rainfall, irrigation and capillary rise from the water table were leached through the profile downward into the water table for the 21, 65, 102 and 225 mS m^{-1} irrigation water salinities. Of this salt only 21, 26, 28 and 36%, respectively, were totally removed from the potential root zone, while the rest was transported back through capillary rise. At the end of the 20 year simulation period, the salinity of the soil irrigated with 21 mS m^{-1} water therefore decreased by 3 mS m^{-1}, while the 65, 102 and 225 mS m^{-1} irrigated soil increased by 14, 27 and 58 mS m^{-1}, respectively. Salt removal occurred mainly during 10 of the 39 crop seasons at a mean rate of 120, 129, 135 and 140 mS m^{-1} per season, respectively, with a standard deviation of 107, 114, 120 and 131 mS m^{-1}, respectively. The result was that the soil salinity decreased to minimum values of 0.1, 0.2, 0.2 and 0.3 times the initial soil salinity during the 20 years, with mean values of 2.1, 2.3, 2.4 and 2.8 times the initial soil salinity, respectively, for the different irrigation water qualities.

Contrary to the results that were obtained, it was expected that a lot more salts would accumulate with a scheduling strategy of minimising drainage and leaching over a period of 20 years. The same findings were presented by Van Rensburg et al. (2008) with the Aragües (1996) and Du Preez et al. (2000) with the SWB model of Annandale et al. (1999). Estimations with the Aragües model showed that between 78 to 87% of the added salts leached from the soil, while the SWB model leached 95 to 98% of added salts depending on soil type and irrigation scheduling strategy.

The salt removal results of both soils showed that although leaching will always be effective, its efficiency will increase from a low to high soil salinity content, which is supported by findings from Monteleone et al. (2004) and Barnard et al. (2010). The large standard deviation in salt removal per season of both soils during the 20 year period is due to the variation in frequency and amount of rainfall and salt concentration in the soil. Under limited drainage and leaching conditions the simulations showed that care, in terms of salt accumulation, should be taken when irrigating a drier Hutton soil without a water table with poorer quality water since soil salinity over a period of 20 years increased by 1.5 mS m^{-1} (R^2 = 0.94) per unit increase in irrigation water salinity. This was despite the fact that rainfall contributed significantly towards lowering the salt concentration in the potential root zone, decreasing soil salinity during 12 of the 39 crop growing seasons.

The fact that the wetter Bloemdal, which is a water table soil, seems a good soil to irrigate with poorer water quality when drainage and leaching is minimised was surprising. This is because soil salinity increased over a period of 20 years by only 0.3 mS m^{-1} (R^2 = 0.96) per unit increase in irrigation water salinity. Care should however be taken, since the simulations showed that salt did accumulate at a higher rate compared to the Hutton during the 20 years. Since salt leaching is more efficient with increasing soil salt concentrations, a higher amount of salt was removed from the potential root zone because soil salinity decreased during 10 of the 39 crop growing seasons when rainfall exceeded evapotranspiration, especially during the end of the summer growing season. A pre-requisite for the removal of salt in water table soils, like the Bloemdal, is the presence of natural lateral drainage. If not present, artificial drainage systems will be required for medium- to long-term irrigation sustainability.

In terms of salt build-up it is clear that poorer quality water can be used to irrigate soils with adequate natural and/or artificial drainage with a scheduling strategy for minimising drainage and leaching. This is because rainfall in the central parts of South Africa plays a significant role in leaching accumulated salts. Additional leaching might be required during periods of low rainfall, when poorer quality irrigation water is used to ensure that soil salinity is kept low in order to obtain sustainable seed yields. These aspects need further attention. The latter will be addressed by examining the seed yield of wheat and maize that were simulated during the 20 years on both soils when irrigated with increasing irrigation water salinities.

7.3.2.3 Seed yield

Figure 7.3 shows the relative seed yield of each wheat and maize season during the 20 years, together with the mean salinity of the soil profiles (Hutton and Bloemdal). In Figure 7.4, the concomitant effect that irrigation water quality had on seed yield through its impact on the profile available water capacity (PAWC) are illustrated as well.

Generally when the Hutton soil was irrigated with poor quality water, the seed yield of maize, which is the more salt sensitive crop, was reduced (below 20%) during more seasons than was the case with wheat. For wheat the number of seasons affected were 3, 8, 12 and 15 when 21, 65, 102 and 225 mS m^{-1} irrigation water was used, respectively. For maize the number of seasons amounted to 8, 10, 17 and 18, respectively. These reductions corresponded almost always with periods when soil salinity peaked. After periods of excessive rain and leaching, when soil salinity decreased considerably, the seed yield of wheat and maize increased again.

For the Bloemdal soil, the seed yield of the wheat-maize crop rotation was less affected than in the Hutton soil; only 2, 4 and 8 seasons were lower than 20% for the irrigation water salinities of 65, 102 and 225 mS m^{-1} water, respectively. Thus, additional leaching will be required when a sandy to sandy loam soil, without a water table, is irrigated with poorer quality water, compared to soil where a water table is present. The decrease in yields due to salt build-up under the different irrigation water salinity levels can be explained by Figure 7.4. The soil salinity reduced the plant available water (PAW) in the Hutton (PAWC = 80 mm) by increasing the osmotic effect and thus the soil water content where the total soil water potential prevents plant water uptake (lower limit of plant available water).

The results show that the mean soil salinity induced by 21, 65, 102 and 225 mS m^{-1} irrigation water, during the maize seasons, reduced the PAW by 12, 20, 24 and 36 mm, respectively. When compared to the wheat seasons these reductions in PAW were higher. This explains why the seed yield of maize was reduced over more seasons when compared to wheat. When the maximum soil salinities of the maize seasons were used, PAW was reduced by 25, 39, 46 and 60 mm, respectively, for the various irrigation water qualities. This illustrates the importance of additional leaching when a sandy to sandy loam soil without a water table is irrigated. Salts need to be removed, increasing the osmotic potential, to make maximum use of the PAWC.

The high PAWC (436 mm) of the Bloemdal soil, due to the presence of a water table, played a pivotal role in sustaining the seed yield of wheat and maize over the 20 years. Like the Hutton soil, the mean soil salinity induced by 21, 65, 102 and 225 mS m^{-1} irrigation water, during the maize seasons, reduced the PAW by 9, 10, 11 and 13 mm, respectively. During the wheat seasons, however, no reductions in PAW were simulated. For the maximum soil salinities during the maize seasons, the PAW was reduced by 34, 38, 40 and 46 mm, respectively, for the various irrigation water qualities. During the wheat season PAW were reduced by 14, 15, 17 and 20 mm, respectively. These reductions in PAW were similar to the Hutton soil. However, when compared to the Hutton soil the large volume of soil water available for plant uptake of the Bloemdal soil masked the effect of salinity. Sandy to sandy loam water table soils, such as the Bloemdal, therefore seems to be a good soil to irrigate with poorer quality water, when a scheduling strategy of minimising drainage and leaching is employed.

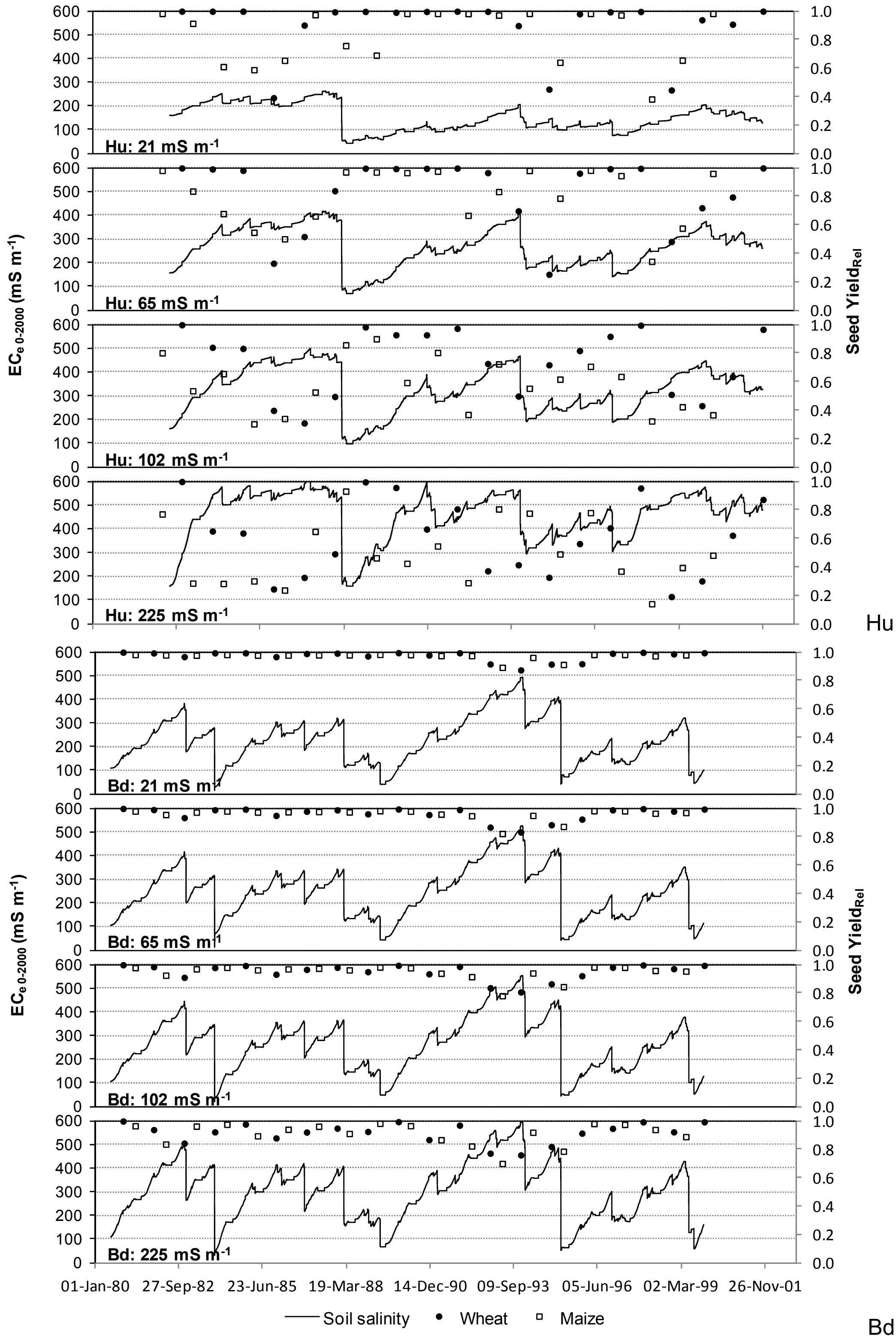


Figure 7.3 Relative seed yield of wheat and maize during every season, together with the mean salinity of the soil profiles , *viz*. Hutton (Hu) and Bloemdal (Bd), induced by the 21, 65, 102 and 225 mS m^{-1} irrigation water.

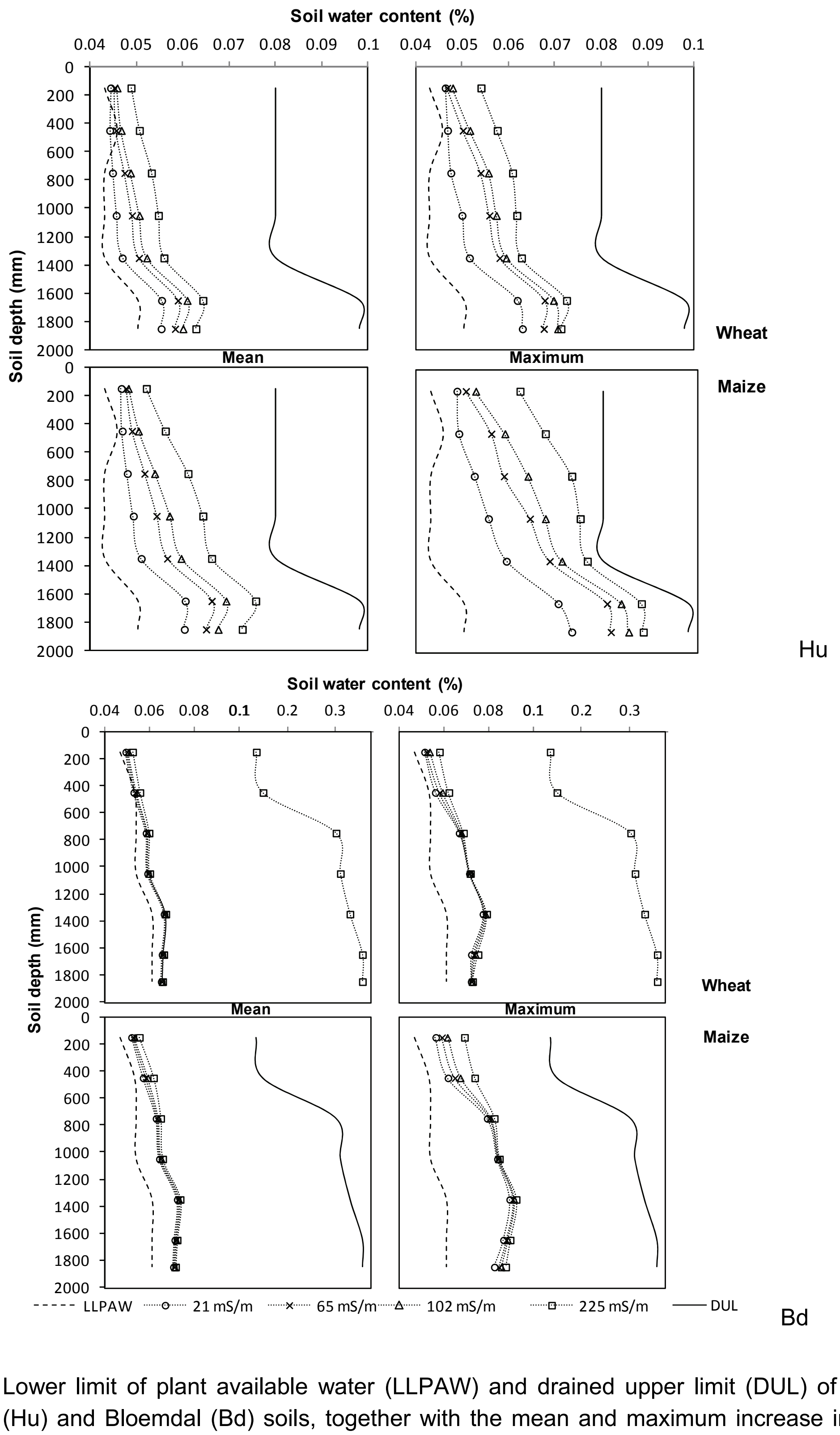


Figure 7.4 Lower limit of plant available water (LLPAW) and drained upper limit (DUL) of the Hutton (Hu) and Bloemdal (Bd) soils, together with the mean and maximum increase in the lower limit during the wheat and maize seasons, induced by 21, 65, 102 and 225 mS m^{-1} irrigation water quality.

7.4 Conclusions

In situ water quality assessment

The assessment of water utilized at Orange-Riet and Vaalharts showed an increase, in cation and salt concentration, from the irrigation water, to the soil, to the water table, to the artificial drainage water. All these water have a low sodicity hazard. Irrigation water from the Orange River has a low salinity hazard, while Vaal River irrigation water has a medium salinity hazard. Blended irrigation water however, can pose a low, medium or high salinity hazard, depending on the blending ratio and which mixture of water is utilised (Orange River, Vaal River, Riet River, Lower Riet River and artificial drainage water). It was concluded that, with respect to the available quality range of water at Orange-Riet and Vaalharts, these salt concentrations can range from 21 to 225 mS m^{-1}.

Effect of irrigation water quality on crop production

The results showed that poorer irrigation water quality (< 225 mS m^{-1}) can be utilised to irrigate wheat and maize that are grown on sandy to sandy loam soils with water tables (or high profile available water capacity), with a scheduling strategy of minimising drainage and leaching. If the crop and/or soil do not allow it, in terms of salt sensitivity and low profile available water capacity, additional leaching will be required. The findings of previous research (Chapter 2), where poorer quality irrigation water was used safely and even advantageously, to irrigate certain crops grown in specific soils that were irrigated with specific scheduling practices, were therefore confirmed. It was concluded that excessive rainfall exceeding the crop water use during parts of the growing season, especially during the late maturity growth stages of summer crops, results in leaching of salt from the root zone. This leaching is more effective on wetter soils with a water table in the lower part or just below the root zone. To prevent the accumulation of salts in the water table, artificial or natural drainage is essential.

It is clear that in terms of suitable crop production, with regard to on-site and off-site irrigation-induced salinity, any crop, soil and water quality can be selected by a farmer, if irrigation is scheduled to control soil salinity while minimising drainage and leaching (Chapter 8).

CHAPTER 8
ASSESSING IRRIGATION SCHEDULING METHODS

8.1 Introduction

Sound irrigation scheduling methods hold the key to sustainable irrigation farming. This is the opinion of many scientists in the field of research and the development of technologies and approaches for improving water productivity. These methods and approaches were classified by Stevens et al. (2005) according to the mode of operation, i.e. atmospheric-based quantification of evapotranspiration, soil water measurement, crop-based monitoring and integrated soil water balance approach. The latter class encompasses both real time and pre-programmed methods. All these methods were categorised as objective, indicating that they are based on scientific theory or measurements. Methods outside this group were classed under intuitive or subjective (Montagu & Stirzaker, 2008). This group relies on personal skills and the experience of the farmer to make decisions on when and how much to irrigate for a given on-site situation. However, irrespective of whether the method or approach are objective or subjective, the goal should be the same; using an appropriately designed irrigation system to maintain an acceptable water productivity without harming the natural resources (water and soil) and the downstream environment (Hillel, 2000).

From the above definition it is clear that the irrigation method, i.e. the type of irrigation system, is an essential tool in the process of converting irrigation water into crop yield. Irrigation systems are divided into three broad classes; flood irrigation (basin, border, furrow and short furrow), mobile systems (centre pivot, linear, etc.), and static systems (quick-coupling, drag-line, hop-along, big-gun, micro sprayers etc.) (Reinders et al., 2010). Irrigation systems are designed for a field situation, taking into account technical, economical and environmental issues. However once designed and erected, the system demands regular testing to ensure that it applies water efficiently. Irrigation efficiency, according to Reinders (2011), implies that the system should apply water at the desired amount, at an accurate application rate and uniformly over the entire field, at the precise time, with the smallest amount of non-beneficial water consumption, and should operate as economically as possible. A primary step in the assessment of irrigation systems is the measuring of the irrigation efficiency coefficients. For example, centre pivots are assessed using indicators such as the coefficient of uniformity (CU), distribution uniformity (DU), the system efficiency (SE) and the application efficiency (AE) (Koegelenberg et al., 2003). Accordingly, the CU gives an indication of how evenly water is distributed over the field, while DU reflects on the uniformity of water distribution. The SE is a combination of CU and DU, while the AE reflects on how much water effectively reaches the soil.

Central to the activity of efficient conversion of irrigation water to crop yields (water productivity) is the irrigator, who has to make daily decisions on when and how much to irrigate. Stevens et al. (2005) conducted a survey amongst 332 irrigation schemes (including 51 small-scale irrigation schemes) covering an irrigation area of about 1.6 million hectares in South Africa. The report states that the majority of the irrigators (82%) use subjective irrigation scheduling methods. A similar trend was observed by Montagu & Stirzaker (2008) in Australia, where two third of the irrigators were using subjective irrigation scheduling methods and approaches. This information was derived from a water survey conducted in 2003 by the Australian Bureau of Statistics, including 7280 irrigators representing an irrigated area of about 2.2 million hectares. These results were generally perceived as disappointing because of the lost opportunity to improve the irrigation water use efficiency over vast areas. Nevertheless the message is clear; scientists need to re-think their research and development processes and should find ways to improve the “transferable” products as also suggested by Stevens et al. (2005).

In line with these observations Annandale et al. (2011) proposed four avenues of improving irrigation scheduling research and development, *viz.* the user-friendliness of systems that support existing scheduling tools, advance of existing soil-water measuring technologies, further development of new innovative technologies (for example remote sensing), and the development of simple monitoring tools and conceptual frameworks that enable structural learning for irrigators.

Montagu & Stirzaker (2008) argued that subjective methods will continue to dominate in enterprises that do not benefit primarily from improved crop water management, such as pastures, unless new drivers other than profitability or water productivity emerge. Jackson et al. (2008) proposed that irrigators should be assessed against broader issues. Issues that stretch beyond the crop field and that are of local, national and global importance, *viz.* energy consumption, greenhouse gas emissions, soil salinity and sodicity, groundwater impacts, etc. These issues will eventually become the new drivers for protecting the environment against harmful impacts of irrigation. Inputs not utilized by the production system will eventually be left behind in the soil, or will find their way to ground- and river water sources. Thus, irrigation has the potential to impact negatively on downstream resources and communities.

Khan et al. (2008) suggested that the paddock (irrigated crop field) represents the basic decision-making unit that reflects on the choices made by irrigators. An irrigation assessment at the crop field level is of the utmost importance so that improvements can be made on a field scale, leading to efficient and environmentally friendly production systems at the global scale.

The aims of this chapter are firstly to conduct a general assessment of irrigation practices under centre pivots. This assessment focused on irrigation system efficiencies, water productivity and the impact of salinity on the environment. The second aim was to conduct a detailed assessment on two irrigation scheduling methods; subjective versus objective. The third aim was to assess different irrigation strategies for managing plant available water. These strategies were tested in prevailing soil and climatic conditions at Orange-Riet and Vaalharts, when irrigation-induced drainage and leaching were minimised.

8.2 Methodology

8.2.1 General assessment of irrigation practices

The indicators used to assess the selected measuring points for the impact of different irrigation practices included irrigation system efficiency, irrigation scheduling methods, crop water productivity, soil salinity, presence of a water table and drainage. Irrigation systems efficiency was measured using the coefficient of uniformity (CU), distribution uniformity (DU), the system efficiency (SE) and the application efficiency (AE) (Section 3.3.5), as described by Koegelenberg et al. (2003). The general system efficiency norm is 85%.

Irrigation scheduling methods and approaches for these measuring points (as listed in Table 8.2) were grouped into subjective and objective methods as proposed by Stevens et al. (2005). Objective scheduling methods comprised measuring soil water content with the neutron soil water meter (CPN) and capacitance probes (WIN). The CPN method was used by GWK Cooperation as part of their service to farmers. They measure soil water content on a weekly basis and make recommendations with regard to water applications and other agronomical aspects. The capacitance technology was one of the early innovations introduced by a farmer in Vaalharts. The farmer extended this service to other farmers. The crop water productivity was calculated as the ratio of seed yield (kg ha^{-1}) versus rainfall-plus-irrigation applied (mm). Soil salinity was measured on five occasions during the measuring period as discussed in

Section 3.3.2 and drainage calculated from the soil water and salt balance of the measuring point as discussed in Chapter 4.

8.2.2 *In situ* case study assessment of scheduling methods

8.2.2.1 Location and description of measuring points

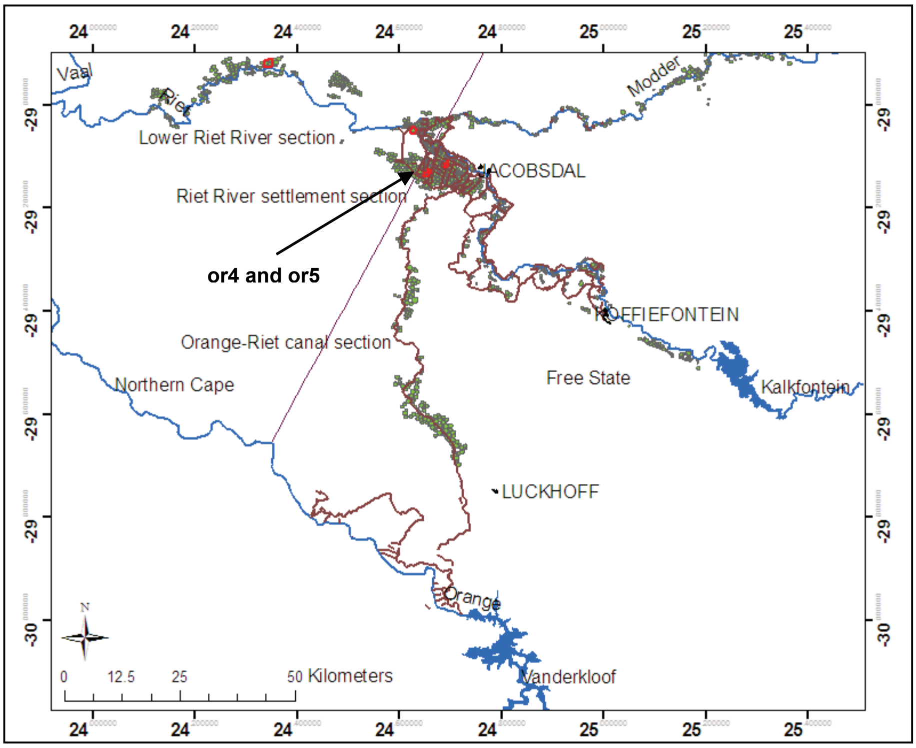
For this case study, four measuring points situated on two different fields were selected. The one field was located in the Settlement section (or4 and or5) at Orange-Riet and the other in the F-block section (v11 and v12) at Vaalharts (Figure 8.1a and b). Measuring points or4 and or5 were located on a 30 hectare centre pivot and v11 and v12 on a 51 hectare centre pivot that rotates just half of a circle, as shown in Figure 8.2a and b, respectively.

The soil of measuring points or4 and or5 comprises aeolian sandy deposits on lime and was classified as a Hutton form and Ventersdorp family (Soil Classification Working Group, 1991). The profile has four diagnostic horizons; Orthic A with 4% clay (0-300 mm), red apedal B1 with 8% clay (300-600 mm), red apedal B2 with 10% clay (600-1500 mm) and an unspecified C with 10% clay (+1500 mm). The A and B1 horizons fall in the fine sandy textural class and the B2 and C horizons in the fine loamy sand, all exhibiting an apedal massive structure. This soil has an underlying water table that fluctuates between 1600 and 1900 mm, and could therefore also have been classified as a Bloemdal due to signs of wetness in the C horizon. It was however classified as a Hutton due to the classification depth limitation of 1500 mm. The soil at measuring point's v11 and v12 is for all practical purposes the same as the soil at or4, or5. This is because it consists of also aeolian sandy deposits on lime but was classified as a Bloemdal form and Roodeplaat family (Soil Classification Working Group, 1991). Again four diagnostic horizons were identified; Orthic A with 4% clay (0-400 mm), red apedal B1 with 6% clay (400-1100 mm), red apedal B2 with 8% clay (1100-1500 mm) and an unspecified C with 10% clay (+1500 mm). The A, B1 and B2 horizons fall in the fine sandy texture class and the C in the fine loamy sand, all with apedal structure. The only difference between this soil and the soil at or4 and or5 is the fact that there were enough signs of wetness at a depth of 1100 mm, due to a fluctuating water table, to classify this soil as a Bloemdal.

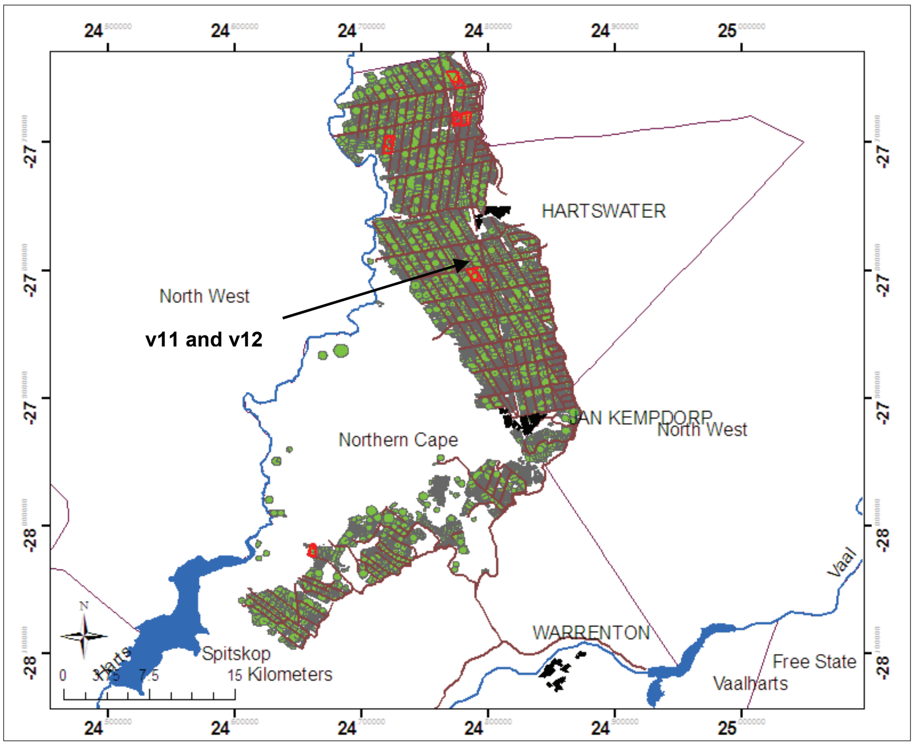
The internal drainage system at or4 and or5 consisted of a single lateral (650 m) installed at a depth of 1800 mm through the middle of the field in order to remove sub-surface drainage water. This lateral was privately installed in 1995 as part of an emergency measure to reclaim what was then a water logged area. According to the farmer, the area below the irrigation dam in the southern part of the field was most affected by waterlogging (Figure 8.2a). Measuring point or4 was located above the lateral and measuring point or5, 60 m to the west of the lateral. The internal drainage system at v11 and v12 was already installed when the farm was purchased. Figure 8.2b displays the position of the laterals relative to the main drainage lateral in the field. The laterals were spaces at intervals of 50 m along the main drain, except for the lower part of the southern half of the centre pivot where one lateral was installed. Each of these 50 m spaced laterals drains an area of about 5 to 6 hectares, while the last lateral drains about double the area of the others. It is not clear why the drainage laterals of the southern half were designed in this way.

8.2.2.2 Agronomic practices at the measuring points

The farmer at measuring point's or4 and or5 followed a wheat-maize crop rotation during the measuring period of two years, while the farmer at measuring points v11 and v12 also used a wheat-maize crop rotation during the first year, followed by a barley-maize cycle during the second year.

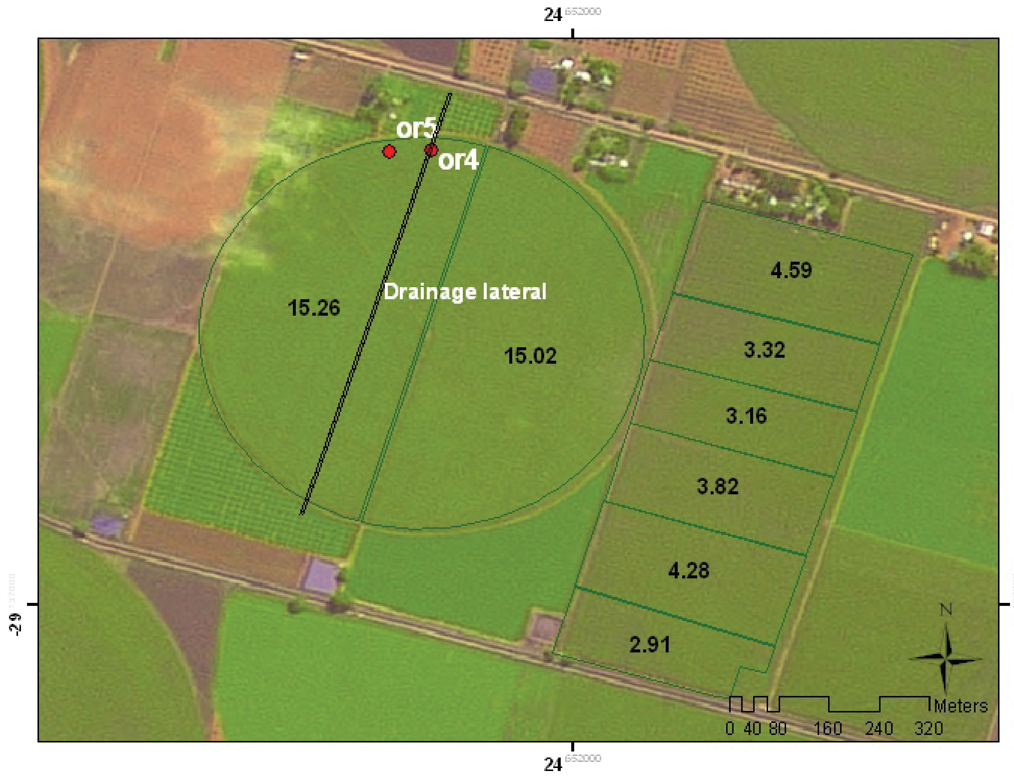


(a)

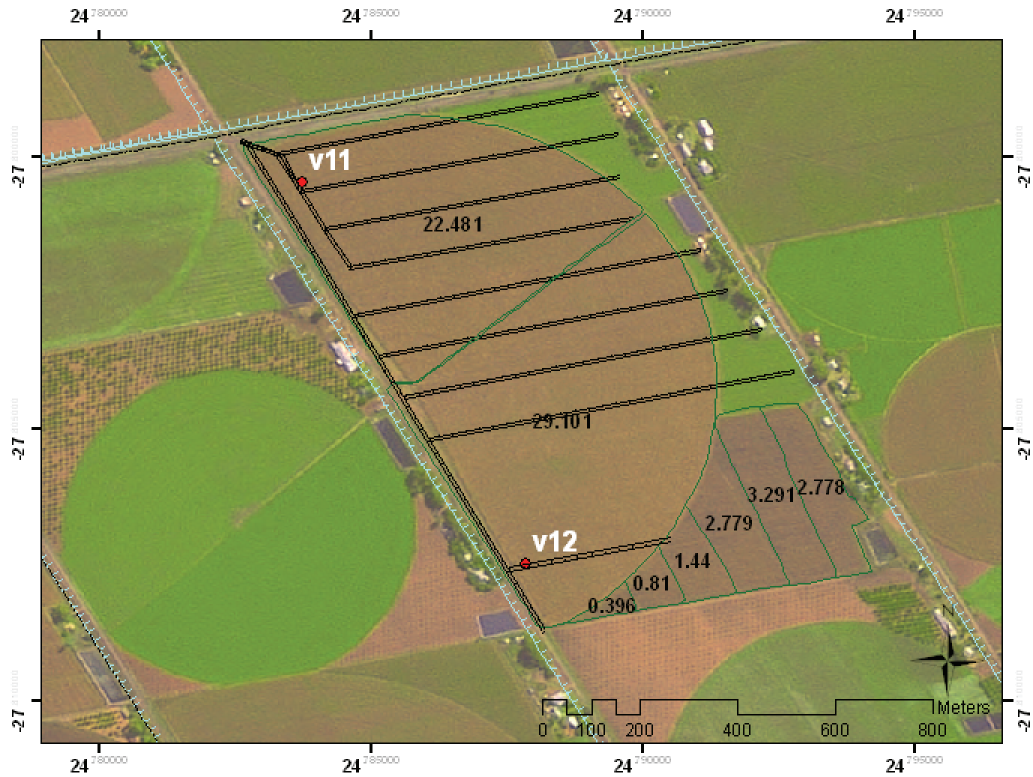


(b)

Figure 8.1 Geographical position of measuring points (or4 & or5) and (v11 & v12) at the Settlement section of the Orange-Riet Irrigation Scheme (a) and the F-block section of Vaalharts Irrigation Scheme (b), respectively.



(a)



(b)

Figure 8.2 Location of measuring points (or4 & or5) and (v11 & v12) on the irrigated fields at the Settlement section of the Orange-Riet Irrigation Scheme (a) and the F-block section of Vaalharts Irrigation Scheme (b), respectively.

Low wheat yield in the first season (4500 kg ha^{-1}) at v11 and v12 was attributed to the fungus *Gaeumannomyces graminis var. Tritici,* commonly known amongst farmers as "Take-all". Wheat was consequently replaced with barley during the second year. Details of the other agronomical practices for the two fields is summarised in Table 8.1. These practices are conventional for the two irrigation schemes where two cereal crops are planted annually. Conventional land preparation practices were followed, which basically consisted of burning or baling and removing the crop residue, followed by a disk and/or plough, and/or rip action before planting.

Table 8.1 Summary of agronomic practices followed during the four crop seasons at measuring points (or4 & or5) and (v11 & v12)

Measuring points or4 & or5				
Crop rotation	**Wheat**	**Maize**	**Wheat**	**Maize**
Cultivar	Duzie	Pannar 6236 B	Carnia 826	Pannar 6236 B
Planting date	July 2007	December 2007	July 2008	December 2008
Harvesting date	December 2007	July 2008	December 2008	July 2009
Planting density	85 kg ha^{-1}	85 000 seeds ha^{-1}	110 kg ha^{-1}	90 000 seeds ha^{-1}
Fertilizer applied	200 kg ha^{-1} 2:3:2 (22) 440 kg ha^{-1} 10:1:2 (24) 375 L ha^{-1} UAN (32) 1 kg ha^{-1} Tri-pholate	300 kg ha^{-1} 4:2:1 (28) 350 L ha^{-1} 10:1:2 (24) 225 L ha^{-1} UAN (32) 300 L ha^{-1} 3:1:2 (20) 2 kg ha^{-1} Maize pholate 1 L Marinure DS	200 kg ha^{-1} 2:3:2 (22) 220 L ha^{-1} 10:1:2 (24) 330 L ha^{-1} UAN (32) 1 kg ha^{-1}Tri-pholate 2 kg ha^{-1} Wheat pholate 0.5 L ha^{-1} Marinure DS	350 kg ha^{-1} 4:3:4 (33) 600 L ha^{-1} UAN (32) 150 kg ha^{-1} 8:1:1 (18)
Total kg N ha^{-1}	214	215	159	256
Total kg P ha^{-1}	27	41	23	35
Total kg K ha^{-1}	29	45	21	45
Pest management	Seed treated with 5 L t^{-1} – Montrae Dual	Seed treated with 50 mL Teprosyn & 250 mL Gaucho per bag	Bentrol – 2 L ha^{-1} MCPA – 1 L ha^{-1}	Atrazine – 1 L ha^{-1}
Cultivation practices	Burn, disc & plant	Burn, disc & plant then rip between rows after 24 days	Burn, disc & plant	Burn, disc & plant – After harvest – Burn & disc
Measuring points v11 & v12				
Crop rotation	**Wheat**	**Maize**	**Barley**	**Maize**
Cultivar	Carnia 826	Pannar 6236 B	Cocktail	Pannar 6236 B
Planting date	June 2007	December 2007	June 2008	December 2008
Harvesting date	November 2007	May 2008	November 2008	May 2009
Planting density	100 kg ha^{-1}	85 000 seeds ha^{-1}	75 kg ha^{-1}	90 000 seeds ha^{-1}
Fertilizer applied	500 kg ha^{-1} 7:2:3 (31) 500 kg ha^{-1} ANO_3 (21) 100 kg ha^{-1} Ureum (46)	300 kg ha^{-1} 4:3:4 (33) 400 kg ha^{-1} 10:1:6 (20) 400 kg ha^{-1} UAN (32)	250 kg ha^{-1} 2:3:4 (30) 500 kg ha^{-1} ANO_3 (21)	350 kg ha^{-1} 4:3:4 (33) 600 kg ha^{-1} UAN (32)
Total kg N ha^{-1}	242	211	122	239
Total kg P ha^{-1}	26	30	25	35
Total kg K ha^{-1}	39	50	33	47
Pest management	Buctril	Curater – 20 kg ha^{-1} Armadillo –1.2 L ha^{-1} Diamond – 1.4 L ha^{-1}	Buctril MCPA	Deusis – 60 mL ha^{-1} Armadillo – 1.3 L ha^{-1} Gardiun – 1.3 L ha^{-1}
Cultivation practices	Burn, plough, won-der till & plant	Bale, burn, rip & plant	Burn, wonder till & plant	Bale, burn, rip & plant

8.2.3 Desktop assessment of irrigation scheduling strategies for salinity control

All the simulations were done, as in the previous chapters, with the verified model (Chapter 4) SWAMP (Bennie et al., 1998). The same climatic data of Orange-Riet and Vaalharts, as discussed in Chapters 6 and 7, were used in this simulation study. Based on the results of the previous chapters, it was decided to simulate conditions generally inherent to Orange-Riet and Vaalharts, which will be discussed.

8.2.3.1 Soil conditions

It was decided to use the same two soils as in Chapter 7 because they represent the majority of soils irrigated at Orange-Riet and Vaalharts, *viz.* sandy to sandy loam with or without a water table. The two soils represent a Hutton (or17), which has no water table and a Bloemdal (v11), where a water table was present. The soil inputs required by the model are the *in situ* soil conditions as listed in Table 6.2 and discussed in Section 6.2.3.1. The water table was kept constant at a depth of 1500 mm from the surface with an electrical conductivity of 132 mS m^{-1}, while the same salt distribution coefficient was used as well as the same amount of salt applied through fertilizers as discussed in Section 6.2.3.1.

8.2.3.2 Crop choices and rotation system

The same double crop rotation system of wheat and maize planted alternately every year as discussed in Section 6.2.3.2 was used. A maize drying and harvest period, which was basically a simulation of a fallow period, was again also included.

8.2.3.3 Meteorological parameters

The daily calculated evaporative demand and rainfall data for the simulation period at Orange-Riet and Vaalharts were used as explained in Section 6.2.3.3 and imported into SWAMP.

8.2.3.4 Irrigation strategies

The four selected irrigation strategies were based on the work of Ehlers et al. (2007) and Chapters 5, 6 and 7 of this study. The principle aim of these strategies were to conserve water and minimise irrigation-induced leaching, while maintaining optimum yields, by managing the level of plant available water (PAW).

Strategy A: In this strategy, irrigation is scheduled to meet only the potential evapotranspiration, ($ET_{potential}$) or crop water demand (CWD, mm day^{-1}) simulated by SWAMP. This strategy takes into account rainfall and the contribution from the water table, when present. The irrigation requirement (IR, mm) for a specific time interval is calculated by subtracting the rainfall and water table uptake (WTU, mm) from the CWD.

$$\mathbf{IR=CWD-R-WTU} \tag{8.1}$$

This is a typical water conservation strategy, minimising both salt additions to the soil by irrigation and leaching induced by irrigation, while maintaining the PAW at an optimum level. When salt accumulates to a level that is harmful to the crop, due to insufficient leaching by rain, the actual evapotranspiration (ET_{actual}) will be lower than $ET_{potential}$. Under these conditions irrigation will exceed ET_{actual}, resulting in irrigation-induced salt leaching.

Strategy B: This strategy is similar to A, except that the contribution from the water table is ignored in the calculation of the irrigation requirement. This is a typical practice employed by farmers at Orange-Riet

and Vaalharts. This strategy makes provision for over-irrigation to an amount roughly equal to the potential water table uptake by the crop.
Strategy C: This strategy differs from Strategy A in that irrigation requirement is calculated using ET_{actual} instead of $ET_{potential}$. Rainfall and the contribution from the water table, when present, are also taken into account. Under crop water or salinity stress conditions the ET_{actual} is lower than $ET_{potential}$ or the CWD, thus reducing the irrigation requirement accordingly. This strategy will therefore conserve more irrigation water and add less salt to the soil than Strategy A, thus making no provision for salt leaching by irrigation water.

Strategy D: This strategy is similar to strategy C in the absence of salt-induced crop water stress. Unlike Strategy C, salt is allowed to build-up in the soil until the crop water stress index (SI) is smaller than 0.8. The SI was calculated as the ratio between ET_{actual} divided by the profile water supply rate. Irrigation at this point was increased to maintain the PAW at a level equal to the drained upper limit. With strategy D, irrigation water will also be conserved and leaching induced by irrigation will be minimised.

8.3 Results and discussion

8.3.1 General assessment of irrigation practices

The efficiency and uniformity of irrigation water application by centre pivot irrigation systems directly affected the results of irrigation scheduling and have a direct impact on crop water productivity. The evaluation results of the different irrigation system efficiency parameters of the centre pivots at 17 measuring points are listed in Table 8.2. Selected agronomic and environmental indicators of sustainability are listed in Table 8.3 for the 17 different measuring points. The results listed Table 8.2 show that the irrigation uniformity of the centre pivots was generally good (mean CU = 91%) with the lowest at measuring v10 where the centre pivot covers 66 ha. The high uniformity and efficiency suggest that the type of sprinklers and the spacing of sprinklers are sufficient to deliver the desired uniformity. The results show further that the mean application efficiency is 92%, with the lowest efficiency associated with systems that irrigate areas larger than 50 ha.

Table 8.2 Irrigation system efficiency parameters of the centre pivots at the various measuring points

Scheduling method	**Measuring point**	**Irrigation system efficiency (%)**				**Area (hectare)**	**Design application rate (mm day^{-1})**
		CU	**DUlq**	**AE**	**SE**		
Subjective	**or4, or5**	90	87	94	81	30	14
	or12, or13	93	90	91	82	42	11
	or14, or15	91	87	98	85	30	13
Objective	**or17**	93	90	99	89	32	12
	or19	93	91	97	88	20	12
	or18, or20	93	91	97	88	43	12
Subjective	**v6, v7**	90	87	92	80	30	13
	v8. v9	88	81	92	75	38	12
	v10	85	76	85	65	66	11
Objective	**v11, v12**	93	84	74	62	51	11

CU = coefficient of uniformity; AE = application efficiency; SE = system efficiency

A negative relationship between area under irrigation and system efficiency was observed in the measuring points; for every hectare irrigated the system efficiency declined by 0.5% (R^2 = 0.58). Thus the area covered by individual systems play a significant role in their efficiency. However, it can be concluded that these systems are well designed and in excellent working condition. This is one of the reasons why South African farmers invest in this type of irrigation system. Although relatively expensive, it provides easy control over application, it can be matched to virtually any soil in order to eliminate runoff and minimise erosion, and is highly adaptable to a variety of terrain and slope conditions (Reinders et al., 2010). This explains why the farmers in the Vaalharts Irrigation Scheme are replacing flood with centre pivot systems at a rate of 266 ha per annum since 1975.

The water use efficiency achieved under the centre pivots in Orange-Riet and Vaalharts is generally good. This can be seen from the results in Table 8.3 compared to the norms of the areas. The mean rain-plus-irrigation water use efficiency for maize was 21.4 compared to the norm of 21 kg ha^{-1} mm^{-1}, groundnuts was 5 compared to 5.3 kg ha^{-1} mm^{-1}, cotton was 6 compared to 6.5 kg ha^{-1} mm^{-1}, wheat was 10.5 compared to 11 kg ha^{-1} mm^{-1}, barley was 11 compared to 11 kg ha^{-1} mm^{-1} and peas was 6.3 compared to 6.1 kg ha^{-1} mm^{-1}. With respect to the subjective versus objective scheduling methods, the results indicated that there is a slight advantage in using scientific-based knowledge when managing centre pivots. For maize, groundnuts, wheat and barley the mean rain-plus-irrigation water use efficiency, using the objective method were 22.8, 5, 10.9 and 9.9, respectively, compared to 20.8, 4.9, 9.2 and 9.4, respectively, for the subjective scheduling method. The small difference between the two methods was expected due to the ease of management of the centre pivots discussed earlier, and its direct impact on avoiding crop water stress. The risk for inducing crop water stress due to poor water management is low because the centre pivots under discussion (Table 8.2) can apply between 11 and 14 mm day^{-1}. This is equal or higher than the water use of any field crop during a particular day.

This implies that just by running the centre pivot crop water stress is avoided. These results confirm why irrigators invest their resources into centre pivots rather than objective scheduling tools and methods. Another reason for the positive performance of the subjective farmers can probably be ascribed to technology exchange between researchers and farmers conducted over several decades in the region. An example is the application of the BEWAB irrigation scheduling program that has reached about 500 irrigators (Annandale et al., 2011). Most BEWAB users stopped using the program once they were calibrated, illustrating the informal learning process. Nevertheless, it seems that the farmers, irrespective of their scheduling preferences, are educated in irrigation scheduling with the main aim of achieving high yields and crop water productivities. Being economically sustainable in this region is an important skill and asset.

Given the sophisticated irrigation systems that can apply between 11 and 14 mm day^{-1} at any time during the season, the question arises: what is the impact of these irrigation systems and management practices on the soils and groundwater? Three indicators were selected to investigate this impact, *viz*. salinity of the soil, leaching of salt and the presence of water tables (Table 8.3). For all the soils the mean salinity amounted to 112 mS m^{-1} with a standard deviation of 67 mS m^{-1}. Considering the norm of 400 mS m^{-1} (United States Salinity Laboratory Staff, 1969) these soils are far from saline. However, farmers should take notice of the fact that salt sensitive crops, like peas (105 mS m^{-1}) and beans (100 mS m^{-1}), can be harmed. The relatively low soil salinities are probably due to good irrigation water quality, suitable soils and over irrigation. Drainage resulted in the discharge of a mean 1113 kg salt ha^{-1} per season with a standard deviation of 1293 kg ha^{-1}. Some measuring points discharged between 3 and 8 ton salt ha^{-1} per season into the environment, irrespective of the use of subjective or objective scheduling tools and methods. Periodic seasons and sites with high salt discharge have the potential to harm the environment.

Table 8.3 Agronomic [Seed yield, (kg ha^{-1}) divided by rain-plus-irrigation (mm)] and environmental indicators of sustainability [mean electrical conductivity of a saturated extract for the 2000 mm deep soil profile ($EC_{e\ 0\text{-}2000}$) and net gain (+) or loss (-) of salt from the soil profile through drainage ($\pm S_D$)] for the various measuring points

Method	Measuring point	Seed yield / (Rain-plus-irrigation)				$EC_{e\ 0\text{-}2000}$ Sampling (mS m^{-1})					$\pm S_D$ (kg ha^{-1})				Water table
		1st Crop	2nd Crop	3rd Crop	4th Crop	1	2	3	4	5	1st Crop	2nd Crop	3rd Crop	4th Crop	
Subjective	or4	9.94w	24.41m	10.04w	19.33m	73	56	45	54	42	-2592	311	-1166	-2506	Yes
	or5	8.48w	23.76m	9.93w	21.58m	50	65	43	59	44	-1020	-204	-571	-2577	Yes
	or12	7.00w	24.97m	-	14.12m	69	87	77	95	118	-323	578	-	-46	Yes
	or13	10.83w	21.60m	-	12.39m	101	108	108	108	113	-936	-422	-	-929	Yes
	or14	9.22b	22.87m	-	-	61	78	38	-	-	-401	-49	-	-	No
	or15	9.66b	22.45m	-	-	39	57	32	-	-	-297	-1098	-	-	No
Objective	or17	5.69g	-	-	9.88b	53	59	45	107	150	-	-1844	-	-2793	No
	or19	11.33w	-	-	4.29g	50	17	24	161	83	-	-1639	-	-7931	No
	or18	15.69m	-	14.13w	3.32s	97	122	125	123	159	-	-1292	-110	0	No
	or20	22.64m	-	14.11w	5.84s	87	113	147	156	127	-	-113	-199	0	No
Subjective	v6	6.28p	4.53g	7.48w	6.01c	99	117	105	105	102	-1133	-3030	-3840	-3098	Yes
	v7	8.42w	16.06m	-	3.96g	109	139	104	-	140	-1282	-3875	-	-179	Yes
	v8	-	-	11.10w	6.99g	146	149	114	130	136	-	-	-35	-102	Yes
	v9	-	-	13.69w	4.00g	179	159	228	209	167	-	-	92	-179	Yes
	v10	-	-	9.42w	25.59m	-	-	332	342	303	-	-	-	-	No
Objective	v11	11.80w	27.56m	12.97b	22.46m	72	100	90	89	94	-359	-409	647	-1148	Yes
	v12	9.59w	27.18m	13.63b	21.13m	126	150	125	123	110	-453	-1517	188	-2017	Yes

w = Wheat; m= Maize; p = Peas; g = Groundnuts; c = Cotton; s = Sunflower; b = Barley

8.3.2 *In situ* case study assessment of a subjective and an objective irrigation scheduling method

8.3.2.1 Background

From the previous section it is clear that the centre pivot irrigation systems and the scheduling methods, whether objective or subjective, resulted in maintaining high applied water use efficiencies over a variety of field crops. Water use efficiency reflects on how efficient irrigations and rain are converted into yield. It is a good agronomic indicator for farmers, because of the ease with which parameters may be measured and interpreted. However, it cannot be used as a sole indicator to assess irrigation practice with respect to water conservation. All gains and losses need to be considered (Hillel, 2004). Thus, the first part of this section focuses on water management of the two irrigation scheduling methods using both the daily and seasonal water balance. The daily response is depicted in Figures 8.3a in terms of the subjective scheduling method (or4 and or5 measuring points, hereafter called the Orange-Riet plot) and in Figure 8.3b for the objective method (measuring pointv11 and v12, hereafter called the Vaalharts plot).

The seasonal soil water balance is available in Table 8.4 for the subjective and objective methods. In summary, the assessment concentrates on how efficiently the two irrigation scheduling methods utilised rainfall and groundwater (shallow water tables) as water sources in their respective irrigation schedules.

The second part of the section was dedicated to salinity management, using the salt balance results as basis for the assessment. The salt balance for the seasons was summarised and presented in Table 8.5 for the subjective and objective scheduling methods. The assessment focuses on two aspects of salinity management, namely the performance of the scheduling method to minimise salt additions and controlling salt leaching through natural drainage and/or artificial drainage.

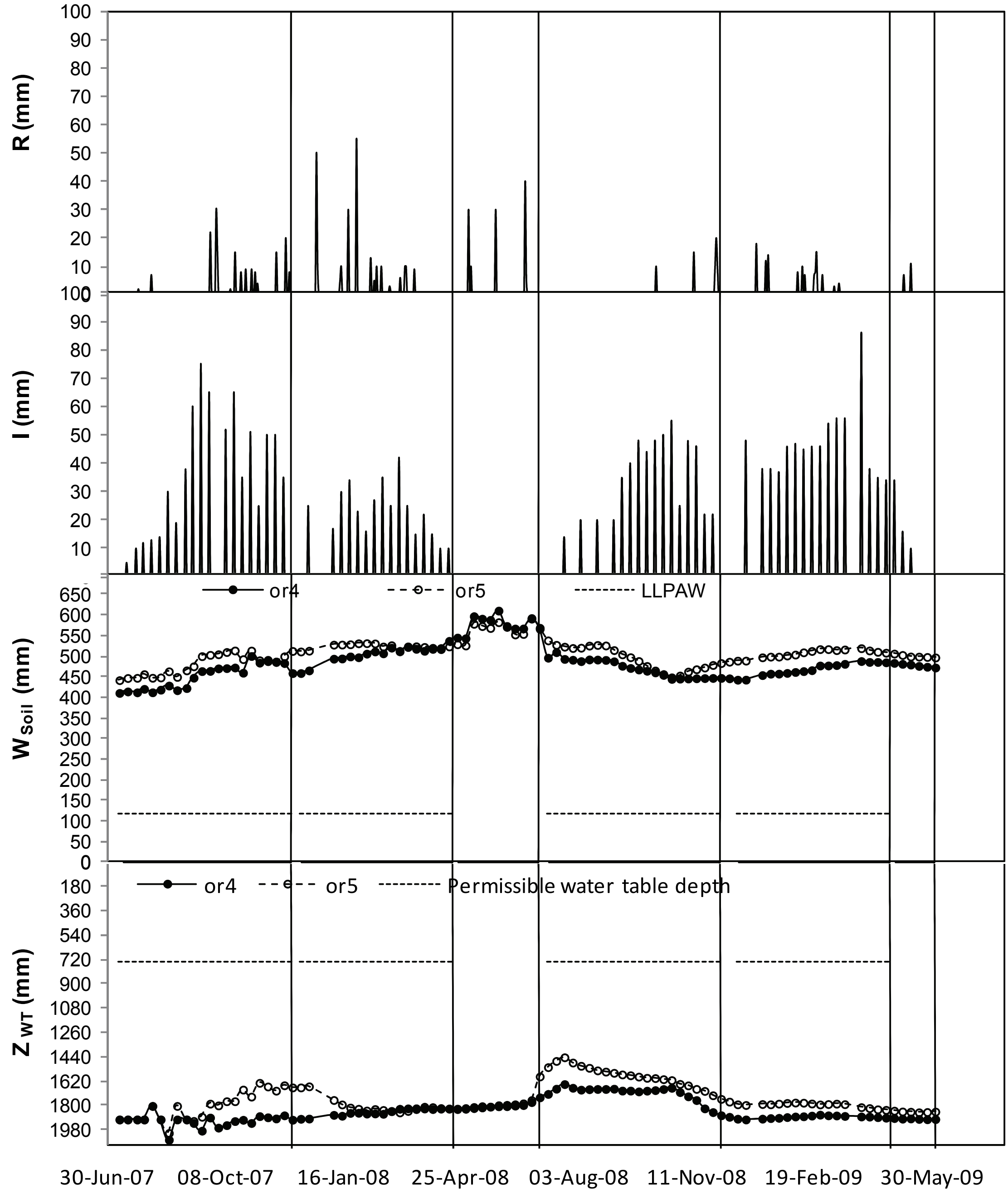
8.3.2.2 Water management

The question that needs to be answered here is: How effectively did the scheduling methods (subjective and objective) integrate rainfall and groundwater (water table) as sources into their respective schedules?

Integration of rain into irrigation schedules

The rainfall characteristics at the two schemes were typical of a semi-arid zone: unpredictable, erratic and poorly distributed. This can be inferred from the rainfall amount and distribution results depicted in the rainfall-graphs (Figure 8.3a and b) and summarised in the soil water balance tables (Table 8.4). Comparing the rainfall of the growing seasons with the long-term mean as reference, suggests that the first winter season (wheat) was very wet, while the second winter season (wheat/barley) was dry at both schemes. Rainfall conditions during the summer growing season (maize) differed amongst the plots; the first maize season was normal at Orange-Riet, while wet at Vaalharts, and the second season dry in Orange-Riet and normal in Vaalharts. Thus, the case study offers a wide variety of weather conditions, which presents a real challenge to integrate rain into irrigation schedules.

In order to assess the irrigation scheduling methods, it was assumed that the water received (rain and irrigation) by the crop should meet the crop water demand, expressed as evapotranspiration in the soil water balance results. For the subjective irrigation scheduling method, the results indicated that there was on average over the four seasons an over-supply (rain and irrigation) of 9%. An over-supply of water to the potential root zone *per se* is not a bad strategy, provided that there is sufficient storage available in the profile. For example, the BEWAB program reserves a rainfall storage volume in the profile when schedules are calculated (Bennie et al. 1988). Nevertheless drainage, is unproductive and does not contribute to crop production. From these results the conclusion can be drawn that the on average 9% over-irrigation, using subjective methods, is probably less than what was expected.



(a)

Figure 8.3 Rainfall (R), irrigation (I), soil water content of a 2000 mm profile (W_{Soil}) and water table depth (Z_{WT}) for measuring points (or4 & or5) at Orange-Riet (a) and (v11 & v12) at Vaalharts (b), together with the lower limit of plant available water (LLPAW) and permissible water table depth.

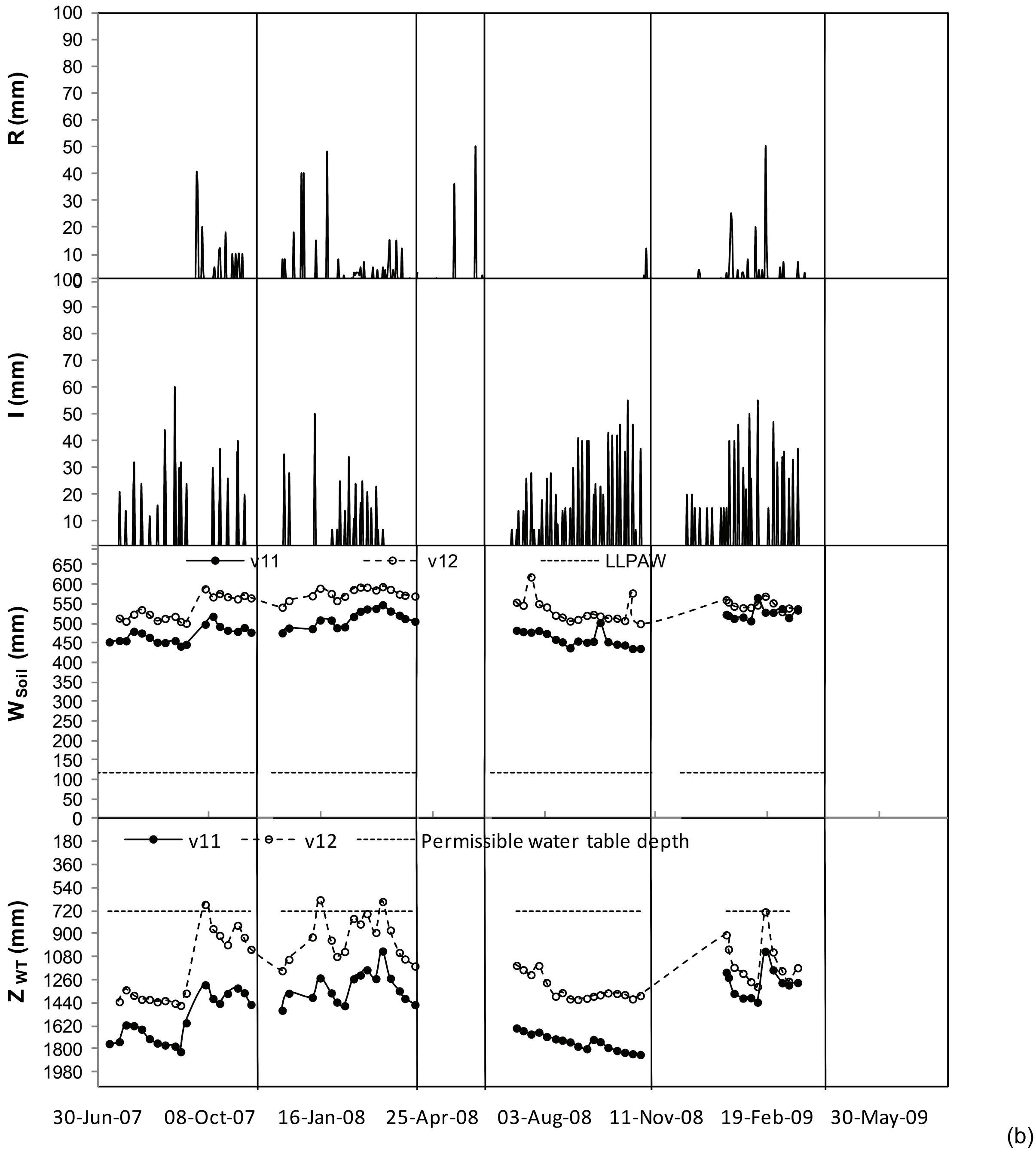


Figure 8.3 continued

In the case of the Vaalharts plot, where the objective scheduling method was used to determine irrigations, the results show that there was a deficit in rain and irrigation received (compared to the crop water demand) in three of the four seasons. The deficits amounted to 85, 134 and 68 mm per season, respectively. The difference in the actual irrigations and the crop water demand were supplied by the profile. Estimations with SWAMP confirmed a net potential inflow from the water table of 192, 305 and 109 mm per season, respectively. Thus, the conclusion can be drawn that scheduling method tools helped to conserve irrigation water. The reason for this is that the capacitance probes, by design measures, soil water content, irrespective of the source. The soil water content was measured on an hourly basis and prior to irrigation the data was retrieved and the deficit calculated. The deficit to be irrigated was calculated as the actual soil water content minus a predetermined upper limit. This is a typical example of how modern soil water sensors are used in practice. There are many variations in the practical application of soil water sensors in scheduling irrigations in South Africa (Van Rensburg, 2010). Thus, it can be concluded that the objective scheduling method enhanced water conservation by integrating rainfall intelligently in the calculation of how much to irrigate.

Integration of groundwater as shallow water table uptake into irrigation schedules

Another important water source for irrigation, often ignored, is groundwater in the form of shallow water tables in or near the potential root zone of crops (Ehlers et al., 2003). This was the case in both the sites, but more in the Orange-Riet plot than the Vaalharts plot, as will be seen in the discussion that fallows.

Subjective method: The water table at the Orange-Riet plot reacted as follows to the irrigation scheduling with the subjective method. At the beginning of the season the water table was at a depth of about 1850 mm from the soil surface. The water level then gradually rose over the wheat, maize growing and maize ripening seasons reaching a depth of about 1800 mm. From there the water table rose sharply and peaked at 1500 mm during the early growth stage of the second wheat season.

After the peak the water table depth increased over the rest of the wheat season and stabilised at a depth of about 1800 mm during the last maize season. The result was that the artificial drain never stopped running over the time span of the project, indicating uncontrolled water loss through drainage. The biggest impact was caused by rain that fell during the drying phase of the first maize season. It rained 115 mm and at this stage transpiration was zero. Water could only be removed by evaporation and drainage. Evaporation was low due to plant cover, hence drainage was the dominant process. The water table depth indicated a delay in its response to high rain of about a month. This was probably due to lateral groundwater flow on top of the lime. However, a considerable amount of groundwater was lost in the process that could have been skilfully utilised in the scheduling program. The drain never stopped running during the measuring period of two years.

Objective scheduling method: The water table depths of the Vaalharts plot gave new insight on the management of soil water sensors with respect to shallow water tables. However, before discussing the statement it is necessary to clarify the prominent difference in the water table depth observed at the Vaalharts plot compared to the Orange-Riet plot. From the water table depth results the following conclusions can be drawn; the water table at the Vaalharts plot was much shallower, the response was much more direct towards rain and irrigation events and drainage was more rapid than at the Orange-Riet plot. These differences resulted from a difference in the design of the artificial drainage systems as can be seen in Figures 8.2a and b for Orange-Riet plot and Vaalharts plot, respectively. At the Orange-Riet plot the drainage system comprised a single drainage lateral, while at the Vaalharts plot it covered almost the full area, including the flood irrigated field at the eastern side of the centre pivot. Nevertheless, the drains at the southern part of the centre pivot in Vaalharts, where the v12 measuring point was located, were poorly designed; they were probably just an emergency measure. This explained why the water table depths of v12 were always shallower (closed to the surface) than v11. The rapid rise of the water table can be directly linked to rain and irrigations, and the internal drainage of the unsaturated zone above the water table. This aspect will be discussed at a later stage. The rapid decline in the water table can be attributed to the superior design of the drainage system at the Vaalharts plot. The owner of the plot also cleaned the drains regularly. Over the measuring period of four seasons a total of 465 mm water drained from the plot which amounted to 57% of the rainfall or 35% of total irrigations which is significant.

Table 8.4 Net gain (+D) or loss (-D) of water from the potential root zone through upward or downward drainage for measuring points (or4 & or5) at Orange-Riet and (v11 & v12) at Vaalharts as calculated from the change in soil water content (ΔW_{Soil}), rainfall (R), irrigation (I), evaporation (E), transpiration (T), water table uptake (WTU), percolation into the water table (P, mm) and drainage from the artificial drainage system (AD)

Subjective scheduling method: Orange-Riet plot (or4 and or5)											
Crop	**Measuring point**	**ΔW**	**R**	**I**	**E**	**T**	**ET**	**AD**	**± D**	**WT_{Uptake}**	**P**
		mm									
1st Wheat	or4	48		561	61	569	631	10	-50	198	248
	or5	71	177	578	80	521	601	10	-74	178	252
	Mean	**59**		**570**	**71**	**545**	**616**	**10**	**-62**	**188**	**250**
1st Maize	or4	78		359	34	708	742	22	+203	265	62
	or5	11	262	359	61	677	738	22	+153	321	168
	Mean	**45**		**344**	**47**	**693**	**740**	**22**	**+178**	**293**	**115**
1st Maize drying	or4	21		0	56	0	56	16	-22	0	22
	or5	40	115	0	49	0	49	16	-11	0	11
	Mean	**31**		**0**	**52**	**0**	**52**	**16**	**-17**	**0**	**17**
2nd Wheat	or4	-49		550	48	516	564	23	-77	251	328
	or5	-55	65	552	67	517	584	23	-72	320	392
	Mean	**-52**		**551**	**58**	**516**	**574**	**23**	**-75**	**286**	**360**
2nd Maize	or4	42		739	39	565	604	10	-198	203	401
	or5	19	115	733	53	647	700	10	-119	236	354
	Mean	**31**		**736**	**46**	**606**	**652**	**10**	**-159**	**220**	**378**
2nd Maize drying	or4	-11		26	29	0	29	3	-23	0	23
	or5	-9	18	56	35	0	35	3	-45	0	45
	Mean	**-10**		**41**	**32**	**0**	**32**	**3**	**-34**	**0**	**34**
Objective scheduling method: Vaalharts plot (v11 and v12)											
Wheat	v11	25		362	53	573	625	68	163	229	66
	v12	52	193	321	51	565	615	67	220	355	135
	Mean	**38**		**342**	**52**	**569**	**620**	**68**	**192**	**292**	**100**
1st Maize	v11	30		178	48	566	614	141	292	357	65
	v12	29	313	172	49	581	630	141	318	451	134
	Mean	**29**		**175**	**49**	**573**	**622**	**141**	**305**	**404**	**99**
1st Maize drying	v11	-23		0	31	0	31	34	-48	0	48
	v12	-15	90	0	30	0	30	34	-41	0	41
	Mean	**-19**		**0**	**30**	**0**	**30**	**34**	**-44**	**0**	**44**
Barley	v11	-47		459	57	524	581	90	152	290	138
	v12	-55	14	428	63	408	472	90	65	318	253
	Mean	**-51**		**444**	**60**	**466**	**526**	**90**	**109**	**304**	**196**
2nd Maize	v11	14		375	37	488	525	132	93	315	222
	v12	-26	205	339	36	429	465	132	25	334	309
	Mean	**-6**		**357**	**37**	**459**	**495**	**132**	**59**	**324**	**265**

The sophisticated soil water measuring device used in the objective scheduling monitored the water content in only the top 600 mm or 30% of the root zone. The water table depth of the plot oscillated between depths of 1080 and 1800 mm from the soil surface at v11 and between 720 and 1440 mm at v12, which is beyond the depth of the capacitance probes (maximum probe depth was 600 mm). The estimated potential water table uptake, expressed as a percentage of transpiration amounted to 32%. Ehlers et al. (2003) measured water table contributions to various field crops and observed that the water table contributes between 30 and 60% of the total evapotranspiration. Thus, irrigations could have been reduced further, forcing the crop to use more groundwater. Practically, this means that the farmers should have used longer probes, or the probes should be used in conjunction with piezometers installed at critical points in the field. Another example of what the farmer could have done to manage the water table, is to manage the drainage-outlets with control valves, or simply plug the outlet when the water table dropped to a predetermined depth. This is not a new intervention. Herold & Baily (1996) reported that farmers in Vaalharts had plugged the drainage outlets during intense drought periods when water stocks were low. However, controlling drainage outflow also requires good knowledge of groundwater quality and its impact on crops. This aspect will be discussed in the next section.

8.3.2.3 Salinity management

As was discussed in Chapter 6 and 7, root zone salinity affects the profile available water capacity (PAWC) of soil-crop-atmospheric production systems, and becomes important in (shallow soils) low PAWC soils. This aspect is often overseen when irrigation schedules are compiled. For example, the main interest of the irrigators at the two sites under investigation was to ensure that the crop received sufficient water to meet the crop water demand, without considering strategies to manage salinity. Thus, this section will focus on analysing the fate of the salt related to the two irrigation scheduling methods, using a salt balance, with the aim of understanding salinity in real-world situations. Lessons learned from the specific situations can lead to better formulation of best management practices.

Salt balance

The salt balance of the Orange-Riet plot and the Vaalharts plot is summarised in Tables 8.5, respectively. Before discussing the salt balance, it should be explained that SWAMP manages groundwater as both a source (S_{WTU}) and a sink (S_P). For budget purposes, the net flow of salt to the root zone is given as +D, while the net outflow is represented by –D. For the Orange-Riet plot there was a net outflow of salt in all the seasons, except the first maize season (501 kg ha^{-1}). The same trend was observed at the Vaalharts plot, where a net inflow occurred during the dry barley season (703 kg ha^{-1}). Given this explanation it is clear from the salt balance that the water table is not a significant source of salt, but should rather be identified as a sink. The major sources of salt are irrigation water and fertilizers. From the total salt additions to the soil irrigation contributed 68% at the Orange-Riet plot (total additions was 5238 kg ha^{-1}) and 80% at the Vaalharts plot (total additions was 8084 kg ha^{-1}). Fertilizers deposited 29 and 23% of the total salt at the respective plots. The higher salt additions at the Vaalharts plot are due to the poorer water quality of the respective river sources; Vaal River EC_i is 68 mS m^{-1} compared to 21 mS m^{-1} of the Orange River. In the case of the Orange-Riet plot more salts were leached than added, implying that the soil quality had improved over the measuring period (Figure 8.4a). For the Vaalharts plot only 5% of the total salt added remained in the profile (Figure 8.4b), hence there was no risk of harming the crop due to salinity. The high leaching in both plots can be ascribed to the presence of water tables linked to artificial drains, plus the tendency to over irrigate. The artificial drains at Vaalharts, which operated well, removed 4933 kg ha^{-1} of salt over the two years of measurement. This represents 50% of the total salt additions. The rest of the salts probably leached laterally to lower lying fields.

Table 8.5 Net gain ($+S_D$) or loss ($-S_D$) of salt from the potential root zone (2000 mm) through upward or downward drainage as calculated from the change in salt content of the soil (ΔS_{Soil}), addition of salt through fertilizers (S_F), rainfall (S_R), irrigation (S_I) and capillary rise (S_{WTU}) as well as movement of salt into the water table through percolation (S_P) and out of the potential root zone through the artificial drainage system (S_{AD}) for measuring points (or4 & or5) and (v11 & v12)

Crop	Measuring point	ΔS_{Soil}	S_F	S_R	S_I	S_{AD}	$\pm S_D$	S_{WTU}	S_P
		kg ha^{-1}							
Subjective scheduling method: Orange-Riet plot (or4 and or5)									
1st Wheat	or4	-952	387	27	926	87	-2205	1588	3793
	or5	+734			1040	87	-633	1565	2198
	Mean	**-109**			**983**	**87**	**-1419**	**1577**	**2996**
1st Maize	or4	+1587	448	39	565	225	759	1810	1051
	or5	+1071			565	225	244	2306	2062
	Mean	**+1329**			**565**	**225**	**501**	**2058**	**1557**
1st Maize drying	or4	-1672	0	17	0	154	-1535	0	1535
	or5	-1964			0	154	-1827	0	1827
	Mean	**-1818**			**0**	**154**	**-1681**	**0**	**1681**
2nd Wheat	or4	+59	286	11	866	223	-880	2089	2969
	or5	+657			869	223	-285	2411	2696
	Mean	**+358**			**867**	**223**	**-583**	**2250**	**2833**
2nd Maize	or4	-637	419	17	1109	96	-2087	1593	3680
	or5	-718			1100	96	-2158	2072	4230
	Mean	**-678**			**1104**	**96**	**-2122**	**1833**	**3955**
2nd Maize drying	or4	-11	0	3	41	29	-26	0	26
	or5	-79			88	29	-141	0	141
	Mean	**-45**			**65**	**29**	**-84**	**0**	**84**
Objective scheduling method: Vaalharts plot (v11 and v12)									
1st Wheat	v11	1437	419	29	1656	728	60	2147	2087
	v12	1168			1469	715	-34	4850	4884
	Mean	**1302**			**1562**	**722**	13	**3498**	3485
1st Maize	v11	-121	419	47	868	1465	10	3534	3524
	v12	-1259			839	1465	-1098	5517	6615
	Mean	**-690**			**853**	**1465**	-545	**4525**	5070
1st Maize drying	v11	-2205	0	14	0	461	-1758	0	1758
	v12	-1988			0	461	-1540	0	1540
	Mean	**-2097**			**0**	**461**	**-1649**	**0**	**1649**
Barely	v11	2442	286	2	2169	947	933	2918	1985
	v12	1965			2151	947	504	3774	3270
	Mean	**2204**			**2160**	**947**	703	**3331**	2628
2nd Maize	v11	216	362	30	1997	1388	-786	3304	4090
	v12	-844			1805	1388	-1655	2853	4508
	Mean	**-314**			**1901**	**1388**	-1221	**3078**	4299

From the above discussion it is clear that leaching is very easy in sandy soils with water tables near or in the root zone, providing that the natural flow of the groundwater is not restricted. In the case of the Orange-Riet plot, a single drainage line was installed to boost the natural groundwater flow. At the Vaalharts plot the hydraulic gradient is too small to control water removal during periods of high rainfall, hence the full scale artificial drainage system installed in the plot. In normal to dryer periods the natural flow contributes 52% of the leaching at this particular plot.

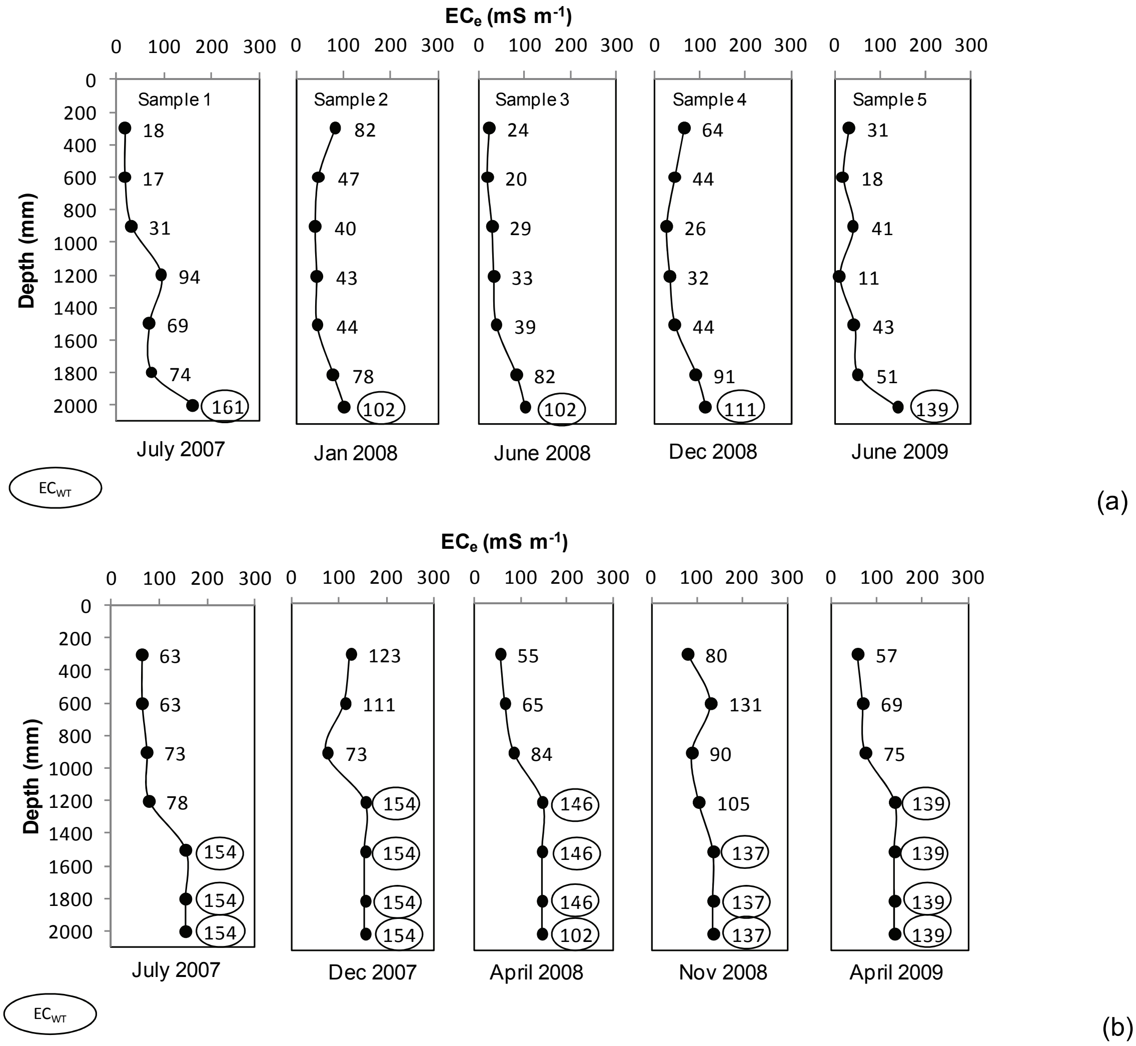


Figure 8.4 Mean salt distribution in the soil profile, expressed as the electrical conductivity of a saturated extract (EC_e), of measuring points (or4 & or5) (a) and (v11 & v12) (b) for the five samplings taken during the measuring period.

The artificial drains are in most cases linked to river systems, which means the communities downstream are the recipients of the salt. This implies that irrigators need to control the discharge of salt into the broader water ways. The case study demonstrates the need for developing tools and technologies to integrate both water and salt management for site specific situations. The next section will focus on the testing of integrated water and salt management strategies.

8.3.3 Desktop assessment of irrigation scheduling strategies for salinity control

8.3.3.1 Freely drained soils

The four strategies (Section 8.2.3.4) were assessed in terms of their objectives, *viz*. to conserve irrigation water, minimise irrigation-induced drainage and leaching, minimise salt addition, and manage PAW in order to maintain optimum seed yields. Results of irrigation strategies A, C and D that were simulated on the freely drained Hutton soil over a period of 20 years are presented in Figure 8.5. The results include the mean daily salinity of the soil profile and the yield per season, expressed relatively to the potential or target yield. Strategy B is not applicable to freely drained soils without a water table.

Over 20 years of irrigation, a total of 94 and 91% of the target yield were obtained by applying strategies A and D, respectively. With strategy C, which makes no provision for irrigation-induced salt leaching, the seed yield varied considerably during the 20 years, due to occasional salt accumulation in the root zone. It is interesting to note that where the EC_e reached ± 400 mS m^{-1}, the yields were drastically reduced; they decreased below 60% of the target yield. These seed yields were the result of a mean irrigation of 434, 274 and 407 mm per season for strategies A, C and D, respectively. Rainfall amounted to a mean of 118 mm per season over the 20 years for all three irrigation strategies. The result was a mean drainage of 53, 27 and 44 mm per season for strategy A, C and D, respectively. Despite the differences in irrigation and drainage between strategies, the daily soil salinity over the 20 years did not differ much, a mean of 203, 254 and 223 mS m^{-1} for strategies A, C and D, respectively. Similar amounts of salts were applied through irrigation and leached with strategies A and D, namely 2116 and 1984 kg ha^{-1} of salt per season were applied, while 1893 and 1790 kg ha^{-1} of salt per season were leached from the root zone. Less salt was applied through irrigation (1336 kg ha^{-1} $season^{-1}$) and leached from the root zone with strategy C, *viz*. 1304 kg ha^{-1} per season, or a total of 52102 kg ha^{-1} over the 20 year simulation period.

The objective of conserving irrigation water and minimising irrigation-induced drainage and leaching was achieved with all three strategies. Under these conditions salt accumulated to approximately 2.3 fold the initial value within 5 years of continuous irrigation. High rainfall events played a significant role in controlling and reducing soil salinity (Figure 8.5). It is important to note that salt will accumulate considerably faster in the root zone between high rainfall events with a corresponding increase in irrigation water salinity. In the absence of high rainfall events, an irrigation strategy for irrigation-induced leaching is therefore a prerequisite, especially where an increase in irrigation water salinity is observed. Barnard et al. (2010) showed that for sandy soils approximately 160 mm additional water will be required in order to leach the soil back to its initial salinity.

This simulation study shows that for prevailing climatic conditions leaching through over-irrigation is not a necessity, but optimum PAW should be maintained in order to obtain optimum yields. In this respect, strategies A and D performed the best, as can be observed from the yield results (total relative yield > 0.9). The reason for this is that the PAW was kept higher with strategies A and D during the simulation period when compared to strategy C. This was observed from the cumulative frequency analysis (probability of non-exceedence) of daily PAW during the 20 years in Figure 8.6. The results showed that with strategies A and D there was a 30% chance that the PAW would drop below 40 mm (PAWC = 80 mm), compared to the 65% when strategy C was applied. With strategy A this can be expected because with this strategy the aim is to minimize the dependence on stored PAW. What was interesting is the fact that Strategy D performed similar to A, even though strategy D was aimed at making maximum use of PAW. The similarities are ascribed to the fact that with strategy D, PAW and hence PAWC were recharged to its maximum, prior to the onset of crop water stress. Thus strategy D had a clear water saving advantage over A, because it required 6% less irrigation water. Strategy D can therefore conserve more irrigation water, when soils with a higher PAWC and soil salinities are irrigated.

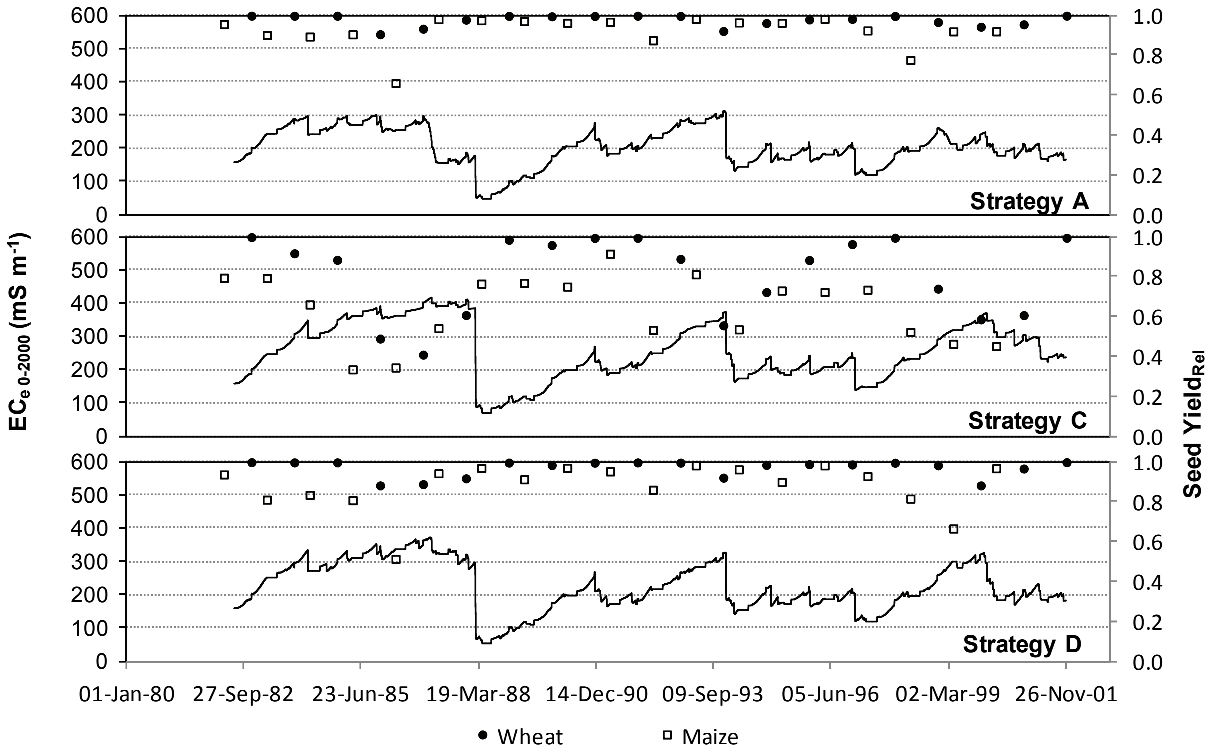


Figure 8.5 Mean daily salinity of the soil profile ($EC_{e\ 0\text{-}2000}$) and the seed yield for each season, expressed relatively to the potential or target seed yield, for strategies A, C and D, used on the freely drained soil.

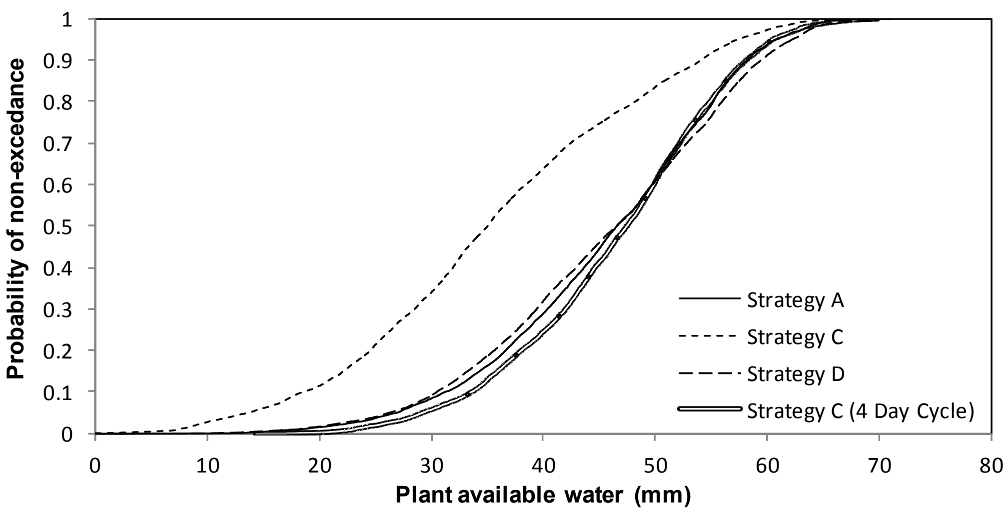


Figure 8.6 Probability of non-exceedence of daily plant available water when irrigation strategy A, C and D were used for a wheat-maize crop rotation, grown on a freely drained sandy soil over a period of 20 years.

Another aspect that needs to be considered when managing PAW is irrigation frequency, especially on soils with a low PAWC. When the irrigation frequency was changed from 7 to 4 days, irrigation strategy C performed better (Figure 8.6). With the four day cycle 94% of the total target yield was obtained compared to the 70% with the 7 day cycle. The reason for this discrepancy was because the soil was kept wetter (constant higher PAW), similar to strategies A and D, with the 4 day cycle spanning 20 years as shown in Figure 8.6. Shorter irrigation cycles increase the total irrigation requirement because of higher unproductive soil water evaporation.

Minhas (1996) also reported an increase in unproductive evaporation losses, and when saline water is used, the salt load in the upper soil layers will be increased. Sinha & Sinha (1976a, b), as cited by Minhas (1996) also showed that by keeping the soil wet, the higher transpiration rates may actually increase the osmotic potential adjacent to roots considerably, when compared to the bulk soil.

As a final assessment of the application of strategies A, C and D on freely drained soils, it can be concluded that:

i) Strategy A will over the long term (> 20 years) result in occasional short term (5 years) salt accumulation in the root zone. These salts will be leached from the root zone during high rainfall events. In the absence of high rainfall events occasional over-irrigation, during periods of low crop water demand towards the end of a crop growing season, might be required.

ii) The same conclusion is true for strategy D except that an additional saving in irrigation water can be expected, 6% in the simulated example.

iii) Applying strategy C, with a weekly irrigation cycle, will result in further irrigation water savings (>30%), with a reduction in salt additions through irrigation. But the occasional salt accumulation in the root zone will result in crop yield losses. The effect can be reduced by using shorter (< 5 days) irrigation cycles. This would be a high risk strategy on shallow (< 1 m) soils.

8.3.3.2 Water table soils

Soil salinity and seed yield results for irrigation strategies A, B, C and D that were employed on the water table soil (Bloemdal), are presented in Figure 8.7. The strategies were assessed again in terms of their objectives (Section 8.2.3.4).

From the results it was clear that by applying any of the four strategies on water table soils, 95% of the target yield will be obtained. For strategies A, C, D and B, mean irrigation amounted to 181, 165, 182 and 405 mm per season, with a mean rainfall of 155 mm per season for all the strategies. From these water applications a mean 104, 100, 99 and 251 mm per season recharged the water table when strategies A, C, D and B were used, respectively. The net result was that a mean 51 mm per season drained laterally to lower lying fields when strategy C was used. For strategies A, C and D there was a net inflow of water into the potential root zone from higher lying fields, *viz*. a mean of 96, 103 and 100 mm per season, respectively. The similar response in soil salinity for strategies A, C and D, which were observed in Figure 8.7, are attributed to the similar irrigation and drainage amounts. Salt additions through irrigation with strategies A, C and D amounted to 860, 805 and 885 kg ha^{-1} season^{-1}, respectively, while strategy B applied almost doubly (1926 kg ha^{-1} nseason^{-1}). Clearly strategy B, involving much more leaching, resulted in more salt (1810 kg ha^{-1} season^{-1}) draining laterally from the soil to lower lying fields, compared to strategy A (1071 kg ha^{-1} season^{-1}), C (1110 kg ha^{-1} season^{-1}) and D (1111 kg ha^{-1} season^{-1}).

It is clear that the objectives of conserving irrigation water and minimising irrigation-induced drainage and leaching were achieved only with strategies A, C and D. Under these conditions, salt accumulated faster when compared to freely drained soils; soil salinity was about 4 fold the initial value within 3 years of continuous irrigation. High rainfall events at the end of these periods again helped to control soil salinity because of lateral drainage to lower lying fields and/or artificial drainage. In the absence of high rainfall events and lateral drainage, over-irrigation and artificial drainage will be necessary.

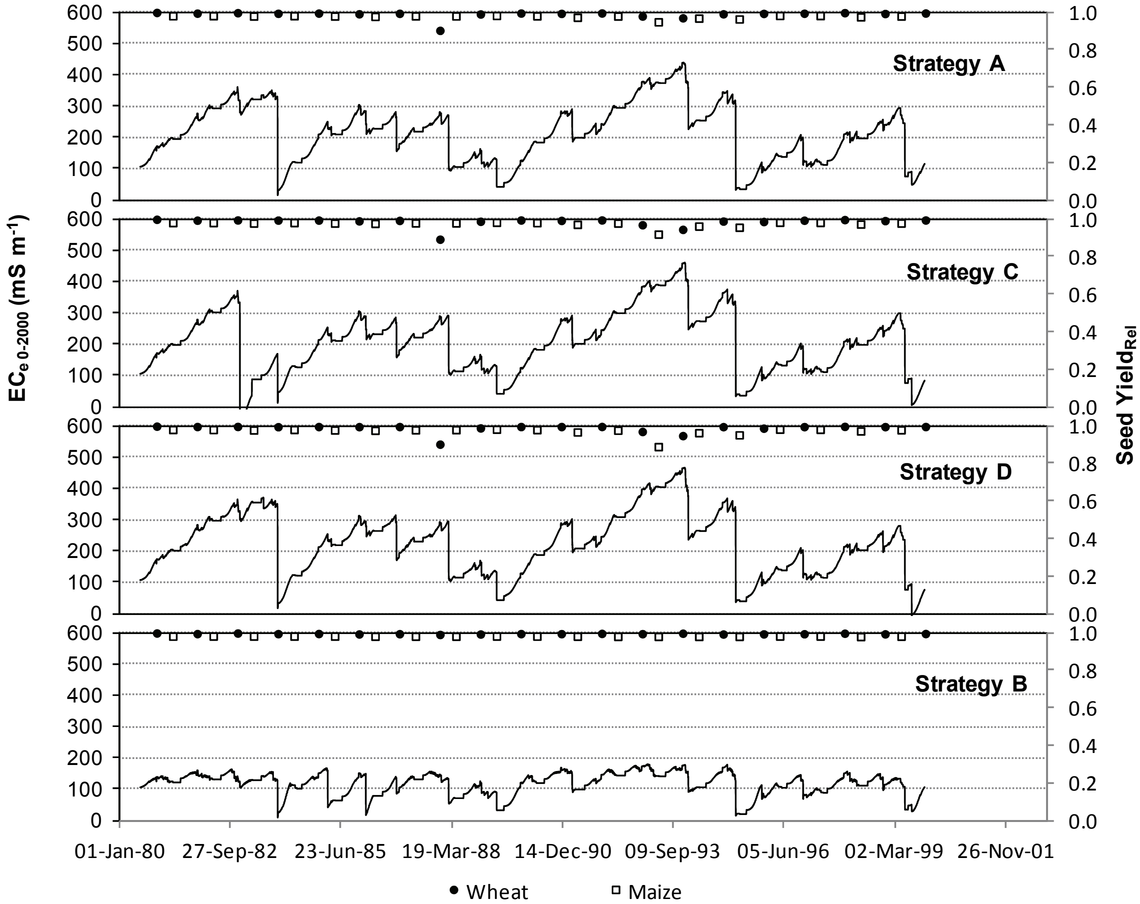


Figure 8.7 Mean daily salinity of the soil profile ($EC_{e\ 0\text{-}2000}$) and the seed yield for each season, expressed relatively to the potential or target seed yield, for strategies A, C, D and B, used on water table soils.

Strategy B is a typical over-irrigation strategy employed by farmers at Orange-Riet and Vaalharts, because crop water supply from the presence of a water table is ignored. The popularity of this strategy is reflected in the fact that the water table acts as a buffer supplying water to crops during dry spells reducing the need for objective scheduling methods. With this strategy, soil salinity never increased above 200 mS m^{-1}. Hence, management of soil salinity was never considered to be an important factor.

Under the prevailing climatic conditions, as used in the simulation and when over-irrigation was minimised (strategies A. C and D), as shown in Figure 8.7, the soil salinity increased to 400 mS m^{-1} after which it decreased on five occasions to below its initial value. This is only true when PAW is carefully managed in order to obtain optimum yields. With all three strategies, where over irrigation was minimised, yields were optimised (relative yield > 90% of target yield) as shown in Figure 8.7.

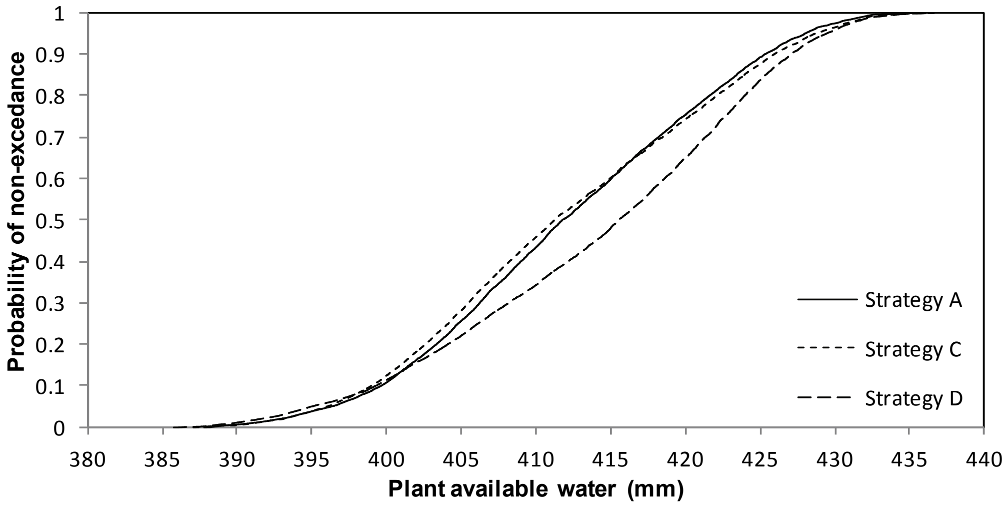


Figure 8.8 Probability of non-exceedence of daily plant available water when irrigation strategy A, C and D were used for a wheat-maize crop rotation, grown on a sandy to sandy loam water table soil over a period of 20 years.

The cumulative frequency analysis (probability of non-exceedence) of daily PAW in Figure 8.8, during the 20 year's application of these three strategies, showed that with strategies A and C there was about 45% chance that PAW would decrease below 410 mm (PAWC = 446 mm), compared to about 35% when strategy D was applied. Considering the high PAWC of these soils, the differences in PAW between the strategies are insignificant in terms of causing crop water stress. However, with strategy D where soil salinity increases and PAW decreases, the opposite is true, as shown in Figure 8.6. With strategy D, adequate PAW is ensured by regular recharge of the PAWC to its maximum prior to the onset of crop water stress.

Assessing the results obtained from applying different irrigation scheduling strategies, on deep sandy soils with a shallow water table, revealed the following:

i) The application of strategy B, where the potential water uptake by crops from the water table is ignored, results in significant salt additions through irrigation and irrigation induced leaching of salts. For the simulated example the mean "over-irrigation" was approximately 150 mm per season or 150%. This ensured that the salt content of the root zone remained constantly low during the simulated 20 years. This approach is presently used by most farmers and also explains the low salt content of the soils.

ii) The use of strategies A, C and D results in considerable irrigation water savings, while salt additions through irrigation are reduced. Due to a lack of irrigation induced salt leaching, short term (3 years) salt accumulation in the root zone can be expected, but leaching by rain occurred frequently. These strategies, when used by some farmers will be sustainable but when all the irrigators on the schemes convert to either of these strategies, a real time salt monitoring system should be put in place.

8.3.3.3 Irrigation schedules for sandy to sandy loam soils

The discussed irrigation scheduling strategies can be simplified into a practical schedule for farmers. Such an example is summarised in Table 8.6, for strategies A and D. These schedules represent prevailing climatic conditions (mean of 20 years) at Orange-Riet and Vaalharts for wheat and maize grown on sandy to sandy loam soils with or without water tables.

Once a strategy is selected, the irrigator can follow the schedule according to days after plant. With these schedules applied water use efficiencies can be 12 kg ha^{-1} mm^{-1} for wheat when strategies A and D are used on freely drained sandy soils, and 18 kg ha^{-1} mm^{-1} when wheat is irrigated on sandy to sandy loam water table soils. For maize, the applied water use efficiency with these two strategies amounts to 21 kg ha^{-1} mm^{-1} when freely drained sandy soils are irrigated and 35 kg ha^{-1} mm^{-1} for sandy to sandy loam water table soils. In wet years the irrigation amount can be reduced according to the standard deviation, which is provided, and vice versa during dry years. These schedules are aimed at those irrigators who are currently not interested in using sophisticated tools and irrigation scheduling methods (subjective). According to Stevens et al. (2005) they are by far the most prominent group; 82% of all irrigators. For the objective scheduling farmers, real time sensors such as wetting front detectors and capacitance probes can be combined with models such as BEWAB, SWB and SAPWAT3, to provide scheduling strategies for decision-making units (site specific irrigated fields). These strategies should aim at managing the level of PAW in order to obtain optimum yields, by minimising drainage and leaching induced by irrigation.

Table 8.6 Irrigation schedule for wheat and maize grown at Orange-Riet and Vaalharts on sandy to sandy loam soils with or without water tables, considering the prevailing climatic conditions

	Wheat							
	Freely drained soils				**Water table soils**			
Days after plant	**Strategy A**		**Strategy D**		**Strategy A**		**Strategy D**	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
7	2	1	1	1	2	2	1	2
14	3	1	7	8	4	2	26	5
21	5	1	5	3	5	2	10	1
28	8	2	10	6	7	2	11	2
35	10	2	15	9	8	2	11	1
42	11	3	11	3	9	2	11	1
49	15	1	15	1	10	2	12	2
56	17	2	17	2	11	3	12	3
63	20	3	20	3	12	2	13	2
70	23	6	22	5	13	2	12	2
77	27	2	27	2	12	3	11	2
84	30	5	29	6	14	2	12	2
91	31	8	31	5	15	2	11	3
98	31	8	30	7	12	5	11	3
105	28	10	27	10	12	4	10	3
112	28	10	28	9	13	4	10	2
119	31	7	31	7	12	4	10	3
126	27	10	26	9	12	4	10	3
133	29	8	29	8	11	5	10	4
140	24	8	24	8	11	4	10	3
147	20	8	20	8	10	3	10	2
Total / Mean*	**420**	**5***	**425**	**6***	**215**	**3***	**234**	**2***
Rainfall	**118**	**108**	**118**	**108**	**118**	**108**	**118**	**108**

Table 8.6 continued

Maize								
Days after plant	**Freely drained soils**				**Water table soils**			
	Strategy A		**Strategy D**		**Strategy A**		**Strategy D**	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
7	10	2	6	2	13	3	9	3
14	14	5	9	2	15	4	9	2
21	18	7	14	5	13	6	11	4
28	24	2	22	4	12	5	12	4
35	24	5	23	4	14	4	13	2
42	26	9	23	8	12	5	13	4
49	30	8	29	5	12	5	11	5
56	31	12	27	11	13	6	11	5
63	31	10	27	10	11	5	10	5
70	41	5	36	8	14	5	12	3
77	32	13	29	12	14	4	12	3
84	36	9	33	9	11	7	12	3
91	36	8	32	9	15	4	13	4
98	37	8	31	7	13	6	12	4
105	38	8	31	8	13	6	13	4
112	32	11	31	10	12	5	11	4
119	26	12	25	9	11	4	10	4
126	21	7	20	7	11	3	11	3
Total / Mean*	**504**	**8***	**448**	**7***	**229**	**5***	**205**	**4***
Rainfall	**155**	**125**	**155**	**125**	**155**	**125**	**155**	**125**

SD = standard deviation

8.4 Conclusions

The study demonstrated that valuable lessons can be learned from the assessment of irrigation scheduling methods using real-world-situations. Firstly, modern irrigation systems (centre pivots) allow irrigators to irrigate more accurately in terms of amounts applied and intervals between irrigations. Very high applied water use efficiencies were observed in the case study, irrespective of the type of irrigation scheduling methods applied. The efficiencies and uniformity of application of the centre pivot systems are very good, above 90%, with the irrigation application rate designed between 11 and 14 mm day^{-1}. This has the advantage that crop water stress can be prevented at any time during the season, apparently down-scaling the need for objective scheduling tools and methods. Secondly, the management of drainage systems required immediate attention. The case studies illustrate that groundwater can be utilised more efficiently by crops. This meant that irrigation and drainage systems should be managed collectively with the aim of reducing water applications (minimising salt additions) without harming the crop. This can be done either through objective scheduling methods or innovations which should be brought to the farmer controlling the outlet of drainage systems. Lastly, the simulation study demonstrated the value of some objective scheduling methods, for managing both water and salt using long term input data. These innovations need to be transferred to the farmer in practical ways in order to minimise water applications and hence control salinity within the soil, groundwater and river environment. If these improvements can be made at field scale, they would pave the way to efficient and environmentally friendly production systems at scheme, national and eventually global scale.

CHAPTER 9
DISCUSSION OF BEST MANAGEMENT PRACTICES AND GUIDELINES

9.1 Introduction

A review of all possible aspects that need to be considered when formulating best management practices for soil salinity was provided in Chapter 2. Distinctions were drawn between recommendations for implementation on an individual field or farm scale and on a regional Water User Association (WUA) scale.

The best management practices for implementation on field or farm scale were formulated as follows:

- Use of efficient irrigation systems.
- Use of irrigation scheduling practices aimed at optimising water and salt application and reducing drainage losses.
- The utilization of shallow water tables to supplement the crop water requirement and reduce the irrigation requirement.
- Monitoring of root zone salinity, in order to decide when to apply controlled, irrigation-induced leaching for salt removal.
- The interception and re-use of unavoidable drainage water either by blending with better quality water or irrigating higher salt tolerant crops.
- Selection of crops with salt tolerance adapted to the situation.

Aspects that need consideration on a WUA scale include the following.

- Interception, isolation and re-use of drainage water for irrigation and/or disposal.
- Blending of drainage water with better quality water to be used for irrigation downstream or to be disposed of.
- Provision of incentives for water users to promote water conservation.
- Development of a policy which accommodates groundwater use, originating from shallow water table uptake by crops.

A discussion and guidelines on the applicability, importance and potential application of these proposed best management practices will be presented. Before this can be done it will be valuable to discuss some of the facts that became apparent during this and other previous investigations.

9.2 General observations and conclusions

- Salinity to the extent that it results in severe yield losses of the major crops grown at Orange-Riet and Vaalharts, is not a major problem. Cases where the yield of salt sensitive crops, like green peas, was reduced were recorded.
- Periods of high rainfall, where the cumulative rainfall exceeds the cumulative potential evapotranspiration by a factor of at least 2, is responsible for leaching of considerable amounts of salts from the root zone. These events occur usually at 5 to 6 year intervals and often for short periods during the year.
- Salt leaching through high rainfall events and/or over-irrigation is more effective on wet soils with a shallow water table than on drier freely drained soils without a water table. On the other hand, salts accumulate more rapidly, during dry spells, in soils with a water table compared to freely drained soils.

- The fate of salt removed by drainage from the root zone depends on prevailing conditions. On freely drained soils, without a restricting soil layer or water table below the potential rooting depth of a crop, salts will accumulate below the root zone and gradually precipitate or leach deeper into the substrata. This will eventually contaminate the groundwater. On water table soils it is estimated that approximately 50% of the salts are removed by the artificial drainage system. This water is blended with overflow irrigation water in the drainage canals, and ends up in the Riet and Harts Rivers to be re-used downstream. The majority of the salts remain in the groundwater below the root zone. It is expected that the groundwater flows laterally along the sloping topography at a steady rate. Salts leached from the root zone are mixed into this stream of lateral flowing groundwater and are eventually removed from the system, where they end up in an unknown sink.
- The shallow groundwater table is presently an underutilized source of water. Depending on the depth of the water table, crops can through water table uptake extract up to 50% of their water requirements from the groundwater. Subtracting the potential water uptake from the shallow water table, from the irrigation requirement of crops, results in substantial irrigation water savings. When this is done gradual salt accumulation will occur in the root zone, which will be removed during high rainfall events. The fact that this source of water supply is presently not taken into account by irrigators, when scheduling irrigation, results in over-irrigation of between 30 and 50%, resulting in turn in constant leaching and low salt levels in the root zone.

Keeping these observations in mind it is possible to proceed with the discussion on best management practices and the presentation of guidelines for controlling root zone soil salinity and improving irrigation water use efficiency on the Orange-Riet and Vaalharts Irrigation Schemes.

9.3 Best management practices on farm level

9.3.1 Use of efficient irrigation systems

On both the Orange-Riet and Vaalharts Irrigation Schemes, the general trend is converting from wide-bed flood irrigation to centre pivot sprinkler irrigation. The application efficiency of flood irrigation was not measured, but it can be assumed to be in the order of 60%. The measured mean application efficiency of 10 centre pivot systems was 92%, with a mean coefficient of uniformity of 91% (Section 8.3.1). Replacing flood with the more efficient centre pivot irrigation systems is a step in the right direction, improving irrigation water use efficiency on both schemes.

9.3.2 Use of irrigation scheduling practices aimed at optimising water and salt application and reducing drainage losses

The majority of irrigators at Orange-Riet and Vaalharts schedule irrigation subjectively, based on intuition and years of experience. This approach seems to satisfy their needs due to the low acceptance of more objective, scientifically sound irrigation scheduling methods, and the fact that soil salinity seems to be kept under control. Results discussed in Section 8.3.2 have shown that a 9% saving can be obtained by using capacitance probes that monitor soil water content. When replacing the present irrigation scheduling by intuition, with more sophisticated, scientifically sound scheduling methods, the following aspects need consideration.

i) *Crop water requirement:* The basis of all irrigation scheduling methods is obtaining the crop water requirement for a specific irrigation cycle. This is quantified by indirectly estimating the crop water demand with either of several available methods, or the periodic or continuous direct measurement of plant available soil water depletion.

ii) *Rainfall:* The most important conclusion from this study is probably that salt leaching from the root zone, during periods of excessively high rainfall, plays the most important role in maintaining sustainable salinity levels in soils. There are three options for dealing with rainfall in irrigation scheduling. Firstly, provision can be made to capture rain that falls directly after irrigation in the root zone. This is achieved by subtracting the selected rain storage capacity from the upper limit of plant available water. Secondly, rain that fell during the previous irrigation cycle can be subtracted from the irrigation requirement of the present cycle. This option is already to a certain degree part of the general scheduling by intuition. When included properly into an irrigation scheduling method, irrigation water savings equal to the growing season rainfall can be achieved. Applying either of these options reduces drainage losses to a minimum, but at the same time this approach also reduces the potential for salt leaching. Thirdly, rainfall during the growing season can be totally ignored, by not subtracting the rainfall from the irrigation requirement or soil water deficit. This option increases the potential for rain water induced salt leaching. Options 1 and 2, tested in Sections 6.3.3 and 8.3.3, is recommended as a best management practice on deep freely drained soils, irrigated with good quality water, and on soils with a shallow water table. Option 3 is recommended for freely drained soils, irrigated with poor quality water where salt accumulation in the root zone, during periods of low rainfall, is a problem (Section 6.3.3). Artificial drainage is essential for removing excess drainage during periods of high rainfall.

iii) Presence of a shallow water table: Shallow water tables occurring, in or just below the potential rooting depth of annual crops, at depths ranging between 1 and 2 meters from the surface, can supply 30 to 50% of the crop water requirement. Subtracting the estimated potential water table uptake from the indirectly calculated irrigation requirement results in considerable irrigation water savings. When the water content of the root zone is measured over the entire rooting depth, the measured water deficit will already include the contribution of water table uptake.

iv) Salinity status of the root zone: When the mean salinity of the root zone increases beyond the threshold value of the irrigated crop, the actual evapotranspiration (ET) will become less than the potential value because of the increase in osmotic suction (decrease in osmotic potential). If the estimated crop water demand, and thus the irrigation requirement, is corrected for the osmotic effect, the saving in irrigation water will be equal to the decline in actual crop water use. This has been illustrated in Section 8.3.3 (strategy C), but is a dangerous option because of more rapid salt accumulation, resulting in noticeable yield losses. As a best management practice it is recommended that the irrigation requirement should not be decreased to accommodate the osmotic effect. The corresponding over-irrigation will result in higher irrigation-induced leaching of salts. This auto-adjustment of salt leaching is nature's way of keeping soil salinity within acceptable levels. A disadvantage of most direct measurements of soil water depletion (neutron probe) is that the measured irrigation requirement will be equal to the actual salinity induced lowered crop water use. In such cases it is recommended that the irrigation requirement is multiplied by an acceptable leaching factor. When real time simulation models with a salinity function are used to estimate the actual ET or irrigation requirement, it is recommended that the osmotic correction option should be disenabled.

9.3.3 The utilization of shallow water tables to supplement the crop water requirement and reduce the irrigation requirement

Shallow groundwater, found in places at Orange-Riet and Vaalharts is a vast good quality water resource that can be utilized, free of charge, by crops. It was impossible to measure the contribution from shallow water tables towards crop water uptake, because the depth of the water table at the various measuring sites remained constant, or even rose, during the season. This was the case, irrespective of sound irrigation scheduling practices. Fortunately, the use of the improved verified version of SWAMP made it possible to simulate potential water uptake from the water table (Chapter 4). Ehlers *et al*. (2003) developed empirical equations for estimating the potential water uptake by crops from a shallow water table, for different soils. As discussed earlier, the irrigation requirement of crops grown on these soils can be reduced by as much as 50%, resulting in the same saving in water, pumping costs and addition of salts. This was illustrated by all the simulation studies reported in Sections 5.3.2, 6.3.3, 7.3.2 and 8.3.3. It was also found that a water table, at for example a depth of 1500 mm, enhances the leaching of salts as well as the removal of the leached salts by saturated lateral subsurface flow of the groundwater. The depth of the water table follows the surface topography but becomes very shallow in places. At these places artificial drainage systems were or are presently being installed. Crop water uptake from the water table is presently ignored by most irrigators, contributing to a high degree of "over-irrigation". The benefit of this practice is that the corresponding irrigation plus the rain-induced leaching, keeps the salinity level of the soils low. Individual farmers will benefit significantly by deducting the water table uptake from the irrigation requirement of crops, without causing a major disturbance in the salt balance. When this is promoted as a best management practice to all irrigators farming on soils with water tables, it will have a major regional impact. This will be discussed in Section 9.4.

9.3.4 Monitoring root zone salinity

Measurements of root zone salinities at all the sites did not reveal any real problems. The most significant data were obtained from measuring point's or17, or18, or19 and or20, which are discussed in Section 6.3.2. These measuring points were situated in the Lower Riet River section of the Orange-Riet Irrigation Scheme, with irrigation water qualities that were poor at times. On this farm drainage water is also intercepted, blended and re-used for irrigation. A simulation of the salt and water balances over a 20 year period at these measuring points (Section 6.3.3), showed considerable accumulation of salt in the freely drained Hutton soil. Situations like this might necessitate regular monitoring of root zone salinity. Although root zone salinity at both schemes seems to be under control, it will still be good practice to regularly monitor subsoil salinity especially when and where yield reductions are observed.

9.3.5 The interception and re-use of drainage water

The interception and re-use of drainage water, for blending with better quality water or for use in the irrigation of salt tolerant crops, is not a common practice on both schemes. Only one good example, namely measuring points or17 to or20 could be found. This case study was discussed in Section 9.3.2. It is impossible to formulate a best management practice from the gathered data. If the system is designed so that the drainage water from a field or farm is continuously blended with irrigation water and re-used on the same field or farm over and over again, it does not seem sustainable. One such measuring point was identified but when the measurements started, and the irrigator realised what he was doing, he immediately aborted the practice.

9.3.6 Selection of crops with salt tolerance adapted to the situation

An assessment of all the gathered and simulated data discussed in Section 5.3, revealed that the yield of only salt sensitive crops, like green peas, is affected by salinity. This will occur during periods of low rainfall, or when irrigating with poor quality water (Section 7.3). Green pea is a very minor crop on both schemes.

9.3.7 Guidelines

The best strategy to manage salinity on an individual field or farm is to use the most appropriate method of determining the irrigation requirement for specific conditions. No single method to suite all conditions can be recommended. The chosen method should not be rigid but must be adapted to changing conditions, for example periods involving water restrictions. Another example of adaptable applications is when water allocations are reduced during drought. Subtracting water table uptake from the irrigation requirement, in the short term, will allow farmers to plant larger areas. The soil types irrigated in the area under the jurisdiction of the Orange-Riet and Vaalharts Water User Association can be classified into three groups:

- Sandy to sandy loam (25% coarse silt-plus-clay) freely drained soils without a shallow water table in or just below the rooting depth of annual crops (<2.5 m), mainly Hutton and Clovelly.
- Sandy to sandy loam soils with a shallow water table in or just below the water table, mainly Hutton, Clovelly, Bainsvlei and Bloemdal soils.
- Sandy clay loam to clay loam soils without a shallow water table but slow internal drainage, mainly Valsrivier and Oakleaf soils.

The irrigation water quality varies from very good Orange River water with an EC_i of less than 25 mS m^{-1} to as high as 200 mS m^{-1} in the lower Riet and Spitskop areas. The quality of the irrigation water can therefore, for guideline purposes, be classified into the traditional S1 to S4 salinity classes. The alkalinity of the water is very low.

- S1 – EC_i less than 25 mS m^{-1}, Orange River.
- S2 – EC_i of 25-75 mS m^{-1}, Vaalharts and Lower Riet with moderate to high stream flow.
- S3 – EC_i higher than 75 mS m^{-1}, Lower Riet and Lower Harts Rivers during periods of moderate to slow stream flow.

These classifications result in 12 possible soil type and irrigation water quality combinations. For each of these combinations the following on-farm best management practices can be considered for controlling the root zone salinity.

- Dealing with rainfall: i) Provision can be made for rain storage in the root zone by not wetting the soil to the drained upper limit. ii) Rain that has fallen during the previous irrigation cycle can be subtracted from the irrigation requirement of the present cycle. iii) Rainfall can be ignored when determining the irrigation requirement (IR, mm) to promote rain induced leaching.
- Subtracting simulated or calculated water uptake by crops from the capillary zone in water table soils, from the IR to save irrigation water.
- Multiply the IR by an appropriate leaching factor to promote irrigation induced leaching of salts.
- Monitor the salinity of the root zone.
- Re-use of collected drainage water on the farm.
- Avoid planting salt sensitive crops.

Recommended best management practices for the different soil type and irrigation water quality combinations are summarised in Table 9.1.

9.4 Best management practices on scheme and water user association levels

Recommendations on best management practices, to be implemented on this scale, can only be made after proper consultation with the relevant Water User Associations. The following aspects need to be discussed.

Table 9.1 Recommended on-farm best management practices for controlling root zone salinity on different soil type-irrigation water quality combinations

Soil type-irrigation water combinations		On-farm best management practices (see discussion in text)						
		Managing rainfall						
Soil type	**Electrical conductivity irrigation water (mS m^{-1})**	**Provision for rain storage**	**Subtraction of rainfall from IR***	**Subtracting of water table uptake from IR***	**Multiplying IR with leaching fraction**	**Monitor salinity of root zone**	**Re-use of drainage water**	**Avoid salt sensitive crops**
Sandy to sandy loam freely drained soils without a water table	**< 25**	Yes	Yes	-	No	-	Yes	No
	25-75	Yes	Yes	-	No	Yes	No	No
	> 75	No	No	-	When necessary	Yes	No	Yes
Sandy to sandy loam soils with a shallow water table	**< 25**	Yes	Yes	Yes	No	-	Yes	No
	25075	Yes	Yes	Yes	No	-	Yes	No
	> 75	No	Yes	Yes	When necessary	Yes	No	Yes
Sandy clay loam to clay loam soils	**< 25**	No	Yes	-	No	Yes	Yes	No
	25075	No	Yes	-	When necessary	Yes	No	Yes
	> 75	No	No	-	When necessary	Yes	No	Yes

*IR = Irrigation requirement per cycle

9.4.1 Interception, isolation and re-use of drainage water for irrigation and/or disposal

We find that drainage water from a small area is intercepted and disposed of in an evaporation pan only at Orange-Riet. The feasibility of interception and isolation of drainage water on a whole scheme scale was not investigated. The necessity for such extreme measures is questionable, because of the relative good quality of the drainage water. This practice will require separate canals or conveyance systems for drainage and overflow irrigation water.

9.4.2 Blending of drainage water with better quality water for downstream use

This practice is presently in use at both schemes, where overflow irrigation water, drainage water and even runoff from rainfall end up in the same conveyance systems and eventually in the Riet or Harts Rivers. This water is re-used for irrigation downstream. Whether this practice needs intervention was not investigated, but no obvious better practices can be suggested.

9.4.3 Provision of incentives for water users to promote water savings

On most of the farms in both schemes the total farm is irrigated, and billing for water use is based on a specific allocation. There is currently an incentive for irrigators to use less water, or to irrigate a larger area with the excess saved water, given that they are allowed to trade water amongst themselves. In some instances the WUAs also participate in this water trading process when necessary.

9.4.4 Development of a policy to accommodate shallow groundwater use, originating from water uptake by crops

As was explained earlier, crops can be forced to utilize groundwater by decreasing the applied irrigation. This can result in water and cost savings. A problem will arise when this practice is accepted by all irrigators with shallow water table soils. This will result in a temporary surplus of irrigation water in the scheme, and a simultaneous drop in the level and quality of the water table. This might be sustainable in the short term but surely not in the long term. A longer term solution might be to provide incentives to strategically located farmers to employ this practice during periods of restricted water supply, for example, allowing some farmers to trade water with other farmers who may run short of water.

9.5 Recommendations for future research

The following topics are proposed for further research:

1. Cost benefit analyses of suggested best management practices.
2. An investigation into the fate of salts in sandy loam and more clayey soils.
3. Quantification of salinity-related problems below the Douglas weir.
4. Impact of perennial crops on proposed best management practices.
5. Mapping of water table depths at both farm and irrigation scheme level.
6. Regular monitoring of spatial and temporal salt distribution in soils at both farm and irrigation scheme level.

It can be concluded that continuation with the status quo, given a sufficient supply of water, might be sustainable in the long term. Short-term restrictions in water supply can be accommodated, and with the use of the present knowledge, the impact can be minimised. A permanent reduction in the water supply will force irrigators and administrators to introduce more sophisticated management practices, as was proposed in this chapter.

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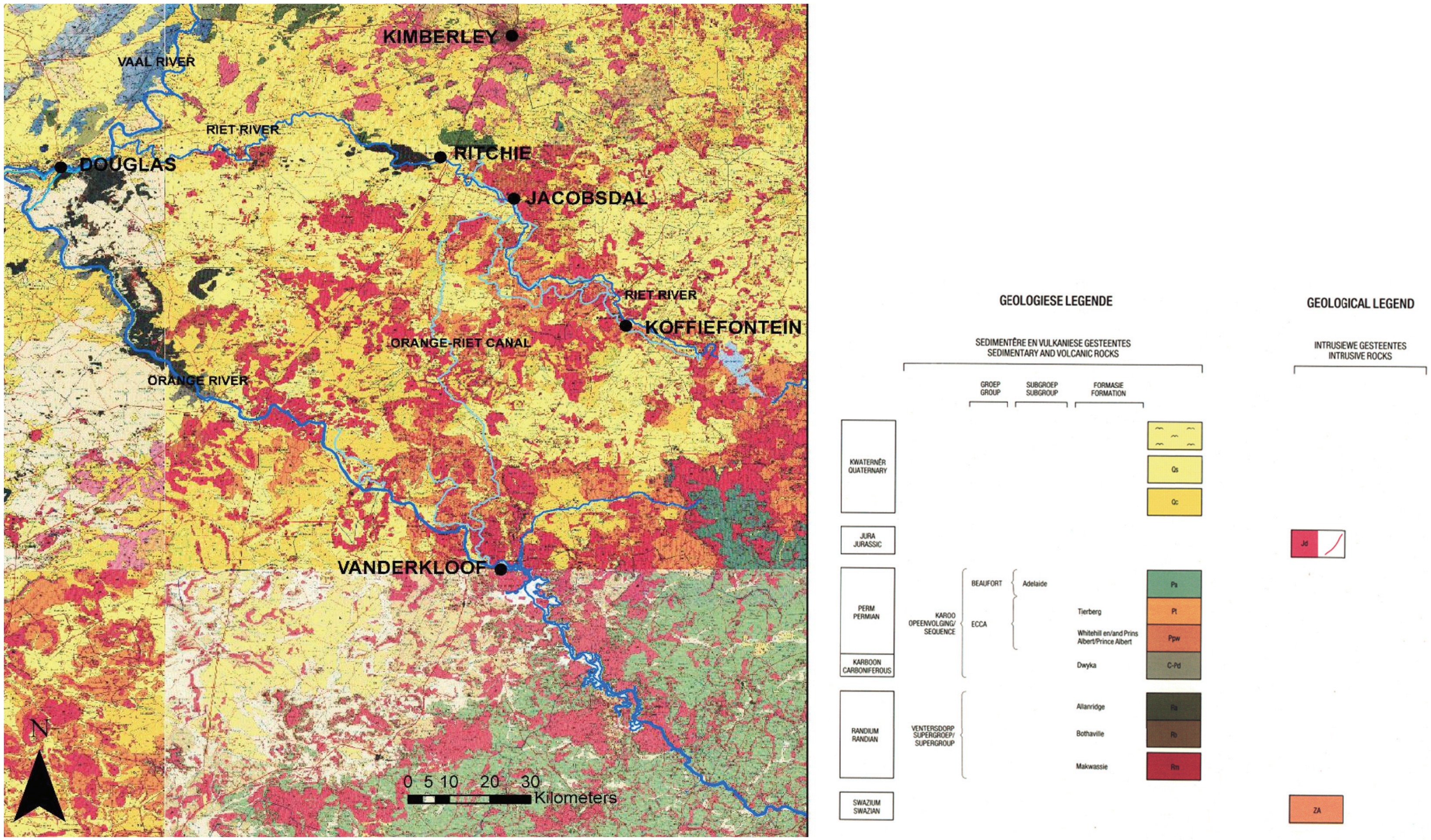
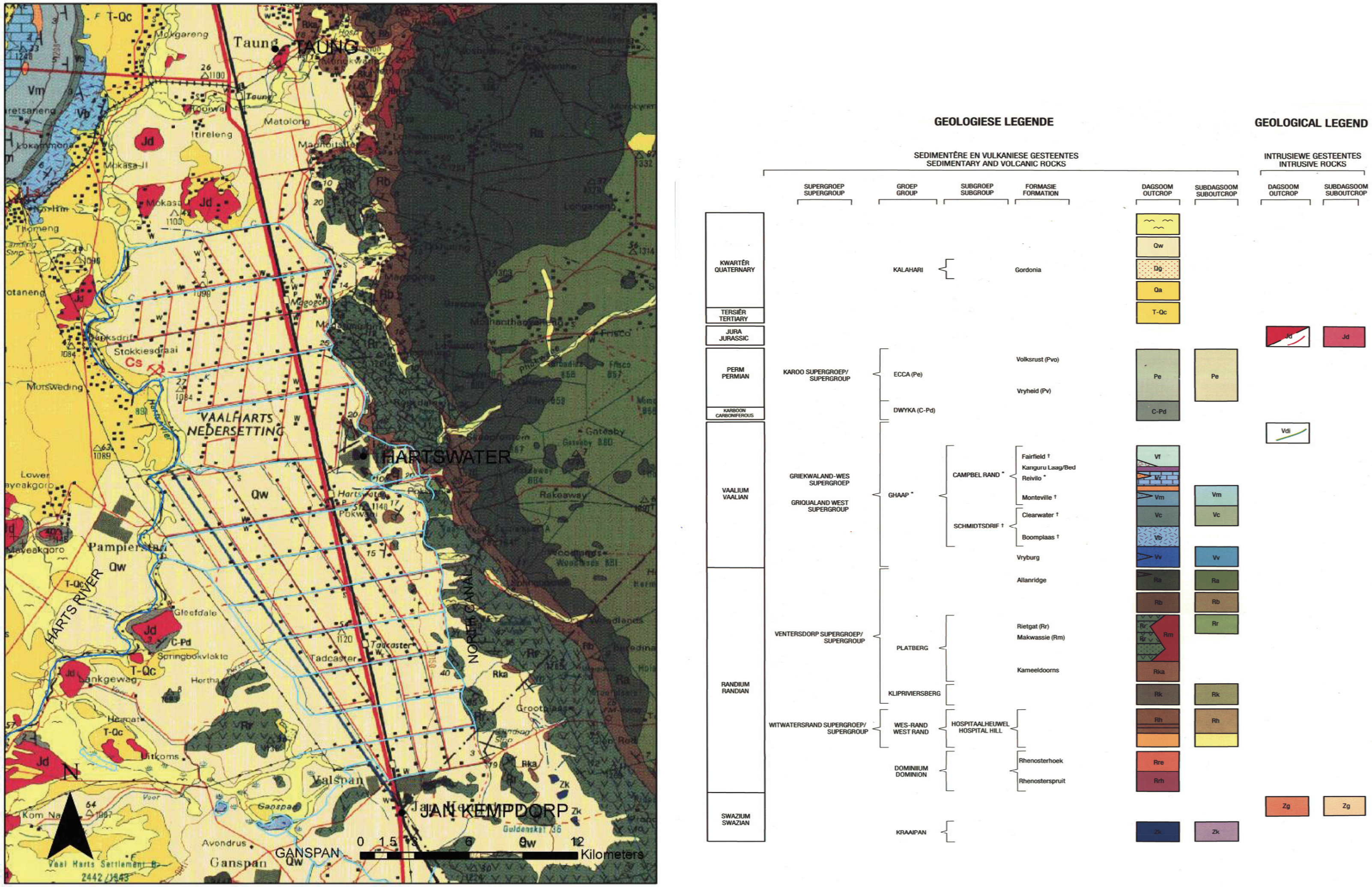
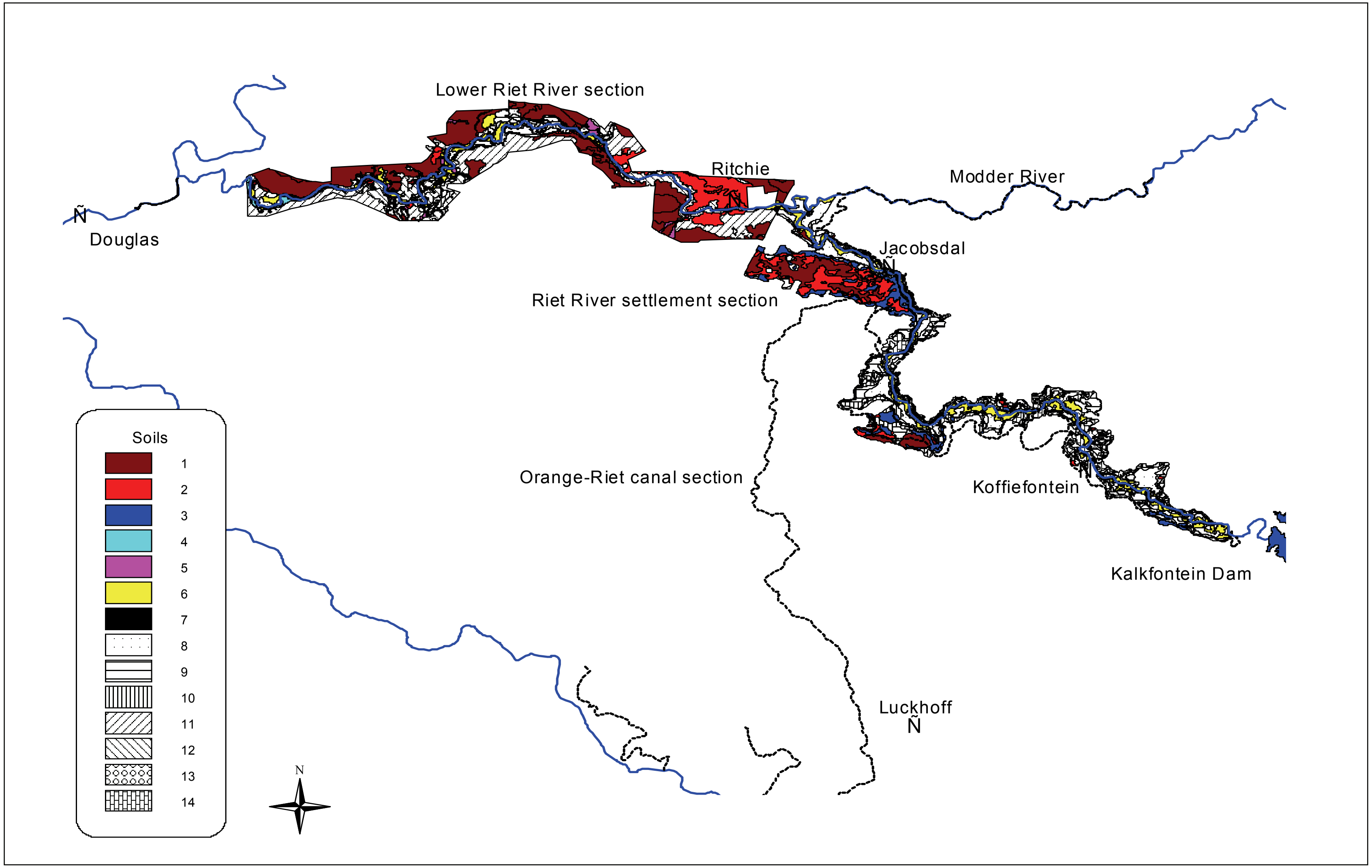
APPENDICES



Appendix 3.1 The 1:250 000 geological maps 2924, 2922, 2824 and 2822 of Orange-Riet Irrigation Scheme.



Appendix 3.2 The 1:250 000 geological map 2724 of Vaalharts Irrigation Scheme.



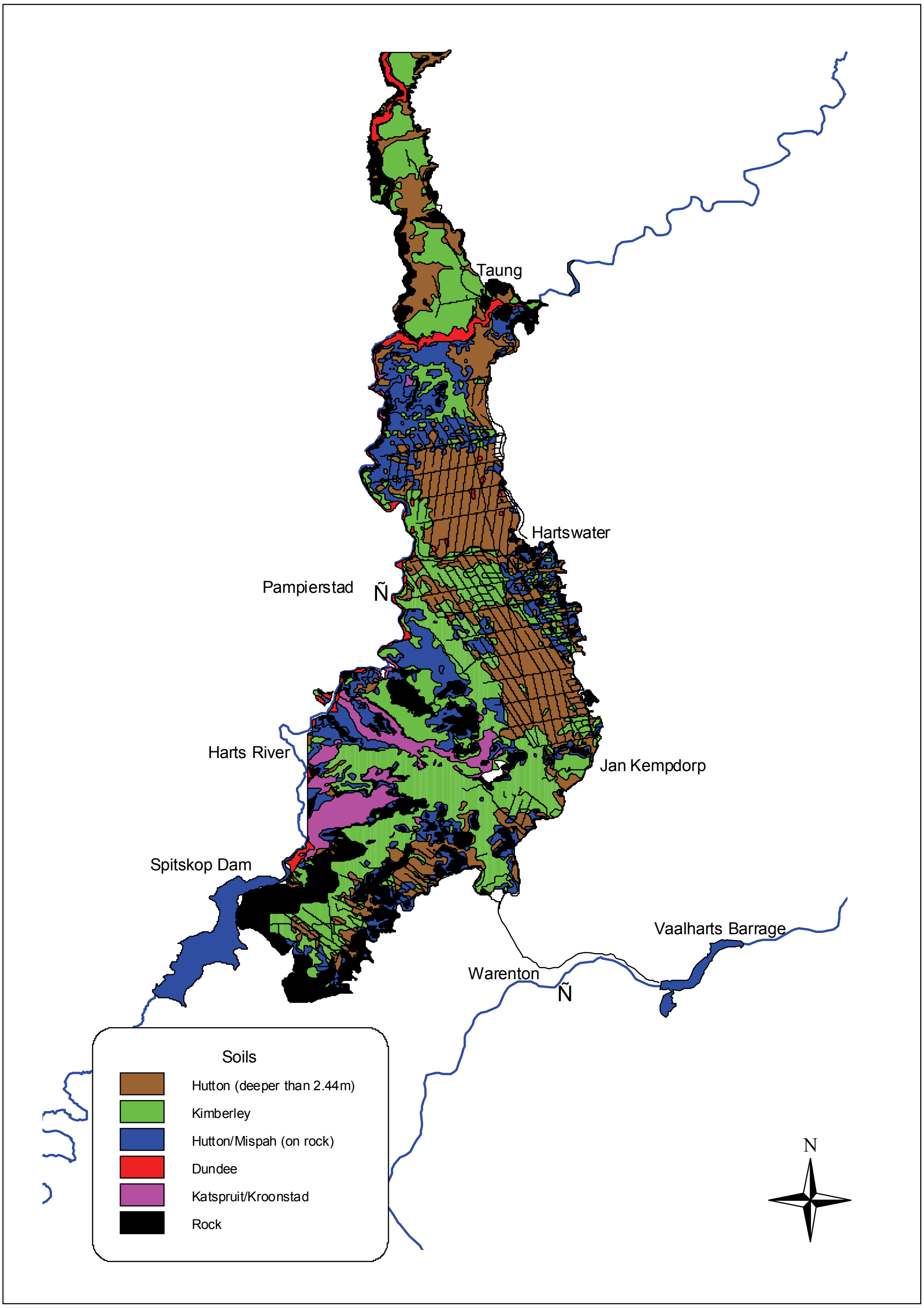
Appendix 3.3 Compiled soil map and legend of the Lower Riet and Riet River settlement section of the Orange-Riet Irrigation Scheme, as described in Section 3.1.4.

Appendix 3.3 continue

<table>
<tr><th colspan="6">Lower Riet River section Legend</th></tr>
<tr><th rowspan="2">Soil type and depth classes</th><th colspan="2">Soil series (1977)</th><th rowspan="2">Soil description</th><th rowspan="2">Underlying material</th><th rowspan="2">Map legend</th></tr>
<tr><th>Dominant (60-80%)</th><th>Sub-dom. (10-30%)</th></tr>
<tr><td rowspan="3">Red apedal soils</td><td>Hu33</td><td>Hu30
Hu36</td><td>Sand to sandy loam (5-10% clay), loose and usually deeper than 1200 mm.</td><td>When <1200 mm, hardpan carbonate</td><td>1</td></tr>
<tr><td>Hu36</td><td>Hu46
Hu33</td><td>Loamy sand to sandy clay loam (10-15% clay), loose.</td><td>Dolerite, andesite</td><td>2</td></tr>
<tr><td>Hu36</td><td>Hu33</td><td>Like HuB but <300 mm to C, rocks on surface.</td><td>Dolerite, andesite</td><td>3</td></tr>
<tr><td>Yellow-brown apedal soils</td><td>46, 43</td><td>Oa46
Hu46</td><td>Sandy loam to sandy clay loam (10-25% clay), soft to loose, frequent soft and hard lime concretions.</td><td>Hardpan and soft carbonate.</td><td>4</td></tr>
<tr><td rowspan="4">Alluvial soils</td><td>Oa26</td><td>Hu46
Hu36</td><td>Red-brown to brown sandy clay loam (15-25%); weak, medium to coarse, sub-angular block structure; hard; frequent worm channels; frequent hard lime nodules; rare Fe/Mn mottles.</td><td>Unconsolidated material</td><td>5</td></tr>
<tr><td>Oa46</td><td>Oa43
Oa47
Du10</td><td>Yellow-brown to dark brown sandy clay loam (15-25%); weak, medium to coarse, sub-angular block structure; hard; frequent worm channels; frequent soft and hard lime nodules.</td><td>Unconsolidated material</td><td>6</td></tr>
<tr><td>Oa46</td><td>Oa43
Oa46</td><td>Yellow-brown to dark brown, sandy loam to sandy clay loam (10-25%) clay; weak medium to coarse sub-angular block structure; slightly hard; many soft and hard lime nodules; frequent worm channels < 600 mm deep; frequent limestone boulders on surface.</td><td>Hardpan and soft carbonate.</td><td>7</td></tr>
<tr><td>Oa47</td><td>Va41
Va46</td><td>Brown to dark brown (35-45% clay); weak to moderate fine, medium sub-angular block structure; hard; few soft and hard lime concretions; few sand and clay in-fillings.</td><td>Unconsolidated material</td><td>8</td></tr>
<tr><td>Duplex soils</td><td>Va41
Va21</td><td>Oa47</td><td>Red to red-brown clay loam to clay (35-50%); moderate to strong, fine to medium angular block structure; very hard; frequent pressure surfaces; frequent sand and clay in-filings; few gypsum crystals in B3 horizon.</td><td>Unconsolidated material</td><td>9</td></tr>
<tr><td rowspan="2">Lithosols</td><td>Sw41</td><td>Va21
Oa47</td><td>Brown to red-brown clay loam to clay (35-50%); moderate, medium angular block structure; very hard; few pressure surfaces and in-fillings; frequent dolerite and shale fragments; <600 mm deep.</td><td>Dolerite and shale</td><td>10</td></tr>
<tr><td>Ms21
Ms20</td><td>Hu33</td><td>Yellowish-brown to brown apedal sand loam to sand clay loam (10-25% clay); loose; frequent dolerite, hardpan carbonate and shale fragments.</td><td>Dolerite, andesite, shale and hardpan carbonate</td><td>11</td></tr>
<tr><td rowspan="2">Diverse soils</td><td colspan="2">Soil rock complexes</td><td>Soil surface stony up to 30%.</td><td></td><td>12</td></tr>
<tr><td colspan="2">Erosion</td><td>Severe donga erosion.</td><td></td><td>13</td></tr>
</table>

Appendix 3.3 continue

Riet River settlement section Legend			
Soil type	**Soil form**	**General description of dominant soils**	**Map legend**
Deep aeolian	Hu	Very deep (>2.4 m) red-brown loamy fine sand.	**1**
Moderately deep aeolian sand	Hu	Moderately deep (0.6-2.4 m) red-brown loamy fine sand overlying hardpan carbonate, rock and occasionally soft carbonate horizons.	**2**
Shallow aeolian sand	Hu	Shallow (<0.6 m) red-brown loamy fine sand soils overlying hardpan carbonate, rock and occasionally soft carbonate horizons.	**3**
Light alluvium	Du Oa	Very deep (>2.4 m) yellow-brown to brown sand to sand loam. Silt and clay layers occasionally occur in some profiles.	**6**
Heavy alluvium	Oa	Very deep (>2.4 m) brown to dark brown clay loam to clay with a dense, strong structured horizon commonly occurring at depths of 800 mm and more.	**8**
Light colluvium	Va	Very deep (>2.4 m) brown, red-brown to dark brown loamy duplex soils.	**9**
Heavy colluvium	Va	Very deep (>2.4 m) brown, red-brown to dark brown clayey duplex soils.	
		Rock and/or stony areas	**12**
		Severely eroded area	**13**
		Surface calcrete	**14**



Appendix 3.4 Compiled soil map and legend of the Vaalharts Irrigation Scheme, as described in Section 3.1.3.