ON-FARM MANAGEMENT OF SALINITY ASSOCIATED WITH IRRIGATION FOR THE ORANGE-RIET AND VAALHARTS SCHEMES

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by

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DECLARATION

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

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

Signed: ....

Johannes Hendrikus Barnard

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Opgedra aan my ouers

"Ouma, hy is uiteindelik klaar"

ABSTRACT

Salinity associated with irrigation is and will remain a major obstacle for farmers in most semi-arid regions throughout the world, like the Orange-Riet and Vaalharts Irrigation Schemes in South Africa. On-farm water and salt management should, therefore, be continually evaluated and/or improved. Especially in water table soils where the saturated zone within or just below the potential root zone is not stagnant and lateral flow occurs to lower lying areas and/or artificial drainage systems, which present unique management complexities. Hence, the aim of this study was to evaluate and/or improve on-farm water and salt management of irrigated field crops grown under these conditions.

To accomplish this aim the following best water and salt management practices were formulated from literature, i.e. i) use of efficient irrigation systems, ii) introduce scheduling practices that optimize water and salt applications and reduce drainage losses, iii) utilize shallow water tables as a source of water for crop water requirements and iv) monitor root zone salinity to decide when to apply controlled, irrigation-induced leaching for salt removal. Some of these practices were evaluated on a case study basis on two farms within the Orange-Riet and Vaalharts Irrigation Schemes by comparing them to current water and salt management practices. Some aspects of this comparison are difficult to accomplish under field conditions. Supplementing field measurements with mathematical modeling was, therefore, critical to the successful completion of the study. This, however, presented some difficulties because most models require extensive effort to determine input variables and unambiguous numerical model parameters. From the multitude of available models, the **S**oil **WA**ter **M**anagement **P**rogram, SWAMP, was selected.

According to the aggregated accuracy, correlation and pattern analysis (I_{SWAMP}) of SWAMP, it was found that water uptake of wheat, peas and maize from non-saline water table soils was simulated well (>70%). Consequently it was shown that the soil water balance under fluctuating water table conditions at field level can be solved successfully by SWAMP with limited easily obtainable input variables. This was accomplished by optimizing simply measured *in situ* field observations, which is vital towards the successful evaluation of water and salt management by irrigation farmers in the region.

However, in order to truly revise on-farm water and salt management practices, mathematical models that can simulate the dynamic response of crops to both water (matric) and salt (osmotic) stress are required. A salinity subroutine for SWAMP was, therefore, developed and validated, i.e. mathematical algorithms that can simulate upward and downward salt movement in water table soils according to the cascading principle, and the effect of osmotic stress on water uptake and yield according to the layer water supply rate approach. It was found that SWAMP was able to simulate the accumulation of salt within the root zone above the water table due to irrigation and capillary rise well, and consequently simulate the effect on crop yield. This was possible because SWAMP was able to successfully (I_{SWAMP} > 70%) simulate a reduction in water uptake during the growing season of field crops due to osmotic stress.

Consequently SWAMP was used in the case study to solve the water and salt balances of two irrigated fields over four growing seasons and investigate whether the farmers employed best water and salt management practices, using different scheduling approaches. It was concluded that with both centre pivots, crop water stress was prevented, therefore, apparently detracting from the merits of irrigation scheduling. However, it was possible to conserve 20% of irrigation water using scientific based objective, compared to intuitive subjective scheduling, while at the same time also reducing salt additions considerably. Despite less irrigation due to objective scheduling, almost all of the applied salt was still leached into the water table. This was because the presence of a water table within or just below the potential root zone limits storage for rainfall and/or irrigation above the capillary fringe, hence presenting favorable leaching conditions. Since the water below the water table, at both fields, was not stagnant, lateral flow of water through the saturated zone was responsible for removal of the salts. This continual removal of salt is generally not considered good practice because ideally salt must be allowed to accumulate and only periodically leached during high rainfall events and/or fallow periods. Although both scheduling approaches resulted in similar yields, better on-farm water and salt management was achieved with scientific objective scheduling. In doing so farmers can address the environmental problems associated with irrigation, i.e. degradation of water resources due to uncontrolled leaching while achieving similar yields using less water.

Keywords: Field Crops; Irrigation Scheduling, Mathematical modeling; Salt balances; Water table soils

CHAPTER 1

INTRODUCTION

1.1 Problem statement

Salt is a major challenge for farmers in most semi-arid regions throughout the world, like the Orange-Riet and Vaalharts Irrigation Schemes of South Africa. The problem is that irrigation changes the natural water and salt balance of the environment because of the high demand for water, fertilizers and chemicals by field crops. For example the 60 000 ha irrigated soils at Orange-Riet and Vaalharts receive annually approximately 405 million m^3 of irrigation water, 75 000 ton of fertilizers and 150 m^3 of chemicals for pest control.

The predicament farmer's face is that these production inputs, especially water and fertilizer, also contain salt, which demands careful management. This is because crop yields (Ehlers et al., 2007), soils (Le Roux et al., 2007), groundwater (Ellington et al., 2004), river water (Herold and Bailey, 1996; Du Preez et al., 2000) and the livelihoods of downstream communities (Viljoen et al., 2006) may be adversely affected by these salt additions. Clearly, the impact of irrigation extends beyond the confines of irrigated fields. Ineffective on-farm water and salt management, therefore, strongly affects the sustainability of irrigation at a local and regional scale.

Sustainable irrigation is, however, theoretically 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 (Van Schilfgaarde, 1990; Letey, 1994; Rhoades, 1997). Hillel and Vlek (2005) emphasized that irrigated agriculture will not only survive, but will also thrive under appropriate management practices that is scientifically sound (Van Wyk et al., 2003).

On-farm water and salt management by farmers should, therefore, be continually evaluated and improved. This is especially true considering that irrigation farmers, produce 30% of the country's crops on 1.5% of the cultivated land with limited potential for expansion (Goldblatt, 2013). Given that irrigation is utilizing 63% of the available surface water in South Africa with 98% of the resources already allocated, farmers will be, under increasing pressure to participate in sustainable management of scarce soil and water resources. This is a view that is shared by most Water User Associations (WUAs) in South Africa that express the need for research that will improve on-farm water and salt management.

In response a Water Research Commission (WRC) funded project (No. 1647/1/12) entitled, "*Managing salinity associated with irrigation at Orange-Riet and Vaalharts Irrigation Schemes*" (Van Rensburg et al., 2012) was initiated by the Department of Soil, Crop and Climate Sciences, University of the Free State. The aim of the project was to develop and/or improve guidelines for managing the salt load associated with irrigation at farm and scheme level. This doctoral study was an integral part of the project and contributed to its successful completion, with the specific aim to assess and/or improve on-farm water and salt management of irrigated field crops grown on water table soils. It is anticipated that the research will bridge the gap between existing knowledge and its application at local farms where water tables, within or just below the potential root zone, flow laterally to lower lying fields and/or through artificial drainage systems, which present unique management complexities.

1.2 Research approach

The research approach was to formulate best water and salt management practices as suggested in literature. Some of these practices were then evaluated on a case study basis on two farms located within the Orange-Riet and Vaalharts Irrigation Schemes during four cropping seasons (July 2007 to July 2009). Thus, the study depended heavily on accurate quantification of water and salt flow in water table soils under field conditions, which is influenced by rainfall, irrigation, evaporation, transpiration, capillary rise, lateral flow and drainage. Providing good approximations requires the integration of soil water and salt movement in order to quantify accurately, these processes. Unfortunately, this is not always possible in the field where water tables are present within or just below the potential root zone because of the difficulty involved in quantifying these processes. Mathematical models that can simulate water and salt flow in water table soils, as influenced by these processes, and the subsequent effect of osmotic stress on water uptake and yield was, therefore, critical to successful completion of the study.

From several models that are available (Ditthakit, 2011), it was decided to use the **S**oil **W**ater **M**anagement **P**rogram, SWAMP (Bennie et al., 1998), because of the specific application, accuracy of simulations, easily obtainable input variables and model parameters required, and the technical support and experience with the model that was available. This, however, together with the research aim led to a number of research questions.

1.3 Research questions

The aim of the study was not to compare different models with varying complexity, but rather improve SWAMP and establish confidence in the outputs, which was critical in justifying the models use to investigate and then improve on-farm water and salt management practices on water table soils.

The research questions were:

- Which strategies are suggested in the literature to manage the salt load associated with irrigation at farm level?
- How credible is the model SWAMP when used to assess current water management practices under water table conditions by farmers in semi-arid regions?
- Will the model SWAMP be able to simulate salt flow in water table soils and the subsequent effect of osmotic stress on water uptake and yield satisfactorily?
- Do farmers with the latest generation of centre pivots employ best water and salt management practices in water table soils, using different irrigation scheduling approaches?

1.4 Study area

The research was conducted in the central part of South Africa on farms located within the Orange-Riet and Vaalharts Irrigation Schemes (Fig. 1.1). 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 (Fig. 1.2). 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 Vaalharts (Fig. 1.2). Vaalharts falls under the Lower Vaal WMA within the component sub-area Harts. 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. 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. 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. Vaalharts Weir in the Vaal River, just upstream of Warrenton, diverts water into the Vaalharts main canal, which supplies the North, West, Klipdam-Barkly and Taung canals. The canal system comprises 1176 km of concrete-lined 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 remove both storm-water and subsurface drainage from the irrigation scheme via the Harts River.

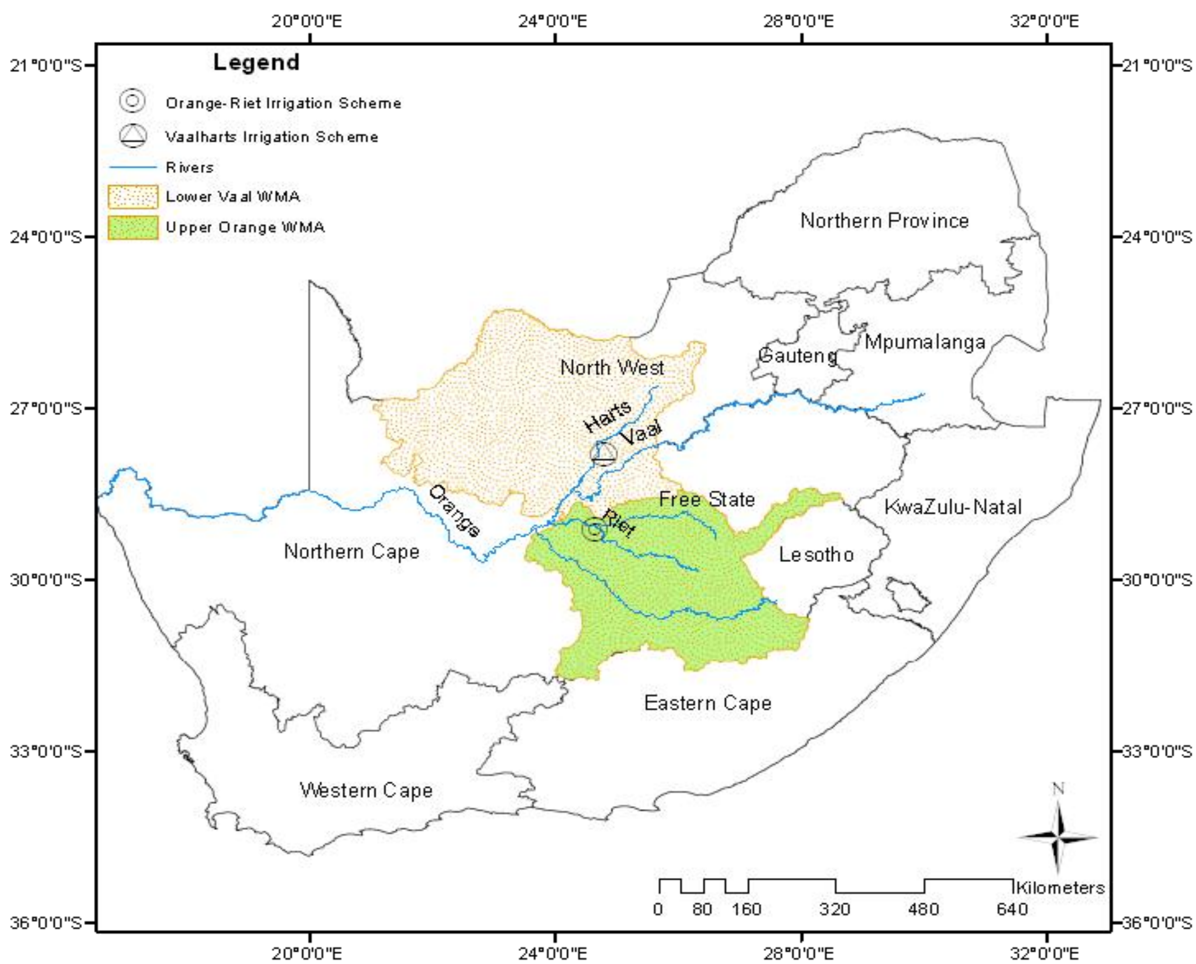
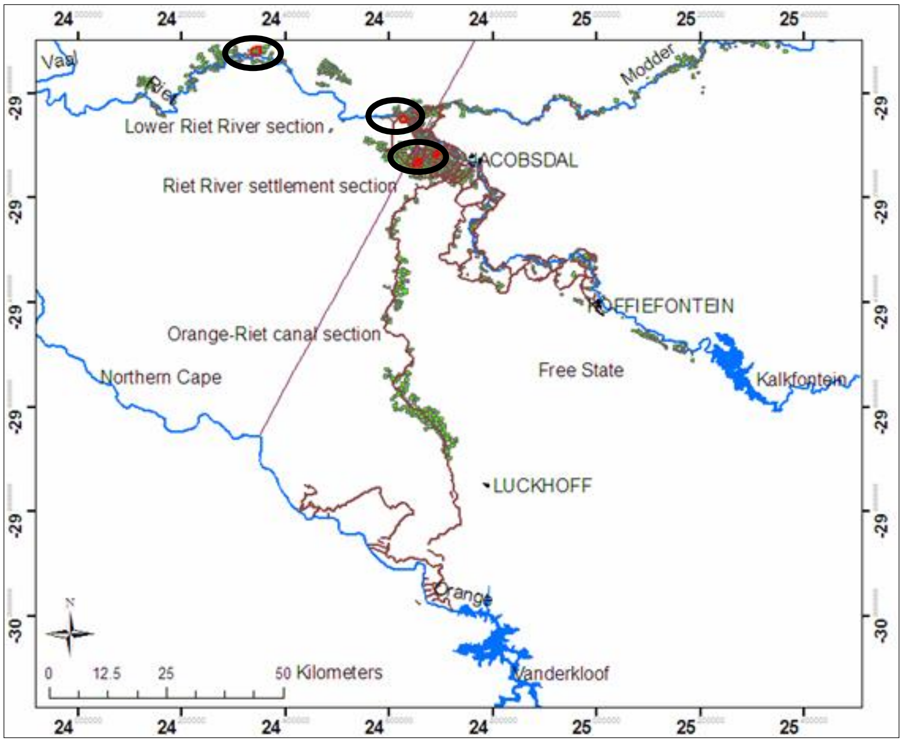
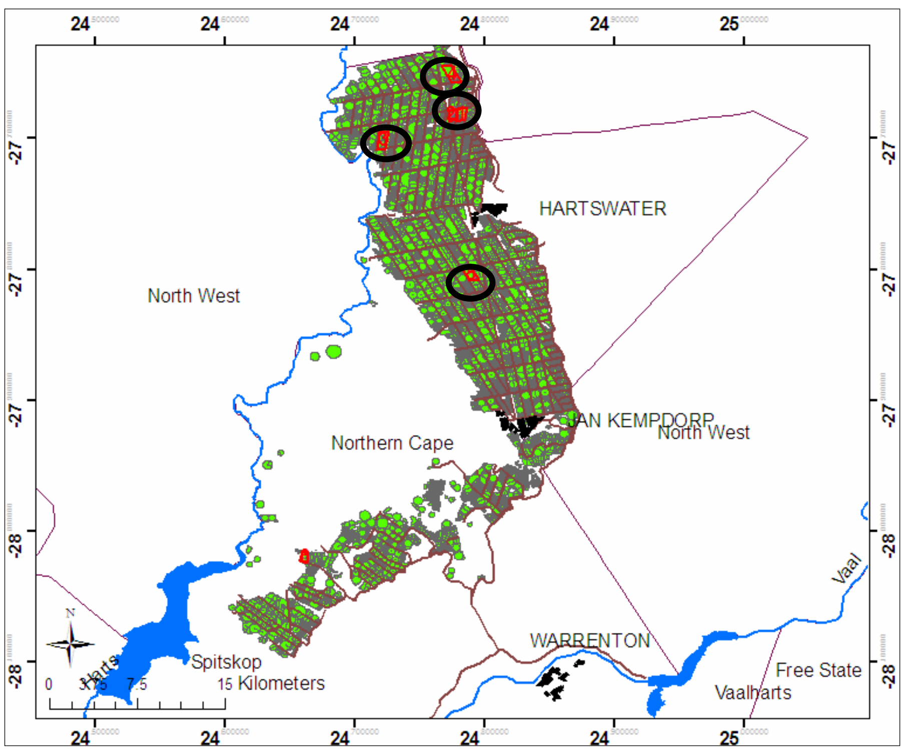


Fig. 1.1 Location of Orange-Riet and Vaalharts Irrigation Schemes within the Upper Orange and Lower Vaal Water Management Areas (WMA), South Africa.

The two irrigations schemes are located in a semi-arid zone, i.e. rainfall is 397 and 427 mm per year for Orange-Riet and Vaalharts, respectively, with corresponding aridity indexes of 0.23 and 0.26, respectively. Rainfall mainly occurs in the form of thundershowers during the summer months at both schemes.



(a)



(b)

Fig. 1.2 Layout of Orange–Riet (a) and Vaalharts (b) Irrigation Schemes, indicating the geographical position of all the measuring points associated with the WRC project (Van Rensburg et al., 2012).

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 temperature 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 in the region of 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 (Ehlers et al., 2012).

The dominant soils occurring at Orange-Riet and Vaalharts are the deep sandy to sandy loam soils of the Hutton and Clovelly forms, reasonably deep sandy soils overlying lime (Kimberley and Plooysburg forms), and deep sandy loam to sandy clay soils of the Hutton and Kimberley forms (Van Rensburg et al., 2012).

According to the two WUAs, farmers in this region grow mainly wheat (*Triticum aestivum*), maize (*Zea mays*) and lucerne (*Medicago sativa*). Other crops also planted, but on a much smaller scale are barley (*Hordeum vulgare*), groundnuts (*Arachis hypogaea*), peas (*Pisum sativum*), cotton (*Gossypium hirsutum*), potatoes (*Solanum tuberosum*), pecan nuts (*Carya illinoinensis*) and grapes (*Vitis sp*.). Given the fact that the total yield of any of these field crops in succession, for a given year, is higher than for a single crop, double cropping is a popular crop rotation system under irrigation in this region. Double cropping involves the harvesting of two successive crops per year and is a popular practice because the rotation system provides an opportunity to increase land productivity and conservation principles.

1.5 Thesis delineation

This thesis comprises of six chapters with the four research questions addressed in Chapters 2, 3, 4 and 5 and the methodology that was followed described in each chapter. Chapter 1 provides the problem statement, research approach, research questions and description of the study area. Chapter 2 presents only a summary of strategies for water and salt management on irrigation farms together with a description of SWAMP, and not a complete review of literature. Thorough reviews of literature relevant to investigate the remaining research questions are included in Chapters 3, 4 and 5. Chapter 3 investigates how accurately SWAMP simulates water use of field crops under water table conditions and how the model can be applied to assess current water management practices under these conditions by farmers. In Chapter 4, adaptations to SWAMP were made and evaluated in order to simulate salt flow in water table soils and the subsequent effect on water uptake and yield of field crops. Thus, Chapters 3 and 4 focuses mainly on the credibility of SWAMP when used to simulate water and salt flow through water tables soils and the subsequent effect of osmotic stress on water uptake and yield. Chapter 5, however, focus on using SWAMP to understand the dynamics of water and salt flow through water table soils under field conditions as influenced by water and salt management practices. Chapter 6 presents the summary and recommendations of the study.

CHAPTER 2

A SUMMARY OF STRATEGIES FOR WATER AND SALT MANAGEMENT ON IRRIGATION FARMS

2.1 Introduction

Research over several decades contributed tremendously to advancing the understanding and management of water and salt on irrigation farms. In 1954 improved understanding of soil physics and chemistry with regard to salinity and alkalinity was published by the United States Salinity Laboratory Staff (1954) situated in Riverside, California. This research was continued with investigations into the sustainability of irrigation by Van Schilfgaarde (1990), Letey (1994) Rhoades (1997), Hillel (2000), Oster and Wichelns (2003) and Hillel and Vlek (2005) to name just a few; who all agreed that sustainable irrigation is possible, as adequate knowledge exists for implementing strategies that focus on water use and salt disposal. Mathematical models played a vital role to obtain this knowledge because of the high complexity and integrated nature of the processes evolved (root zone salinization, irrigation and natural and/or artificial drainage in water table soils), characterised by the many variables. Consequently, a multitude of salinity models were developed that could be used, which include amongst others UNSATCHEM, LEACHC, HYDRUS, SWAP, SOWACH and SALTMED (Ditthakit, 2011; Oster et al., 2012).

The aim of this chapter was not to provide a complete review of literature on water and salt management at farm level and compare or review the vast number of salinity models. This has been done recently amongst others by Du Preez et al. (2000), Oster and Wichelns (2003), Kijne (2006), Ehlers et al. (2007) and Ditthakit (2011). Instead a summary of which strategies to consider in order to effectively and efficiently manage water and salt at farm level was presented and discussed to obtain a broader overview and point of departure for the study. Additionally, the **S**oil **WA**ter **M**anagement **P**rogram, SWAMP (Bennie et al., 1998; Ehlers et al., 2003) will be summarized in order to highlight the strengths of the model and where improvements are needed.

2.2 Selection of crops adapted to salinity

Selecting crops according to a specific expected salinity condition is difficult because their salt tolerance can be modified by different fertilizer applications, irrigation methods and frequencies, and a combination of soil, water and environmental factors (Meiri and Plaut, 1985). However, due to the wide range of crop salt tolerance (Maas and Hoffman, 1977; Maas, 1990; Du Preez et al., 2000; Ehlers et al., 2007), farmers have the opportunity to select crops that will produce satisfactorily under given water and salt management practices and those expected to occur during the growing season.

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. 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 applied 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 potentially lethal salt concentrations. The objective of pre-plant irrigation 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.

2.3 Strategies that prevent excessive salinity in the root zone

2.3.1 Selecting irrigation systems

The irrigation system is an essential tool in the process of converting irrigation water into crop yield and preventing excessive salt accumulation in the root zone. Irrigation systems are divided into three broad classes; flood irrigation (basin, border, furrow and short furrow), mobile sprinkler systems (centre pivot, linear, etc.), and static sprinkler 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, economic 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.

Even after following the best design criteria, on-farm irrigation efficiency of flood irrigation is low (60 - 70%), resulting in excessive irrigation water losses, salt additions and non-uniform 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. On the other hand, irrigating to refill the entire profile at the downstream end, causes deep percolation upstream. The salinity hazard posed by flood irrigation can be minimized if it is properly designed. Land needs to be properly leveled to ensure even distribution of water (Minhas, 1996). 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. Salts tend to accumulate in those regions of the seedbed where the water flow paths converge and water evaporates (Kruse et al., 1996).

Modern mobile sprinkle irrigation systems like centre pivots and linear systems are ideal because of the high irrigation efficiency (>90%) and the fact that the entire field is irrigated uniformly (Reinders et al., 2010). These systems are designed to apply between 11 and 14 mm day^{-1}, which is more than the water requirements of most crops. Hence, salt additions can be minimized by irrigating according to crop water requirements, while leaching of salts can be accomplished with irrigations exceeding crop water requirements. Leaching of salts will be more efficient with sprinkle irrigation as long as the water application rate is lower than the infiltration rate of the soil (Abrol et al., 1988). The lower pore water velocity and water content when sprinkler systems are used compared to flood irrigation result in a larger portion of the applied water flowing through the soil matrix. Preferential or macro pore flow is, therefore, reduced which causes more salt to leach per unit depth of water applied.

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 irrigation 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 affects crop yield less compared to other irrigation methods (Hanson and May, 2004). This is probably because of the regular and frequent supply of water that maintains a constantly higher matric potential in the soil.

2.3.2 Assessing the suitability of irrigation water

In general the most important characteristic for determining irrigation water suitability is the total amount of dissolved salts and the amount of sodium, as indicated by the electrical conductivity (EC_I, mS m^{-1}) and sodium adsorption ratio (SAR_I), respectively. An increase in EC_I (salinity hazard) and the amount of water irrigated will increase the total salt addition to the root zone. Similarly, an increase in SAR_I posses a sodicity hazard which causes swelling and dispersion of clay particles. This can be counteracted by high electrolyte concentrations by increasing the EC_I of the irrigation water (Quirk and Schofield, 1955; Van der Merwe, 1973); preferably by the addition of calcium salts. When the electrolyte concentration of the soil solution increases the thickness of the diffuse electrical double layers surrounding clay colloids is suppressed.

Various general water quality classification guidelines have been developed and agree reasonably well with respect to criteria and limits (Thorne and Thorne, 1954; United States Salinity Laboratory Staff, 1954; Rhoades and Bernestein, 1971; Rhoades, 1972; Rhoades and Merrill, 1976; Ayers and Westcott, 1976). The problem with almost all of the proposed guidelines, 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*. 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 water and salt management practices (Section 2.5).

2.3.3 Irrigation scheduling

Water applications should be minimized thereby reducing salt additions to and losses from the root zone through leaching, which reduces the on-site and off-site environmental impacts of irrigation. Sound decisions on when and how much to irrigate should, therefore, be based on scientific theory and/or measurements (Quiñones et al., 1999; Leib et al., 2002; Annandale et al., 2011). Atmospheric-based quantification of evapotranspiration, soil water content measurement, crop-based monitoring and an integrated soil water balance approach, which encompasses real time and pre-programmed techniques, are amongst others some of the methods that can be used to quantify crop water requirements. Where possible deficit irrigation can be applied by utilizing rainfall and shallow water tables, within or just below the potential root zone, as a water source for crop water requirements, which would otherwise be lost (Ayars et al., 2006; Jhorar et al., 2009; Annandale et al., 2011; Isidoro and

Grattan, 2011; Singh, 2013). When this is done monitoring of soil salinity will be essential as salt can accumulate rapidly, especially in soils with restricted drainage (Ehlers, 2007). Ibrahim and 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.

It is often recommended that once excessive salt levels, harmful to crops, have accumulated irrigation applications should be more frequent. This reduces the cumulative water deficits, both matric and osmotic, between irrigation cycles (Al-Tahir et al., 1997). This higher water availability will result in higher crop water uptake which in turn results in higher yields (Yang et al., 2002). 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 (Minhas, 1996). 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 and 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 lower 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.

2.4 Strategies for controlling root zone salinity and water logging

2.4.1 Leaching

It is recommended that the volume and salinity of leaching water should be reduced by applying periodic leaching 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 salinities. Furthermore, with leaching not only the “bad” salts are removed, but the good as well, i.e., nutrients.

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 than to apply extra for leaching. The assumption was made that free drainage conditions exist where added salts can be removed from the root zone, through natural leaching processes during periods of high rainfall. Under conditions where salt additions exceed removal by leaching, to the extent that crop production will be hampered, the natural leaching of salts should be accelerated by irrigating during follow periods or apply more than the required crop water demand. If possible this should take place during periods of low water and nutrient requirements by the specific crop.

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. 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 can be used to calculate the amount of water required to leach the soil to a predetermined level. 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 and Sharma, 1977; Khosla et al., 1979; Pazira and Sadeghzadeh, 1999; Barnard et al., 2010).

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 swelling 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 applied (Tanton et al., 1995; Armstrong et al., 1998). Unsaturated flow conditions are promoted when water is applied at rates lower than the infiltrability of the soil.

The infiltrability 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 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).

2.4.2 Shallow water table management

Shallow water tables occur extensively in large irrigation regions through the world because of years of inefficient irrigation and excessive loss of water from supply canals or storage dams, especially in irrigated soils with shallow depth or poor internal drainage (Ayars et al., 2006). The installation of artificial drainage in most of these soils is a requisite, to prevent that water tables rise above some specified limit and hence result in water logging. 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 2.1 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.

Table 2.1 Prevalent depths and spacing of drainage pipes in different soil types (Hillel, 2000)

Soil type	Saturated 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 water requirements of crops (Wallender et al., 1979; Ayars, 1996; Ehlers et al., 2003; Ghamarnia et al., 2004; Hornbuckle et al., 2005; Ayars et al., 2006). The successful use of shallow water tables to supplement 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 crop water use from 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.

2.5 Irrigating with saline/sodic drainage water

Irrigation system type and water management strategies need to be taken into consideration when using saline/sodic drainage water for irrigation. Water management strategies that can be considered include network dilution, where different quality waters 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).

Mixing saline (Ca^{2+} and Mg^{2+}) and sodic (Na^{+}) water will reduce the sodic nature of the mix relative to the sodic water, but increase it relative to the saline water. Both salinity and sodicity will be the mean of the saline plus sodic waters. If the saline water is high in CO_3^{2-} and HCO_3^{1-} it is likely that $CaCO_3$ will precipitate in the soil under irrigation giving rise to an effective increase in its SAR. When the saline water is mixed with sodic water, the potential for $CaCO_3$ precipitation will decrease. The mix will then have a lower SAR than for the sodic water alone, but higher than for the saline water (Sheng and 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 good and poor 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 at different times, when available on demand, compared to mixing (Minhas, 1996; Sheng and Xiuling, 1997; Singh, 2004; Sharma and 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 (Sheng and Xiuling, 1997). Because emergence and seedling establishment are the most salt sensitive growth stages for most crops, the better quality water should be utilized for pre-sowing irrigation and during the early stages of crop growth.

Using a validated agro-hydrological model like SWAP (soil water atmosphere plant), 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, had to be done with canal water. Excess irrigation needs to be applied as the salinity of irrigation water increases in order to allow for salt leaching, a favorable salt balance in the root zone and acceptable osmotic potentials for root water uptake.

2.6 Salinity/sodicity reclamation strategies

When the above mentioned strategies fail to manage water and salt successfully, productive soils become unproductive as a result of salinization and/or sodification. Mitigation of saline and/or sodic soils is possible through soil and water amendments and bioremediation, provided that proper management practices are in place.

2.6.1 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 and 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 exchangeable sodium percentage (ESP), cation exchange capacity (CEC) and level to which the ESP should be reduced. In soils where the salinity effect is less significant and the main benefit 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 CEC, soil bulk density, the desired final exchangeable sodium fraction and the depth of soil to be reclaimed (Van der Merwe, 1973). The efficiency of applied Ca^{2+} to remove adsorbed Na^{+} is much greater in the presence of a high ESP. At low ESP the efficiency of Na^{+} exchange is low because a greater fraction of applied Ca^{2+} displaces exchangeable Mg^{2+}. When Mg^{2+} is dominant over Ca^{2+} on the exchange complex, the destabilizing effect of sodium will be enhanced, decreasing soil stability (Hodskinson and 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 and 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 and 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 t ha^{-1}), sulphur (6 t ha^{-1}), filter-cake (350 t ha^{-1}) and sulphuric acid (17 t 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 t ha^{-1} are needed in areas with extremely high sodium levels (Paranychianakis and Chartzoulakis, 2005). Ham et al. (1997) observed however, similar increases in sugarcane yield on sodic soils (ESP < 25) by applying 2 t ha^{-1} gypsum annually dissolved in the irrigation water instead of incorporating 10 ton ha^{-1} gypsum initially to the soil.

2.6.2 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 and 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^+ being 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 and Oster, 2004).

In a summary of 14 experiments, Qadir and 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 facilitate 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 and 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 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 2.2. 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.

Table 2.2 Some crops, shrubs and tree species for potential use in bioremediation of calcareous saline sodic and sodic soils compiled by Qadir and Oster (2004) from different sources

Crops	Kalar grass Sesbania Alfalfa (Lucerne) 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

Qureshi and Barrett-Lennard (1998), according to Qadir and 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.

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 and Oster, 2002). However, it will still be more advisable to prevent saline-sodic and sodic soil conditions from arising, through sustainable water and salt management, as suppose to having to reclaim the soil.

2.7 The Soil WAter Management Program, SWAMP

For farmers to adopt sound water and salt management practices, favorable water and salt balances on individual fields needs to be established. SWAMP quantifies the soil water balance and the influence of matric stress on crop water uptake and yield at ecotope level. An ecotope is defined as land where the three environmental factors affecting yield, namely climate, slope and soil are, for practical purposes, homogenous. The variation of these factors is not sufficient to significantly influence the crops that can be produced, the yield potential of the crops and the production techniques (Macvicar et al., 1974).

2.7.1 Model classification and input variables

SWAMP was classified according to Smith and Smith (2009), i.e. the outputs (information produced by the model), input variables and model parameters (information required by the model), scope (can model be used outside the experiment used in its development) and application (is the model used to explain processes) of the model.

Because SWAMP is used to explain processes with a goal of understanding the dynamic nature of the biological, chemical and physical environment in which crops grow, it is process based or mechanistic. Should a model merely aim to represent or predict the experimental observations, it is described as functional. The outputs of SWAMP can be further classified as quantitative and deterministic. When the value is qualitative, the model describes the nature of the output, whereas if the value is quantitative it will provide a numerical measurement or count. In cases where the quantitative output is given a specific value the model is termed deterministic, or when it is given a range, specifying the probability that the results falls within the range the model is termed stochastic. Since the inputs to SWAMP can change over a series of measurements the model is dynamic and not static, and because the model can be used outside the experiments used to develop it, SWAMP has a predictive scope. Table 2.3 shows the classification of SWAMP.

Daily (d) changes in water content of a multi-layer (k) soil and the influence on crop yield are determined from simulations of evaporation, actual transpiration or root water uptake due to matric stress, capillary rise and percolation. Simulations are based on the principle of conservation of mass, where the change in water content of a given depth of soil must be equal to the difference between water added and lost from the same depth. The climatic, soil, crop and water input variables required by SWAMP are listed in Table 2.4 and are defined as information that does not require calibration. This information differs from model parameters, which require calibration before used in the various algorithms for specific ecotopes..

Table 2.3 Classification of SWAMP

Output	Quantitative
	Deterministic
Input variables and model parameters	Dynamic
Scope	Predictive
Application	Mechanistic

Table 2.4 Input variables required by SWAMP

Climate	Mean atmospheric evaporative demand	ET_o, (mm d^{-1}) *
Crop	Planting date	PD
	Growing season length	GSL (days)
	Target or actual yield	TY (kg ha^{-1})
	Harvest index	HI
Soil	Number of soil layers	-
	Thickness of soil layer k	$z_{(k)}$ (mm)
	Silt-plus-clay of layer k	$SC_{(k)}$ (%)
	Volumetric soil water content of layer k at the start of season	$\theta_{(k)}$ (mm mm^{-1})
	Depth of the water table	Z_{WT} (mm)
	Constant or falling water table	-
Water	Daily rainfall	R (mm)
	Daily irrigation	I (mm)

* = Expressed as reference evapotranspiration of a clipped cool-season grass.

2.7.2 Evaporation

Simulation of cumulative evaporation from bare soil surfaces (E_B, mm) are done with the Ritchie equation (Eq. (2.1)), where C is an empirical parameter and t the amount of days between each rain and/or irrigation event. Simulation of cumulative evaporation from covered soil surfaces (E_C, mm) follows initially the same procedure (Eq. (2.2)). To reduce E_B, a factor equal to one minus the fractional shading (FB) of the soil surface is used.

$$E_B = C(t)^{0.5} \text{ where } E_{B\,(d)} = E_B - E_{B(d-1)} \quad (2.1)$$

$$E_C = E_B(1 - FB_{(d)}) \text{ where } E_{C(d)} = E_C - E_{C(d-1)} \quad (2.2)$$

2.7.3 Transpiration

Potential transpiration for a crop refers to non-limiting water supply from the soil and is, therefore, determined only by climatic conditions and plant characteristics. Seasonal potential transpiration (T_P, mm) in order to ensure maximum biomass production (Y_m, kg ha^{-1}) is determined with Eq. (2.3) (De Wit, 1958, according to Hanks and Rasmussen, 1982), where ET_o is defined in Table 2.4 and m is a crop spesific parameter. The seasonal transpiration requirement (T_R) for a specific target yield (Table 2.4) entered in SWAMP are determined with Eq. (2.4), where Y_a (kg ha^{-1}) is the biomass production (Y_a, kg ha^{-1}) for that yield (Stewardt et al., 1977, according to Hanks, 1983), which was obtained by using the harvest index (Table 2.4). If the entered Y_a are equal to Y_m in Eq. (2.4), seasonal T_P and T_R will be equal.

$$T_P = ET_O\left(\frac{Y_m}{m}\right) \quad (2.3)$$

$$T_R = T_P - [T_P\left(1 - \frac{Y_a}{Y_m}\right)] \quad (2.4)$$

SWAMP determines whether seasonal T_R can be obtained given the specific matric stress conditions during the growing season due to insufficient rain and/or irrigation. This is done by determining daily T_R and the water supply rate of the root zone during the growing season. Seasonal T_R is converted to daily values with Eq. (2.5), using a generated growth curve equation for calculating the relative daily T_R ($T_{R\ Rel}$) during the season, where DAP is days after planting. The number of days until the end of the establishment, vegetative growth, reproductive development and the physiological maturity phases are represented by A', B', C' and D', respectively, while a' and d' represent the relative crop water requirement at the end of phase A' and D', respectively and Q the area under the relative daily T_R line.

$$T_{R\ d} = T_{R(Rel)\ (d)} (\frac{T_R}{Q}) \tag{2.5}$$

$$T_{R(Rel)(d)} = \left(\frac{a'}{A'}\right)(DAP) \ when\ DAP \le A'$$

$$T_{R(Rel)(d)} = a' + \left(\frac{1 - a'}{B' - A'}\right)(DAP - A') \ when\ A' < DAP \le B'$$

$$T_{R(Rel)(d)} = 1 \ when\ B' < DAP \le C'$$

$$T_{R(Rel)(d)} = 1 - [\left(\frac{1 - d'}{D' - C'}\right)(DAP - C')] \ when\ C' < DAP \le D'$$

The supply of water from the root zone (PWSR, mm d^{-1}) must be adequate to provide the crop with enough water to satisfy daily T_R and prevent any matric stress, which is determined with Eq. (2.6), where LWSR is the water supply rate of a rooted soil layer (Eq. (2.7), mm d^{-1})), Ψ_m the matric potential (-kPa), F_{sr} the soil root conductance coefficient ($mm^2\ d^{-1}\ kPa^{-1}$), Lv the root density (mm roots mm^{-3} soil), Ψ_p the critical leaf water potential where plant water stress sets in (-kPa) and θ_o the volumetric soil water content (mm mm^{-1}) where $\Psi_m = \Psi_p$ determined from the retention curve Eq. (2.8). Daily Ψ_m of each soil layer are determined with the retention Eq. (2.8) from daily simulation of θ, where θ_{1500} is the volumetric soil water content of the specific layer at 1500 kPa, θ_{10} the volumetric soil water content of the specific layer at 10 kPa and c equal to Eq. (2.9).

$$PWSR_{(d)} = \sum_{k=1}^{n} LWSR_{(k)(d)} \tag{2.6}$$

$$LWSR_{k\ (d)} = F_{sr} \ln\left(\frac{\theta_{k\ (d)}}{\theta_{o\ (k)}}\right) \Pi Lv_{(k)}^{\ 0.5} \left|\Psi_{m\ k\ (d)} - \Psi_p\right| z_{(k)} \tag{2.7}$$

$$\left|\psi_m\right| = 1500\left(\frac{\theta_{1500(k)}}{\theta_{(k)(d)}}\right)^{c_{(k)}} \tag{2.8}$$

$$c_{(k)} = \frac{-5.0056}{\ln \frac{\theta_{1500(k)}}{\theta_{10(k)}}} \tag{2.9}$$

As the soil is drying, the water potential difference between the root xylem and the surrounding soil solution decreases and result in less water being supplied by the soil when compared to conditions of normally adequate water supply. When PWSR for a specific day is larger than T_R for that day, actual transpiration will be equal to T_R for that day. If the PWSR of a specific day is equal or less than T_R for that day, actual transpiration will be equal to PWSR. This will also indicate the onset of soil induced crop water stress. Actual transpiration (T_A, mm) from a specific rooted soil layer is, therefore, determined with Eq. (2.10). By rearranging Eq. (2.4) and replacing the seasonal T_R with the seasonal T_A, the actual biomass can be determined, which is related then to a new yield with the harvest index. This yield represents, therefore, the yield that can be obtained given the specific matric stress conditions during the growing season.

$$T_{A\,k\,(d)} = T_{R(d)} \left(\frac{LWSR_{k\,(d)}}{PWSR\,(d)} \right) \tag{2.10}$$

2.7.4 Capillary rise

The approach of relating the maximum upward flux from a water table to a specific height above the water table, i.e. the capillary fringe as proposed by Malik et al. (1989), is used. The maximum upward flux (q_m, mm d^{-1}) from each layer within the capillary zone (CZ) is determined with Eq. (2.11), where K_s is the saturated hydraulic conductivity (mm d^{-1}), y an empirical parameter describing the decline in hydraulic conductivity above the water table and Z_f the height between the middle of the layer and the water table surface. The sum of daily uptake (T_A) from each layer within the capillary fringe is taken as water table uptake or depletion (WTU, mm) when T_A for a specific layer is less then q_m for that layer. When T_A for the specific layer is more than q_m for that layer then WTU is equal to q_m. Provision was made in SWAMP to accommodate both constant and falling water tables (Ehlers et al., 2003).

$$q_{m(k=CZ)} = K_s \;(Exp^{y})(Z_f) \tag{2.11}$$

2.7.5 Redistribution of rainfall and/or irrigation

To determine the upper limit of plant available water the model uses a value originally suggested by Ratliff et al. (1983), derived from drainage curves, and termed the drained upper limit (Eq. (2.12), DUL, mm)), where W is the water content of the soil (mm) during the drainage period, a the slope (mm d^{-1}), b the intercept (mm) and T the amount of days after the soil has been saturated. This concept was expanded and the equations describing the drainage curve adapted to be applicable for either a bare (Eq. (2.13)) or cropped (Eq. (2.14)) soil, where E is soil evaporation (0.1 mm d^{-1}) and T_{Maks} the maximum simulated daily transpiration for the growing season.

$$W_{Soil} = -a \ln T + b \quad (2.12)$$

$$DUL_{bare} = b - a \ \ln\left(\frac{a}{E_{(d)}}\right) \quad (2.13)$$

$$DUL_{crop} = b - a \ \ln\left(\frac{a}{T_{Maks(d)}}\right) \quad (2.14)$$

The drained upper limit for each soil layer is determined by using DUL_{bare} or DUL_{crop}, depending on whether a fallow period are simulated or not, and the silt-plus-clay percentage of each soil layer. Daily rain and/or irrigation are redistributed then according to the cascading principle, i.e. infiltrated water will flow into the first soil layer. Once filled to the drained upper limit, excess water will flow to the next layer beneath. This will continue until a soil layer is reached where the inflow of water into the layer is less than the deficit to fill the layer to the drained upper limit.

2.7.6 Model parameters

The parameters for the algorithms described above can be calculated (Table 2.5) by SWAMP from input variables or will be available as default values (Table 2.6). It is anticipated that these parameters will work well for field crops grown in semi-arid regions on sand to sandy clay soils. However, before SWAMP is used it must be tested to achieve credibility with the simulations and as emphasized by Bennett et al. (2013), “characterizing model performance should be an iterative process of craftsmanship, where modelers cannot restrict themselves to one standard recipe”, i.e. a broad range of qualitative and quantitative tools (methods) are required.

Table 2.5 Equations used by SWAMP to determine parameters from input variables

Evaporation	$C = 0.087\ \ z_{(k=1)}\ \ \theta_{(k=1)} - \theta_{a(k=1)}\ \ + 1.36$ $z_{(k=1)} = Exp\left[3.4244\ \ SC_{(k=1)}{}^{2} + 5.7193\right]$ $\theta_{a(k=1)} = 0.0012\ \ SC_{(k=1)}\ \ + 0.006$ $FB_{(d)} = \left(\frac{FB_m}{100}\right)\ T_{R(Rel)(d)}$ $FB_m = FB_1\ \ TY\ + FB_2\ \ when\ \ TY \le FB_3$ $FB_m = 1\ \ when\ \ TY > FB_3$	θ_a = volumetric soil water content at air entre (mm mm^{-1}). θ = simulated volumetric soil water content (mm mm^{-1}). FB_m = maximum fractional cover. FB_1 and FB_2 = default parameters for each crop, which describes the linear relationship between yield and FB_m.
Transpiration	$Lv_{(d)} = \frac{L_{(d)}\left[\ 1 - Exp\ \ -f_{(d)}z_{(k)}\ \ -\ \ 1 - Exp\ \ -f_{(d)}z_{(k-1)}\ \right]}{z_{(k)} - z_{(k-1)}}$ $L_{(d)} = L_m T_{R(Rel)(d)}\left(\frac{FB_m}{1}\right)$ $f_{(d)} = \frac{2.303}{0.7 RPR(d)}$ $\theta_{10(k)} = 0.0345\ \ SC_{(k)}{}^{0.611}$ $\theta_{1500(k)} = 0.00385\ \ SC_{(k)}\ \ + 0.013$	L = root length index (mm mm^{-2}). f = root distribution coefficient. RPR = default root penetration rate for the specific crop (mm d^{-1}).
Capillary rise	$K_s = 2925.8 Exp^{-0.1218\ SC_{k=CZ}}$ $y = 0.0003\ \ SC_{k=CZ}\ \ - 0.011$	$SC_{k=CZ}$ = silt-plus-clay of layer k in capillary zone (CZ).
Redistribution of rainfall and/or irrigation	$a = 45.72 - 1.334\ \ SC_{Soil}\ \ + 0.011\ \ SC_{Soil}{}^{2}$ $b' = 70.99 + 11.67\ \ SC_{Soil}\ \ - 0.117\ \ SC_{Soil}{}^{2}$ $b = \frac{b'\ \ Z_{Soil}}{1000}$	SC_{Soil} = Mean silt-plus-clay of soil profile. Z_{Soil} = Total depth of soil profile.

Symbols not defined in table are defined in Section 2.7

Table 2.6 Default parameters that are available for different crops in SWAMP

Crop	Y_m	m	A'	B'	C'	D'	a'	d'	Ψ_p	F_{sr}
Wheat	14000	110	30	85	145	150	0.2	0.5	2400	Determined through iteration as described in Bennie et al. (1998)
Peas	8400	71	35	70	120	130	0.2	0.5	1500	
Maize	25300	220	30	70	110	145	0.5	0.5	1800	
Groundnuts	14450	143	20	50	140	165	0.3	0.4	1800	
Cotton	18600	184	20	90	140	180	0.2	0.3	1800	

2.8 Conclusions

No single strategy, i.e. plan of action or overall aim, exists to manage water and salt on farms. In most cases a number of strategies should be combined to achieve sustainability by employing best on-farm water and salt management practices. The most effective combination of water and salt management practices depends upon economic, climatic, social and biophysical factors including irrigation water, soils and geo-hydrologic situations. The following best water and salt management practices for 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.

To advance our knowledge in water and salt management, an investigation of whether these practices are employed by local farmers are needed and where improvements can be made. This is because conditions will vary, which necessitate that these practices by tailored for specific conditions, especially where the saturated zone below the water table flow laterally to lower lying fields and/or through artificial drainage systems. In order to accomplish this SWAMP can be employed as a descriptive (what has happened), predictive (what will happen) and managerial (what is the influence of specific decisions on the status quo) tool.

The domain of SWAMP reaches from the canopy of crops to a plane in the water table that is located within or just below the potential root zone, hence the processes are predominantly vertical. SWAMP is, therefore, a one-dimensional model of which the output is quantitative and deterministic, the input variables and model parameters dynamic, the scope predictive and the application mechanistic. Currently SWAMP is restricted to simulating downward and upward water flow in the vadose zone and the influence of matric stress on water uptake and yield of field crops. Characterizing the performance of SWAMP when simulating water uptake of field crops grown in semi-arid regions on sand to sandy loam water table soils, when parameters are determined from input variables are required. Furthermore, improvements in the algorithms of SWAMP to simulate salt flow and the corresponding effect of osmotic stress on water uptake and yield under these conditions are needed, together with an evaluation to establish confidence in these improvements.

CHAPTER 3

SIMULATING WATER UPTAKE OF IRRIGATED FIELD CROPS FROM NON-SALINE WATER TABLE SOILS: VALIDATION AND APPLICATION OF THE MODEL SWAMP

3.1 Introduction

Shallow water tables occur extensively in large irrigation schemes throughout the world and if left unmanaged they can cause secondary salinization, sodicity and water logging, i.e. one-third of the world's irrigated area are affected (Heuperman et al., 2002). However, extensive research, as reviewed by Ayars et al. (2006), has shown that *in situ* shallow water tables can be regarded as an important resource in irrigated agriculture and are, therefore, widely considered in alternative water management options (Jhorar et al., 2009). On-farm management of this resource remains problematic, due to fluctuations in water table depths and the complex interaction of factors affecting crop water use from water tables, i.e. different soils, crops, irrigations systems, presence or absence of drainage system and irrigation frequency and amount.

In order to understand and solve the above mentioned problem several mathematical models were developed and tested under different conditions, i.e. UPFLOW (Raes and Deproost, 2003), TSAM (Jorenush and Sepaskhah, 2003), SWB (Jovanovic et al., 2004), SWIM (Hurst et al., 2004), ISAREG (Liu et al., 2006), DRAINMOD (Sinai and Jain, 2006), SWBACROS (Babajimopoulos et al., 2007), HYDRUS (Shouse et al., 2011), SWAP-MODFLOW-2000 (Xu et al., 2012) and SGMP (Singh, 2013). Most of these studies demonstrated that the models can realistically represent the real world. For example, in India the impact of policy changes on water table depths were analyzed with SGMP (Singh, 2013). In Australia SWIMv2.1 was applied to demonstrate the potential savings in irrigation water that can be achieved where shallow water tables are present (Hurst et al., 2004). Similarly, HYDRUS-1D was used to show that there is a conflict between water, salt stress, and reed water use with variations in water table depth in the Yellow River Delta, China (Xie et al., 2011). Conversely to these studies it was also found, for example, that DRAINMOD could not predict water table depths in irrigated fields with subsurface drainage systems at the Jordan Valley (Sinai and Jain, 2006). This was mainly because the model could not simulate specific field conditions inherent to the Jordan Valley. Hence, field measurements remain important in on-farm management of water tables and models should be a complement to them and not a substitute (Silberstein, 2006). Supplementing field measurements with modeling remains, however, tedious and difficult, because researchers favor more complex numerical models. These models are complex because they are based on fundamental equations for hydraulic and hydrodynamic behavior of water through porous media like soil (Ranatunga et al., 2008), while simultaneously applying crop water uptake functions. They normally require an extensive effort to determine input variables and model parameters. However, as highlighted by Bastiaanssen et al. (2007), complex models have restrictive operational focus, especially in less developed countries, despite their tremendous development over the last 25 years. These authors emphasize that the gap needs to be closed between the supply of various complex models and the application by irrigators.

The **S**oil **WA**ter **M**anagement **P**rogram, SWAMP (Bennie et al., 1998) is proposed as an alternative to the more complex models. Since SWAMP is pragmatic, and designed to support *in situ* field observations of water management, it contributed tremendously toward sustaining dry land crop production in South Africa (Bennie and Hensley, 2001). The strength of SWAMP lies in the fact that the soil water balance can be quantified with limited climatic, crop and soil input variables at ecotope level, i.e. land where the three environmental factors affecting yield namely climate, slope and soil are, for practical purposes, homogenous (Macvicar et al., 1974), as explained in Section 2.7. Additionally, it was also found with an independent test, that SWAMP outperformed various other models in simulating water uptake from a specific soil layer and soil induced crop water stress (Singels et al., 2010). There is, therefore, a real possibility that SWAMP could be used by farmers and agricultural advisers as a descriptive tool to understand their crop production systems to ensure efficient water use under water table conditions.

To establish how credible SWAMP will be when used to assess current water management practices by farmers, two questions were investigated; i) how accurately does SWAMP simulate water use of field crops grown in sandy to sandy loam water table soils in semi-arid regions when model parameters are determined from easily measured input variables and ii) how can SWAMP be applied by farmers to assess their current water management practices under these conditions?

3.2 Methodology

Two data sets were used to accomplish the mentioned objectives. The first set is from a lysimeter experiment described by Ehlers et al. (2007), which was used to evaluate the performance of SWAMP. The second set comes from a case study conducted by Van Rensburg et al. (2012) on an irrigated field located within the Orange-Riet Irrigation Scheme in central South Africa. This was used to show how

SWAMP can be applied by farmers to assess on-farm water management practices on similar ecotopes world-wide.

3.2.1 Evaluation of SWAMP

3.2.1.1 Experimental trial

The experimental trial used to evaluate the performance of SWAMP was conducted at the lysimeter research facility (29˚01'00''S, 26˚08'50''E) near Bloemfontein. The facility (Fig. 3.1) occupies an area of 70 m by 35 m, including the fringes, with 30 round static lysimeters arranged equally in two parallel rows under a moveable rain shelter. The two rows with 15 lysimeters each were filled with soil of the Clovelly and Bainsvlei forms (Soil Classification Working Group, 1991), respectively (Table 3.1). These two soil forms qualify as a Quartzipsamment and Plinthustalf (Soil Survey Staff, 2003).

Fig. 3.1 The lysimeter research facility at Kenilworth Experimental farm of the University of the Free State (Bloemfontein, South Africa) where the trial of Ehlers et al. (2007) was conducted.

In the lysimeter trial, Ehlers et al. (2007) investigated the effect of salinity on the growth and yield of wheat (*Triticum aestivum* L.), peas (*Pisum sativum* L.) and maize (*Zea mays* L.), which were planted on 3

July 2003, 21 July 2004 and 17 December 2004, respectively. A water table was maintained in every lysimeter at a constant depth of 1200 mm from the surface. Agronomic practices were optimal for crop growth, allowing maximum root water uptake and yield. Recharge of the water table and irrigation was done using water with electrical conductivities of 25, 150, 300, 450 and 600 mS m^{-1}. These five water quality treatments were replicated three times per soil type. Crop water uptake of each lysimeter from the 0 to 600 mm soil layer was calculated as the difference between the drained upper limit and the soil water content measured with a neutron probe on a weekly basis. These water deficits were surface applied as weekly irrigations.

Crop water uptake from the 600 to 1200 mm soil layer was replaced through capillary rise from the water table, which was recharged by applying water from the bottom on a daily basis. The sides of the lysimeter could be accessed from a subsurface chamber. The height of the water tables was maintained at 1200 mm with a constant head device. The uptake from the water table was equal to the volume of water added to maintain the water level in the constant head device. Soil water content of the profiles were measured weekly in the two neutron access tubes installed in each lysimeter, while rainfall was zero because the rain shelter was closed during rain events. The soil water balance was, therefore, quantified on a weekly basis. For the purpose of this study only data from the control treatment (25 mS m^{-1}) was used, namely 6 of the 30 lysimeters, i.e. 3 lysimeters per soil type.

Table 3.1 Particle size distribution (%) of the two soils located in the lysimeters for different depths

Soil form	Soil depth (mm)	Coarse sand	Medium sand	Fine sand	Silt	Clay
Clovelly	0-300	1.3	10.7	79.0	4.0	5.0
	300-600	1.4	25.6	65.0	3.0	5.0
	600-900	1.4	25.6	65.0	3.0	5.0
	900-1200	1.4	25.6	65.0	3.0	5.0
	1200-1500	1.4	25.6	65.0	3.0	5.0
	1500-1800	1.4	25.6	65.0	3.0	5.0
Bainsvlei	0-300	0.3	6.4	83.3	2.0	8.0
	300-600	0.2	4.1	77.8	4.0	14.0
	600-900	0.1	3.5	78.4	4.0	14.0
	900-1200	0.1	5.7	76.2	4.0	14.0
	1200-1500	0.1	5.1	70.8	4.0	20.0
	1500-1800	0.2	5.2	70.7	4.0	20.0

3.2.1.2 Model structure, input variables and parameters

According to Ranatunga et al (2008), SWAMP can be regarded as a simple model because soil water flow is simulated with a cascading approach and not by numerically solving of the Richards equation. Furthermore, no extensive exercises are required to determine model parameters to simulate daily evaporation, actual transpiration or crop water uptake due to matric stress, capillary rise and percolation from measurements of rainfall and irrigation in a multi-layer soil, as explained in Section 2.7.

Input variables used in the simulation study of the lysimeter trial are provided in Table 3.2. Six soil layers each 300 mm thick were selected and their silt-plus-clay (SC) contents, as listed in Table 3.1, entered, while the water table was kept constant at a depth of 1200 mm. The initial volumetric soil water content (θ, mm mm^{-1}) was set to the measured value for each layer. Measured weekly irrigations during the growing season of wheat, peas and maize amounted to a total of 266, 451 and 390 mm on the Clovelly soil and 246, 461 and 348 mm on the Bainsvlei soil, respectively. Rainfall was disregarded because of the presence of a rain shelter.

Table 3.2 Input variables used to simulate the lysimeter trial of Ehlers et al. (2007) with SWAMP

ET_o, (mm d^{-1})	4.6	4.7	5.4
Planting date	3 July 2003	20 July 2004	17 December 2004
Growing season lenght (days)	150	130	140
Actual yield (kg ha^{-1})	5678 ^{Cv}, 6032 ^{Bv}	4743 ^{Cv}, 4578 ^{Bv}	14654 ^{Cv}, 12618 ^{Bv}
Harvest index	0.37 ^{Cv}, 0.39 ^{Bv}	0.43 ^{Cv}, 0.45 ^{Bv}	0.47 ^{Cv}, 0.48 ^{Bv}
Number of soil layers k	7		
$z_{(k)}$ (mm)	Depth of layer k = 1 to k = 6 is 300 and 200 for k = 7		
$SC_{(k)}$ (%)	Silt-plus-clay from Table 3.1		
$θ_{(k)}$ (mm mm^{-1})	Volumetric soil water content at start of season		
Z_{WT} (mm)	Constant water table with depth of 1200		
Rainfall (mm)	0		
Irrigation (mm)	266^{Cv}, 246^{Bv}	451 ^{Cv}, 461 ^{Bv}	390 ^{Cv}, 348 ^{Bv}

Cv = Clovelly soil; Bv = Bainsvlei soil; ET_o = Mean atmospheric evaporative demand over growing season, expressed as reference evapotranspiration of a clipped cool-season grass.

The objective of this section was not to calibrate (parameterize) the model, but rather evaluate SWAMP when parameters are determined from input variables. The only parameters that were changed were the drainage curve parameters because it was available, i.e. for the Clovelly soil a = 29 mm day^{-1} and b = 477 mm and for the Bainsvlei soil a = 19 mm day^{-1} and b = 536 mm as defined in Table 2.3. Furthermore, the parameters for describing the growth of the three crops were obtained from Ehlers et al. (2003) for similar cultivars (Table 3.3).

Table 3.3 Model parameters used to simulate the lysimeter trial of Ehlers et al. (2007) with SWAMP

m (crop specific, kg ha^{-1} d^{-1})	110	71	220
A': End of establishment phase (days)	65	60	20
B': End of vegetative growth phase (days)	110	120	55
C': End of reproductive development phase (days)	130	125	80
D': End of physiological maturation phase (days)	150	145	130
a': Relative crop water requirement at end of phase A'	0.2	0.15	0.15
d': Relative crop water requirement at end of phase D'	0.5	0.5	0.25

3.2.1.3 Model performance

A fuzzy-logic based expert system, which aggregates various statistical metrics into a single indicator module, as proposed by Bellocchi et al. (2002) was applied. It was decided, however, to use non-parametric statistics, because the data do not come from populations with normal distributions. These statistics are straightforward to interpret but less powerful to detect differences that are actually present (Townend, 2009). Despite this, it seems the most logical choice because transformation of data did not achieve the desired normal distribution that is required for parametric statistics. Thus, the indices relative median absolute error (RMdAE, Eq. (3.1)) and relative modeling efficiency (REF, Eq. (3.2)) together with the Kolmogorov–Smirnov (KS) test were used (Donatelli et al., 2004b) and aggregated into the Accuracy module. For the KS test the probability value was used and not the KS value. Spearman's rank correlation coefficient (r_s) was used for the Correlation module, while pattern of the residuals against independent variables days after plant ($PI_{v\ DAP}$) and crop type ($PI_{Crop\ type}$) were aggregated into the Pattern module.

$$RMdAE = median_{i=1,\ldots,n} \left| Ms_i - Sm_i \right| \frac{100}{\bar{M}} \tag{3.1}$$

$$REF = median_{i=1,\ldots,n} \left(\frac{median_{i=1,\ldots,n} \left| Ms_i - \bar{O} \right| - median_{i=1,\ldots,n} \left| Ms_i - Sm_i \right|}{median_{i=1,\ldots,n} \left| Ms_i - \bar{O} \right|} \right) \tag{3.2}$$

RMdAE show the median percentage error in simulations by SWAMP, where i is the ith measured (Ms) and simulated (Sm) value, n the number of data pairs and Ō the mean of the measurements. REF compares the simulated values to the median value of the measurements, while r_s is a measure of association between measurements and simulations. The KS test determines the probability that the measurements and simulations have the same distribution. Computation of $PI_{v\ DAP}$ and $PI_{Crop\ type}$ were done by dividing the residuals in four and three groups, respectively, and by calculating the pair-wise differences between average residuals of the groups (Donatelli et al., 2004a). Four and three groups were selected because it corresponds to the growth stages and number of crops, respectively. It was decided to use range-based variable pattern index (PI_v) for the independent variable DAP, because this allows groups with different lengths. For the independent variable crop type the range-based fixed pattern index (PI) was used because the groups can now be of equal length.

To aggregate these statistical indices into the three modules an expert weight according to the relative importance of the index were assigned to each as shown in Fig. 3.2.

Expert weight	RMdAE (%) F: 15 – U: 30	REF F: 0.9 – U: 0.4	KS F: 0.1 – U: 0.05
0	F	F	F
0.3	F	F	U
0.3	F	U	F
0.3	F	U	U
0.4	U	F	F
0.3	U	F	U
0.4	U	U	F
1	U	U	U

Expert weight	r_s F: 1 – U: 0
0	F
1	U

Expert weight	$PI_{v\ DAP}$ F: 3.5 and U: 10.5	$PI_{Crop\ type}$ F: 3.5 and U: 10.5
0	F	F
0.5	F	U
0.5	U	F
1	U	U

Expert weight	Accuracy F: 0 – U: 1	Correlation F: 0 – U: 1	Pattern F: 0 – U: 1
0	F	F	F
0.4	F	F	U
0.2	F	U	F
0.3	F	U	U
0.4	U	F	F
0.3	U	F	U
0.4	U	U	F
1	U	U	U

I_{SWAMP}

Fig. 3.2 The statistical indices and test, three modules and a indicator used to evaluate SWAMP along with the decision criteria and their systematic aggregation (RMdAE = relative median absolute error, REF = relative modeling efficiency, KS = Kolomogorov-Smirnov test, r_s = Spearman's rank correlation coefficient, $PI_{v\ DAP}$ = range-based variable pattern of residuals by days after plant, $PI_{Crop\ type}$ = range-based fixed pattern of residuals by crop type, modules = Accuracy, Correlation and Pattern, I_{SWAMP} = single module indicator, F = Favorable, U = unfavorable).

Next three membership classes were defined, i.e. favorable (F), unfavorable (U) and partially (Fuzzy), and decision criteria to determine when the index is favorable or unfavorable. The weight and decision criteria that were assigned were according to the authors' experience and by consulting various literature sources. These classes together with the corresponding decision criteria and expert weights (Fig. 3.2) were used to calculate (Bellocchi et al., 2002) a dimensionless value of the module that range between 0 (best model performance) and 1 (poor model performance). Finally, the three modules were also aggregated, with the same approach as for the indices, into a single indicator (I_{SWAMP}) that represent the aggregated statistical measure and test performance of SWAMP (Fig. 3.2). Aggregation of the different indices into I_{SWAMP} was done with the data analysis software IRENE (Integrated Resources for Evaluating Numerical Estimates, Fila et al., 2003), while the Statistics/Data Analysis software STATA 11.0 (StataCorp, 2009) were used to do the KS test and to determine r_s.

3.2.2 On-farm utilization of SWAMP

3.2.2.1 Field measurements

After evaluating SWAMP in the previous section *in situ* measurements from a measuring point (or 4) located in a 30-ha center pivot (Fig. 3.3) was used to demonstrate how SWAMP could be used to assess water management practices by farmers. The soil comprised of aeolian sandy deposits on lime and was classified as a Hutton form and Ventersdorp family (Soil Classification Working Group, 1991), with the silt-plus-clay ranging from 11 to 15%, thus qualifying as a Quartzipsamment (Soil Survey Staff, 2003). The internal drainage system 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 (Fig. 3.3). The lateral was installed in 1995 as part of an emergency measure to reclaim what was then a waterlogged area.

The farmer followed a wheat-maize crop rotation during the measuring period of two years (two winter and two summer seasons) from July 2007 to June 2009. Sound agronomic practices were applied of which the most significant ones are summarized in Table 3.4. These practices are conventional for the irrigation scheme where two cereal crops are planted annually. Conventional land preparation practices were followed, which comprised either burning or baling of crop residues to remove excessive material, followed by disking and/or ploughing, and/or ripping before planting.

At the measuring point (4 m × 4 m) two neutron access tubes (2000 mm long), one observation well (3000 mm long perforated 63 mm diameter PVC tube) and a rain gauge were installed. Measurements taken weekly were rain (R, mm), irrigation (I, mm), change in water content ($\Delta\theta_{Soil}$, mm mm^{-1}) of potential root zone between two successive measurements, using a (−) for a decrease and (+) for an increase, the depth of the water table (Z_{WT}) and drainage from the artificial drainage system (AD, L min^{-1}).

Table 3.4 Summary of agronomic practices followed during the four crop seasons at measuring point or4

Crop rotation	Wheat	Maize	Wheat	Maize
Cultivar	Dusi	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}
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

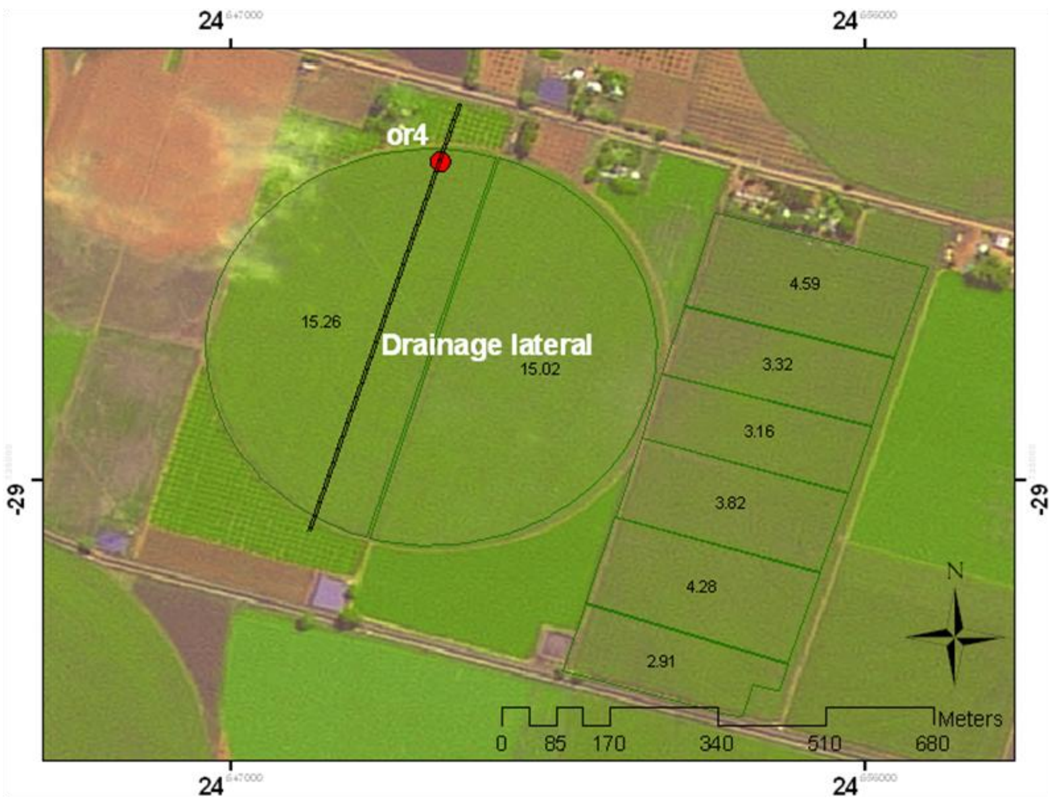


Fig. 3.3 Location of measuring point or4 on an irrigated field at the Orange-Riet Irrigation Scheme, in the central part of South Africa.

Rain and irrigation were measured with rain gauges placed on the soil surface. An area of 6 m^2 was cleared around each rain gauge to prevent interference by the crop. Soil water was measured with a calibrated neutron probe and water table depth in the observation well with a laser-beam device and AD with a bucket and stopwatch, which was converted to mm by taking the area that are drained by the lateral into account. Representative soil samples were taken at 300 mm depth intervals to a depth of 2100 mm. The samples were dried at 40 ˚C sieved through a 2 mm screen and analyzed for particle size distribution with a pipette and sieve method (The Non-Affiliated Soil Analysis Work Committee, 1990). The crop within the measuring point was harvested at maturity, dried, weighed and threshed to determine the seed mass and total biomass.

3.2.2.2 Simulations

SWAMP was used as a descriptive tool to quantify the water and salt balance of the irrigated field during four growing seasons. The measured input variables (Section 3.2.2.1) were entered in SWAMP for each crop and are displayed in Table 3.4. Measured SC contents to a depth of 2000 mm were entered. The *in situ* determined drainage curve parameters for this soil (slope = 32 mm day^{-1} and intercept = 187 mm) were used. The same crop growth parameters given in Table 3.2 were used, while the remaining parameters were calculated from the input variables as explained in Section 2.7.

Table 3.4 Input variables used in the on-farm utilization of SWAMP, i.e. measured growth length, yield and harvest index for each crop, and mean atmospheric demand (ET_o) and water table depth (Z_{WT}) per season

Simulation	Wheat	Maize	DPM	Wheat	Maize	DPM
Growing season length (days)	148	131	71	148	131	36
Actual yield (kg ha^{-1})	7334	15892	-	6172	16510	-
Harvest index	0.48	0.60	-	0.43	0.6	-
Mean ET_o (mm day^{-1})	5.4	6.1	3.2	5.3	4.7	2.5
Z_{WT} (mm)	1900	1895	1820	1711	1895	1890

DPM = Drying period of maize after physiological maturation

A conceptual illustration of the soil water balance for the potential root zone of the measuring point is provided in Fig. 3.5. The maximum rooting depth of the crops under consideration, but in the absence of a shallow water table, was found to vary between 1800 and 2000 mm (Bennie et al. 1988). Thus simulations were done to a depth of 2000 mm, representing the potential rooting depth, but the actual rooting depth was kept the same as the water table depth at the start of the season. The actual root zone (arz) from which crop water uptake occurred consisted of two zones, viz. the unsaturated zone between the soil surface and the capillary fringe, and the capillary zone between the capillary fringe and the upper boundary of the water table. The potential rooting depth included part of the saturated soil below the upper boundary of the water table and the lower depth of 2000 mm.

In SWAMP the potential root zone (prz) will automatically be divided into layers of which the maximum thickness must be specified. As illustrated in Fig. 3.5 crop water uptake from the unsaturated zone layers is recharged by the measured (m) irrigation (I, mm) and/or rainfall (R, mm) and excess water percolate (P, mm) into the capillary zone layers. Crop water uptake from the capillary zone layers is recharged by percolation from the unsaturated zone and/or upward capillary flux from the upper layer of the saturated zone. Excess water from the capillary zone drains automatically into the saturated zone. The simulated (s) upward capillary flux from the saturated zone, to replace root water uptake from the capillary zone layers, is taken as water table uptake (WTU, mm). When the upward capillary outflow from the saturated zone exceeds the simulated downward percolation (P, mm) inflow from the capillary zone the levels of the water table will drop and vice versa. When the level of the water table stays constant, the excess water in the saturated zone is taken as artificial drainage (AD, mm) and net downward or lateral outflow (-D, mm), and a deficit as the net upward or lateral inflow (+D, mm) from sources other than irrigation or rain on the field. Unfortunately, SWAMP does not have a subroutine that can determine these fluxes (D, mm) into or out of the saturated zone. A relatively accurate calculation (c) can be obtained if the water table level remains constant during the growing season. Under these conditions the difference between the simulated (s) WTU and P will represent the net inflow (+D, mm) or outflow (-D, mm) from the saturated zone through these fluxes plus artificial drainage (Eq. (3.3)). Furthermore, the change in water content of the actual root zone (ΔW_{arz}, mm, unsaturated zone + capillary fringe) is determined by SWAMP with Eq. (3.4).

$$\pm D_{(c)} = WTU_{(s)} - P_{(s)} + AD_{(m)} \text{ where water table depth remain constant} \quad (3.3)$$

$$\Delta W_{arz\ (s)} = R_{(m)} + I_{(m)} + WTU_{(s)} - E_{(s)} - T_{(s)} - P_{(s)} \quad (3.4)$$

In reality, under field conditions the water table seldom remain constant and the change in water table depth will be reflected in the change in measured soil water content of the entire potential root zone (ΔW_{prz}, mm). The difference between ΔW_{prz} and ΔW_{arz} will represent, therefore, the additional in or outflow of water through the saturated zone that caused the fluctuation in the water table depth as shown by Eq. (3.5). This equation will provide the same answer as Eq. (3.6), which is the soil water balance of the potential root zone where a shallow water table are present within this zone.

$$\pm D_{(c)} = WTU_{(s)} - P_{(s)} + AD_{(m)} - \Delta W_{prz(m)} - \Delta W_{arz(s)} \quad \text{where water table depth fluctuate} \tag{3.5}$$

$$\pm D_{(c)} = \Delta W_{prz\ (m)} - R_{(m)} - I_{(m)} + E_{(s)} + T_{(s)} + AD_{(m)} \tag{3.6}$$

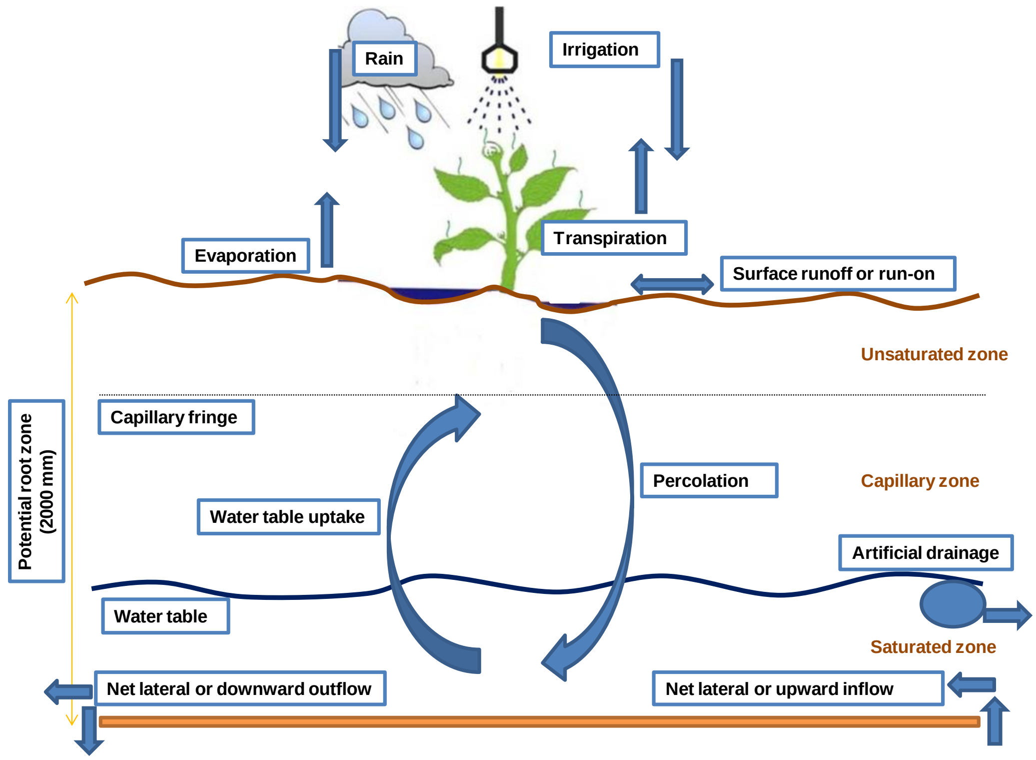


Fig. 3.5 Conceptual illustration of the soil water balance components for a potential 2000 mm depth root zone of an irrigated crop where a water table is present within this zone.

3.3 Results

3.3.1 Model performance- lysimeter study

In characterization of the performance of SWAMP it was found that the model was able to reasonably accurately simulate weekly ET and WTU during the growing season of all three crops grown on both soils. Qualitative visual evidence of this can be found in Figs. 3.6 and 3.7, i.e. weekly measured and simulated ET and WTU during the growing season of the crops for the Clovelly and Bainsvlei soils, respectively. In addition a quantitative analysis was done on the results shown in Table 3.5 and Fig. 3.8.

For this quantitative analysis data of the two soils were grouped because the aim was to do a comprehensive analysis of SWAMP and not compare the soils, which is done later.

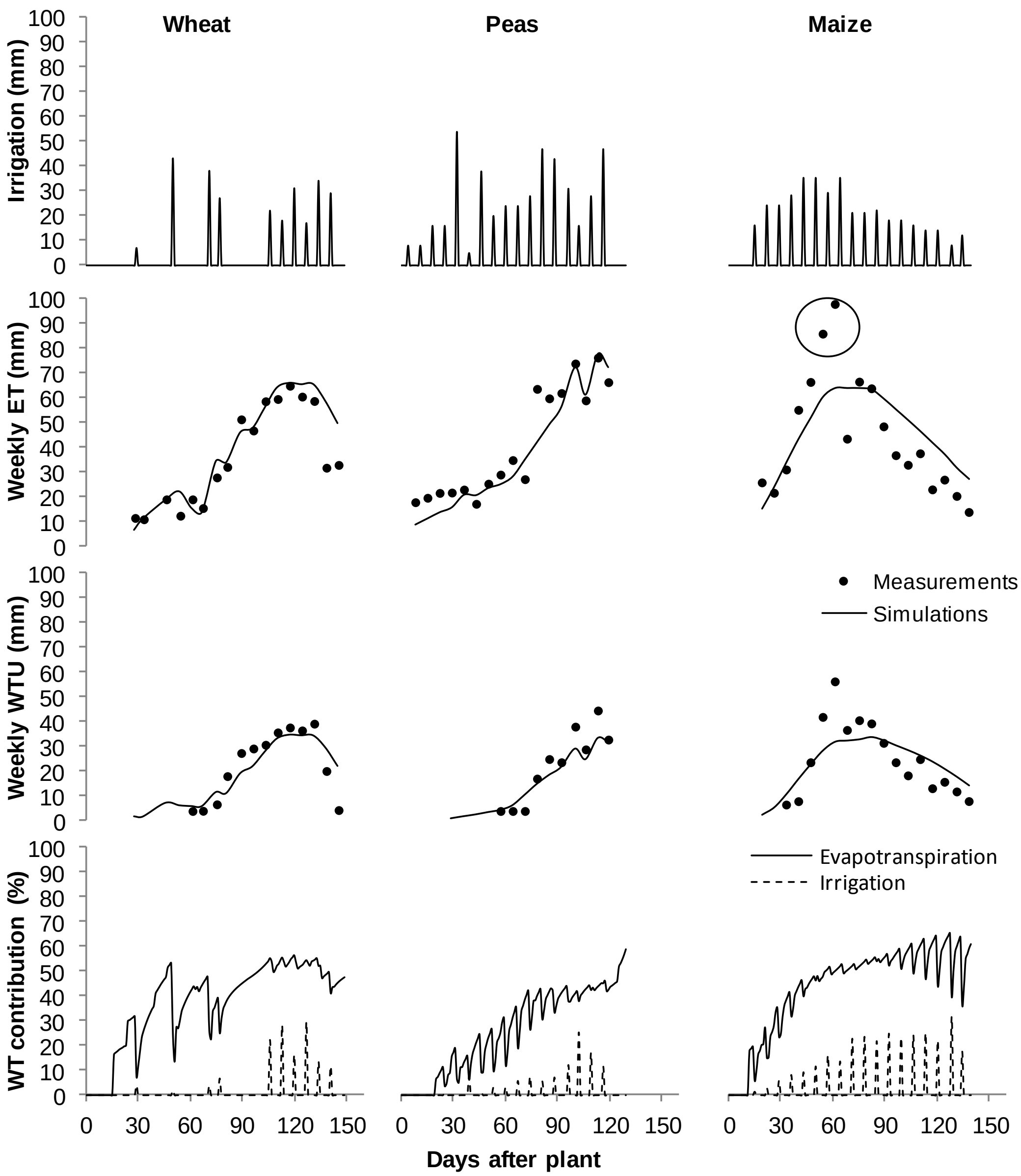


Fig.3.6 Weekly irrigation, evapotranspiration (ET), water table uptake (WTU) and the contribution of the water table to evapotranspiration and irrigation of wheat, peas and maize grown on the Clovelly soil.

Despite the fact that SWAMP simulated weekly ET more accurately than WTU with values of 0.1162 and 0.2110 for the Accuracy module, respectively, overall the accuracy was good (<0.35). The extent with which weekly ET and WTU simulations correlate with measurements was high (Correlation < 0.1) and was, therefore, favorable. Conversely, the value of the Pattern module for weekly ET simulations was elevated (Pattern > 0.7), which indicates the presence of patterns. This was largely due to the high $PI_{V\ DAP}$ value, which was approximately 9 mm higher than the $PI_{Crop\ type}$.

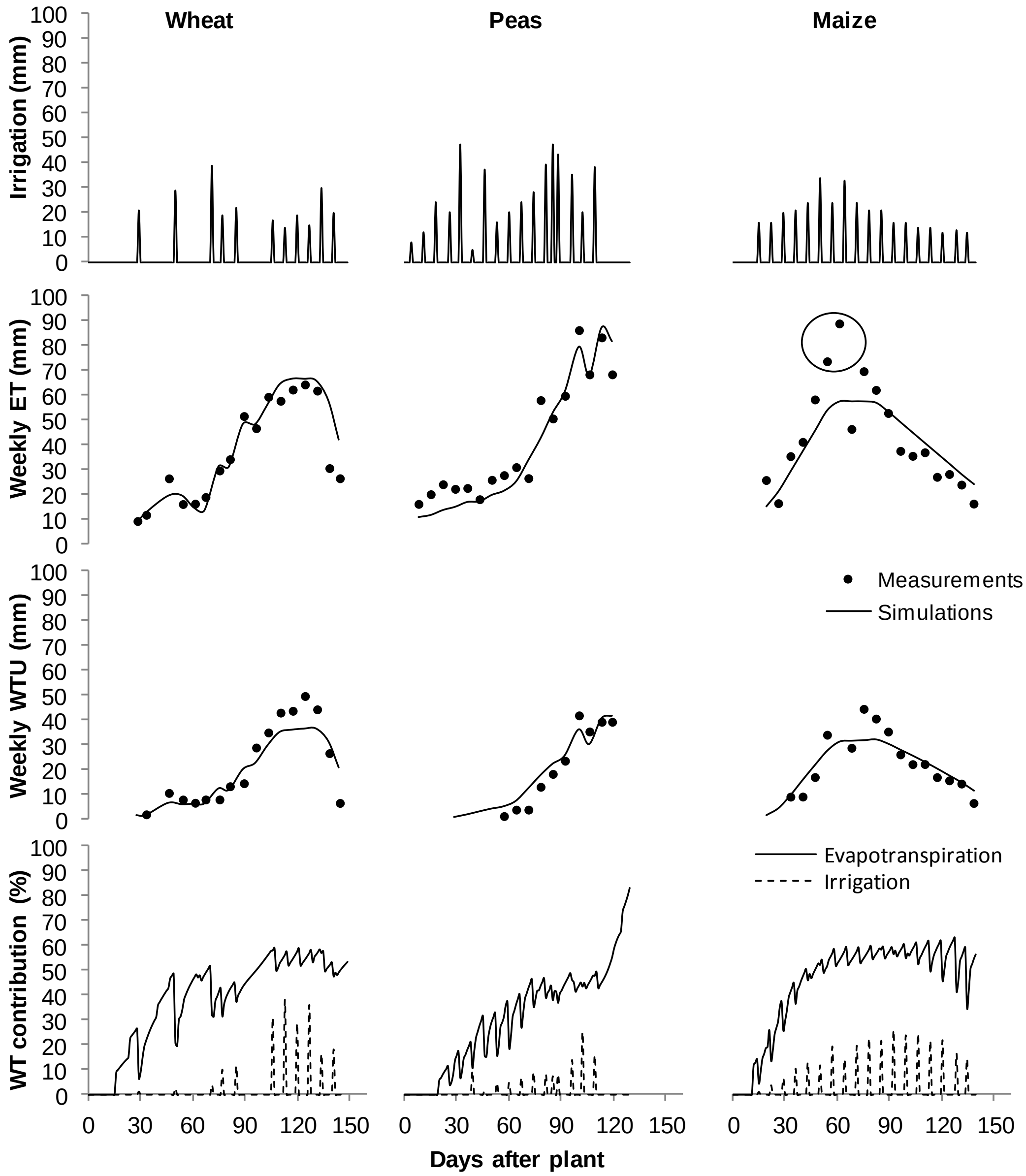


Fig. 3.7 Weekly irrigation, evapotranspiration (ET), water table uptake (WTU) and the contribution of the water table to evapotranspiration and irrigation of wheat, peas and maize grown on the Bainsvlei soil.

A plot of the residuals against DAP and crops confirmed this as shown in Fig. 3.8. In general, weekly ET was under-simulated during the early part of the establishment phase with an equal distribution of residuals toward the end of the growing season. A general over-simulation followed this during the vegetative and reproductive phase. In contrast the residuals were more uniformly distributed when plotted against the different crops, which shows that weekly ET for the different crops was approximately simulated equally well. When weekly WTU was simulated the residuals was more uniformly distributed during the growing season, with slight over-simulation during the early part of the establishment phase. Again weekly WTU simulations for the different crops compared well, which was evident from the uniform distribution of the residuals. Considering the aggregated Accuracy, Correlation and Pattern performance of SWAMP, it was determined that simulations of weekly ET and WTU was generally good ($I_{SWAMP} < 0.35$).

Table 3.5 Statistical indices and test that were used to evaluate SWAMP's simulations of weekly evapotranspiration (ET) and water table uptake (WTU)

Statistical indices and test	Weekly ET	Weekly WTU
RMdAE	15	20
REF	0.68	0.67
KS (p-value)	0.11 (0.581)	0.16 (0.241)
r_s	0.91	0.93
$PI_{v\ DAP}$	15.5	6.7
PI_{Crop}	6.7	2.7
Accuracy	0.1162	0.2110
Correlation	0.0162	0.0098
Pattern	0.7078	0.2140
I_{SWAMP}	0.3329	0.0843

Given these favorable results, it was deemed justified to make several deductions with the help of SWAMP, which would otherwise not be possible. In addition to weekly ET and WTU simulations and measurements, Figs. 3.6 and 3.7 also show the water table contributions to ET and I during the growing season of all three crops. Clearly the type of crop and stage of development had an influence on the contribution of the water table to ET during the growing season. For all three crops, as the growing season progressed, the contribution from the water table increased, reaching a maximum of approximately 50% during the reproductive development phase. This is expected because at this stage the root system reached the water table and was fully developed. In total the water table contributed 46, 35 and 49% to ET of wheat, peas and maize grown on the Clovelly soil. For the more clayey Bainsvlei soil the contribution was slightly higher, as expected with values of 47, 43 and 51%, respectively. The frequency and amount of irrigation also had an impact on the contribution from the water table. At any time during the growing season of all three crops irrigation applications reduced the water table contribution. However, the magnitude of the decrease depends on the amount of water applied and the stage of crop development. For example during peak water demand, which coincide normally with a fully developed root zone system, irrigation only slightly reduced the contribution from the water table, as opposed to stages when the crop water demand was lower. SWAMP was, therefore, able to compensate for water that could not be taken up from a stressed part of the root zone (above the capillary fringe) by increasing uptake from the less stressed part of the root zone (capillary fringe).

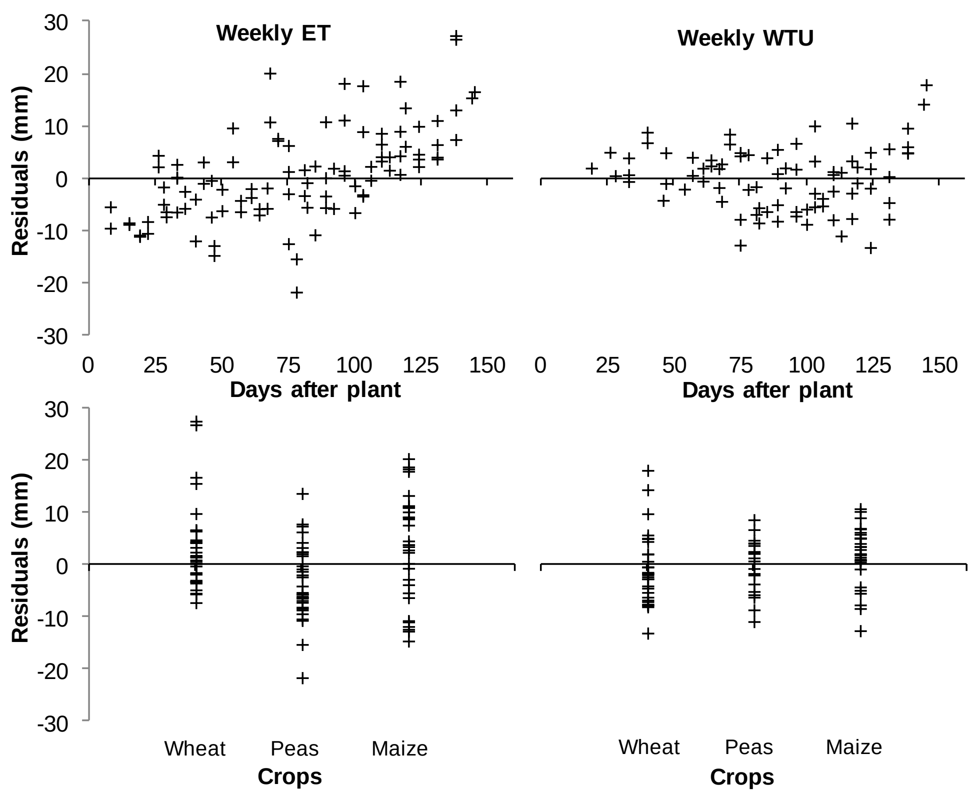


Fig. 3.8 Residuals (difference between simulations and measurements) of weekly evapotranspiration (ET) and water table uptake (WTU) against days after plant and the three different crops.

3.3.2 On-farm utilization- case study

Investigating crop water use from water tables in the field as affected by the farmer's water management practices becomes complex where a fluctuating water table prevails, like with the case study at the Orange-Riet Irrigation Scheme. As shown in Fig. 3.5, the change in water table depth can be caused by excess water that flows laterally from higher lying fields nearby, canal and storage dams that leak, rainfall events and/or over- or under-irrigation.

During the first wheat season simulations with SWAMP showed that if the water table remains constant it will contribute 198 mm (WTU) over the growing season towards the 630 mm of ET. The limited storage for soil water in the unsaturated zone under these conditions, which includes the capillary fringe, means that 289 mm of the 738 mm rainfall-plus-irrigation will recharge the water table through percolation. If 10 mm was removed from the potential root zone through artificial drainage, 81 mm must be removed from the potential root zone through the saturated zone below the water table, as explained in Section 3.2.2.2. The water table, however, did not remain constant and gradually rose during the growing season as shown in Fig. 3.9. Thus, of the 81 mm that had to be removed from the potential root zone through the saturated zone, only 50 mm was actually removed. The farmer made, therefore, no attempt to utilize the water table as a source of water during the growing season and only recharged the water table by over-irrigating.

Similar results were obtained during the second wheat season. When it is assumed in the simulations that the water table remained constant 59 mm of excess water must be removed from the potential root zone through the saturated zone below the water table. Because the water table gradually declined during the growing season, which caused a decrease in the soil water content of the potential root zone, 77 mm was actually removed from the potential root zone through the saturated zone.

For the first maize season, simulations with SWAMP showed that when the water table remains constant it will contribute 265 mm to ET. Of the 621 mm of rainfall-plus-irrigation under these conditions 224 mm will recharge the water table through percolation. Considering that 22 mm was lost through artificial drainage, the 63 mm deficit will be obtained from sources other than irrigation or rain on the field through the saturated zone below the water table (Section 3.2.2.2). The farmer utilized, therefore, the water table as a source of water during the growing season, which resulted in water savings. However, Fig. 3.9 showed that the water table rose gradually during the growing season, which caused the soil water content of the potential root zone to increase. It is evident, therefore, that actually 203 mm flowed into the potential root zone through the saturated zone below the water table. During the second maize season the opposite occurred as 198 mm was removed from the potential root zone through the saturated zone. Hence, the water table was not utilized as a source of water for crop water requirements during the growing season.

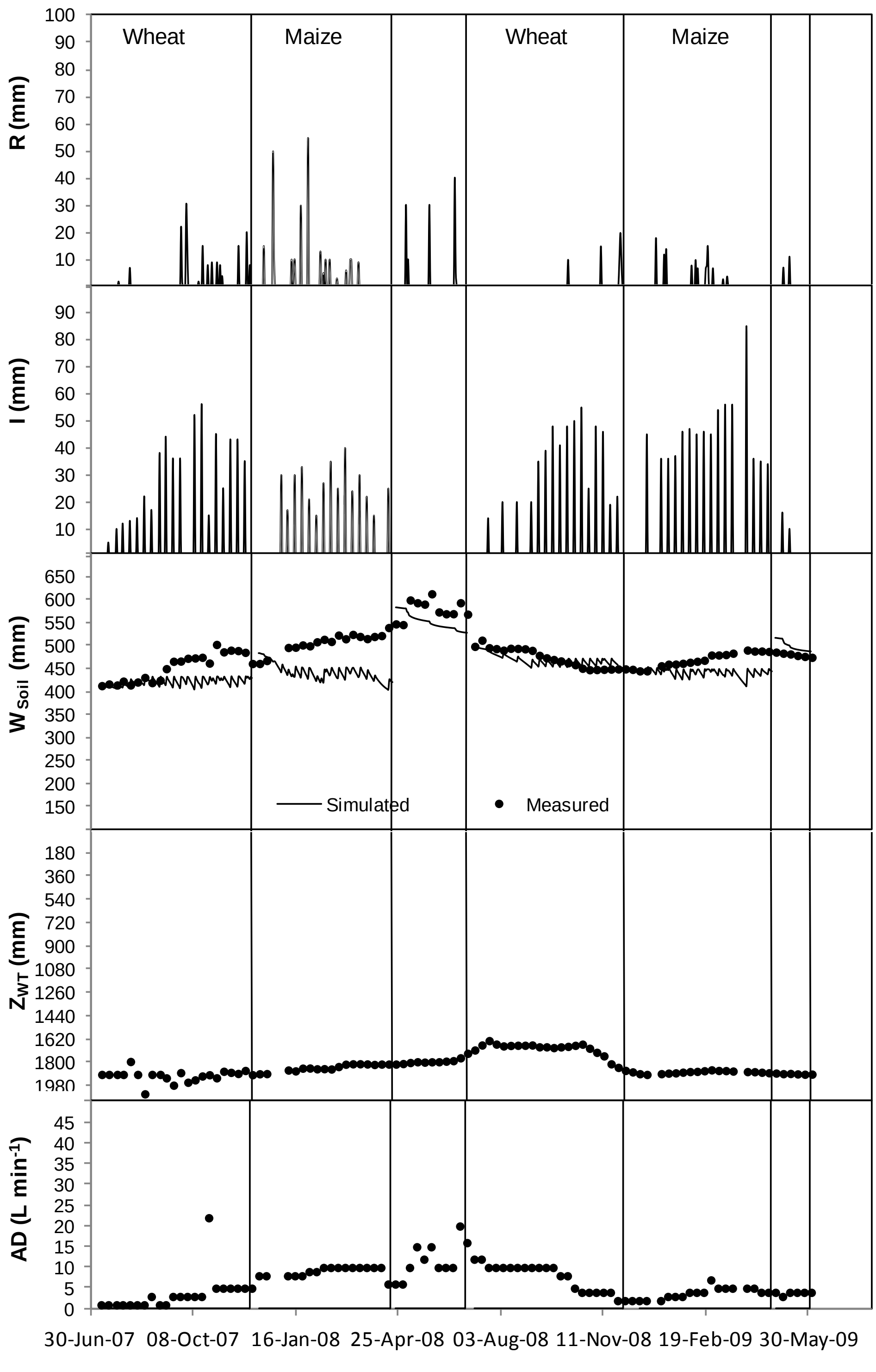


Fig. 3.9 Measured rainfall (R), irrigation (I), soil water content to 2000 mm depth (W_{Soil}), water table depth (Z_{WT}) and water flow from a drainage system (AD) over two years at measuring point or4.

Table 3.6 Net gain (+D, mm) or loss (-D, mm) of water from the potential root zone (2000 mm) through the saturated zone for measuring point or4 as calculated (c) from the measured (m) change in soil water content (ΔW, mm) of the potential root zone (prz), rainfall (R, mm), irrigation (I, mm) and artificial drainage (AD, mm) together with the simulated (s) evaporation (E, mm), transpiration (T, mm), water table uptake (WTU, mm), percolation (P, mm) and change in soil water content of the actual root zone (arz).

Season	Wheat	Maize	DPM	Wheat	Maize	DPM
$\Delta W_{prz(m)}$	48	78	21	-49	42	-11
$R_{(m)}$	177	262	115	65	115	18
$I_{(m)}$	561	389	0	550	739	26
$E_{(s)}$	61	38	56	48	39	29
$T_{(s)}$	569	715	0	516	565	0
$AD_{(m)}$	10	22	16	23	10	3
$\pm D_{(c)}$	*-50*	*203*	*-22*	*-77*	*-198*	*-23*
$WTU_{(s)}$	198	265	0	251	203	0
$P_{(s)}$	289	224	115	333	456	44
$\Delta W_{arz(s)}$	17	-62	-56	-31	-3	-29

DPM = Drying period of maize after physiological maturation

3.4 Discussion

In charactering the performance of SWAMP it was found that weekly ET under controlled conditions with no matric stress, i.e. potential ET, was simulated well for wheat, peas and maize grown on sand to sandy loam water table soils. This was satisfying because no calibration of model parameters was done as SWAMP determined the parameters from input variables. For models like for example UPFLOW and HYDRUS, potential ET must be provided as inputs or boundary conditions. SWAMP falls, therefore, in the same category as SWB and SWAP, where potential ET for the latter is simulated through the reference ET method, which is combined with the use of crop factors. It is anticipated that SWAMP will operate well for these crops grown on similar soils in arid and semi-arid regions, while limitations and uncertainties associated with the model are greater in dissimilar climates. This is mainly because SWAMP uses the empirical De Wit-equation to simulate potential transpiration. Although the results were favorable, it was demonstrated (Fig. 3.8) that an over- and/or-under estimation does occur during the growing season of the three crops. An improvement might be to determine the crop specific factor m, which relates maximum transpiration to maximum biomass yield, for each growth phase (Haka, 2010). Currently the model uses an m factor that represents the mean over the entire growing season. This was, however, beyond the scope of this study.

Compared to most complex models, which simulate the thermodynamic movement of water through capillary rise by numerically solving the Richards equation, SWAMP performed well in simulating weekly WTU. The upward supply of water from the water table is regulated by upward flow rates and heights, which is controlled by the hydraulic properties of the soil layers above the water table (Ehlers et al., 2003). The functions describing these hydraulic properties and relating the upward flow rates and heights to the silt-plus-clay percentages of the soil were developed for mainly sand to sandy loam soils. Therefore, care should be taken when utilizing the model in soils with sandy clay loam to clay textures.

Given these favorable results, SWAMP was able to confidently simulate the effect of irrigation scheduling on crop water use from constant water tables. In addition, the shift in water uptake from stressed to less stressed sections within the root zone and the effect of different crops, growth stages and soil on crop water use from the water tables can be simulated. Despite the model's simplistic nature, in that it requires limited easily obtainable input variables to determine model parameters, the complex interaction of a number of processes could still be simulated.

This success is largely attributed to the water uptake subroutine that simulate soil drying and matric stress. SWAMP is similar to most models in that a macroscopic water uptake approach is used where actual transpiration is related to potential transpiration and a stress function for water uptake (soil drying), which varies between 0 and 1. The stress function used by SWAMP differs however from the generally applied piecewise linear and S-shaped reduction functions (Skaggs et al., 2006). In essence a complex non-linear function accounting for variety of factors in a multi-layered soil profile (Bennie et al., 1998) is used to describe the water supply rate of a specific soil layer. The function was derived from Richards's equation for water flow. The equation was applied to the concept of a soil profile consisting of a network of concentric root-soil cylinders and that water within a root-soil cylinder will move to the root xylem due to a potential gradient (Gardner, 1960). The gradient is quantified by assuming that the root xylem potential is equal to the leaf xylem potential, with the outside border of the root-soil-cylinder determined by the rooting density. In addition, the hydraulic conductivity was substituted with a combined soil-root conductivity, which is estimated from relative water content and a specific soil-root conductivity coefficient. The reduction function or drying of a soil layer is, therefore, proportional to the ratio between the layer water supply rate and the profile water supply rate. It can be argued that SWAMP uses a formulation that is based on a combination of Type I and II, as classified by Cardon and Letey (1992). Type I is based on the work of Gardner (1960, 1964) and simulate the physics of water flow from the soil to, and through, the plant roots with Darcy's law. With a Type II formulation empirical plant-water stress functions are used to relate water uptake to matric and osmotic stress which is then related to potential transpiration.

The water uptake function of SWAMP was independently tested by Singels et al. (2010) and outperformed models like CANESIM, WOFOST, SUCROS and CERES. Cardon and Letey (1992) however found that the Type I formulation was insensitive to salinity and could not simulate a decrease in transpiration as a result of osmotic stress, compared to a Type II formulation. In its original form osmotic potential is not considered by SWAMP. Future research regarding this aspect is, therefore, required. Thus, it is assumed that when SWAMP is used, the effect of irrigation water and water table salinity on crop water use is negligible (low concentrations). If this is true, SWAMP can be used to assess current water management practices by farmers with fluctuating water tables in sand to sandy loam soils located in semi-arid regions, by solving the soil water balance, as shown in Section 3.3.2. In contrast to studies where more complex models were used under field conditions (Singh, 2013; Hurst et al., 2004; Xie et al., 2011), SWAMP accomplishes this with easily obtainable input variables of planting date, length of growing season, seed yield, mean atmospheric evaporative demand over the season, mean water table depth over the season, silt-plus-clay content and volumetric soil water content at the start of the season. In addition it was shown that SWAMP maximizes the use of *in situ* field observations of rainfall, irrigation, fluctuation in water table depth, change in soil water content and artificial drainage, which are easily measured. This is imperative because, as emphasized by Silberstein (2006), data are important and models should be a complement to them and not a replacement. Due to these strengths of SWAMP, i.e. user- and data-friendly, there is a real likelihood that the model would be adopted by the broader irrigation community (Bastiaanssen et al., 2007).

3.5 Conclusions

In this chapter the credibility of SWAMP to assess current water management practices by farmers in semi-arid regions where field crops are grown in sandy to sandy loam soils with shallow water tables was investigated. This was done by establishing confidence in the outputs of SWAMP under constant controlled water table conditions when model parameters were determined from input variables.

It was concluded that the accuracy with which SWAMP simulate weekly evapotranspiration and water table uptake of wheat, peas and maize grown on sand to sandy loam soils was good. Limitations and uncertainties associated with SWAMP will be greater when used in dissimilar climates and soils with sandy-clay to clay textures.

From these favorable results it was concluded that SWAMP adequately simulated the effect of irrigation scheduling on crop water use from constant water tables. Additionally SWAMP can also simulate the shift in water uptake from stressed to less stressed sections of the root zone and the effect of different crops, growth stages and soils on crop water use from water tables. This success was attributed to the complex non-linear function that is used by SWAMP to simulate crop water uptake. The function accounts for a variety of factors in a multi-layered soil profile. However, because the osmotic potential is not currently considered by the function, SWAMP should only be used where the effect of irrigation and water table salinity on crop water use is negligible, i.e. low salt concentrations.

This version of SWAMP can be used to assess current water management practices by farmers, by solving the soil water balance under fluctuating water table conditions at field level (which would otherwise be difficult to achieve). The strength of SWAMP lies in the fact that this is accomplished with easily obtainable input variables, while optimizing the use of *in situ* field observations. It may be argued that this is a step backwards, considering the amount of observations that were used to solve the soil water balance. It is argued, however, that field observations are important and that farmers cannot adopt alternative management practices if they cannot measure their current practices. Hence, this chapter illustrates the means to accomplish this by using the Soil Water Management Program, SWAMP.

CHAPTER 4

SIMULATING WATER UPTAKE OF IRRIGATED FIELD CROPS FROM SALINE WATER TABLE SOILS: ADAPTATION AND VALIDATION OF THE MODEL SWAMP

4.1 Introduction

Mathematical models that simulate water and salt flow in irrigated water table soils and the response of field crops to matric and osmotic potentials are critical towards improving on-farm water and salt management guidelines (Corwin et al., 2007). This is because most of the guidelines originated from steady state conditions, which should be supplemented with transient-state modeling (Letey and Feng, 2007; Letey et al., 2011).

Models like ENVIRO-GRO (Feng et al., 2003), SWAP (Van Dam et al., 2008), UNSATCHEM (Suarez and Šimůnek, 1997), HYDRUS (Šimůnek et al., 2008) and SALTMED (Ragab et al., 2005) numerically solves the Richards equation for variable saturated and unsaturated water flow, and the advection-dispersion equation for solute transport. These models compute root water uptake or actual transpiration according to the macroscopic approach of Feddes et al. (1978) and Belmans et al. (1983). Cardon and Letey (1992) referred to this as Type II formulations, i.e. empirical functions that describe plant water uptake based on a response to water potential. As summarized by Skaggs et al. (2006) the dimensionless water stress response function (α, reduction function) can be postulated for matric and osmotic stress, where h is the pressure head and π the osmotic head. To compute α(h) either a piecewise linear reduction function or an alternative smooth S-shaped reduction function is used, with adjustable parameters to reduce water uptake according to critical pressure heads. The same functions can be used for α(π) except that water uptake is reduced with adjustable parameters for critical osmotic heads, which corresponds normally to the Maas and Hoffman threshold and slope parameters (Maas and Hoffman, 1977; Maas, 1990). In order to combine the matric and osmotic stresses, either an additive or a multiplicative approach is used.

Unfortunately, determination of parameters for α(π) remains a challenge. As highlighted by Skaggs et al. (2006) “more research in this area is needed if the above-mentioned models are to be employed as predictive tools that do not require extensive crop- and site-specific calibration of these parameters, involving inverse modeling”. However, despite these difficulties Type II root water uptake formulations remains popular (Oster et al., 2012). This is because Type I formulations was found to be insensitive to salinity and water content (Cardon and Letey, 1992), i.e. Type I describe the physics of water flow from the soil to and through the plant roots.

The objective of this chapter was to present and evaluate an alternative model that does not rely on these parameters, i.e. the **S**oil **WA**ter **M**anagement **P**rogram (Bennie *et al*., 1998). As mentioned in Chapter 2, SWAMP was originally developed to support field observations of water management for dry land crop production in central South Africa (Bennie and Hensley, 2001; Hensley et al., 2011). Downward water flow is simulated according to the cascading principle, evaporation with the Ritchie equation and capillary rise by relating the maximum upward flux from a water table to a specific height above the water table (Ehlers et al., 2003). Transpiration or water uptake due to matric stress is simulated with a mathematical algorithm that computes the water supply of a rooted soil layer. The supply of water from this layer on a specific day must be adequate to provide the crop with enough water to prevent any stress. As the soil dries the water supply will decrease until the requirement of the crop cannot be satisfied, which causes a reduction in water uptake and yield. Parameters for this algorithm was successfully quantified in a peer reviewed Water Research Commission funded project for a number of different crops grown on a number of different soils by Bennie et al. (1988) and Bennie et al. (1998). Singels et al. (2010) used the same algorithm to simulate matric stress effects on water uptake of sugarcane successfully after parameterization. They recommended that the algorithm must be incorporated into the CANESIM model.

As shown in Chapter 3, SWAMP has an option of determining these parameters reasonable accurately for field crops grown on sandy to sandy loam soils with shallow water tables in semi-arid regions from easily measured input variables. It was envisaged that SWAMP would also be able to simulate a reduction water uptake and yield due to osmotic stress reasonably accurately. This would be possible with limited adaptations to the current algorithm that simulates the water supply of a rooted soil layer and calibration of parameters. However, as Bellocchi et al. (2010) and Bennett et al. (2013) highlighted, the performance of a model must be characterized at each published stage of its development.

4.2 Methodology

4.2.1 Adaptations to SWAMP

Section 2.7 provides a description of the model. The following input variables were added and adaptations made to the model to simulate water uptake under saline conditions and the resulting influence on crop yield. The general principle that was adopted was to determine daily changes in the salt content (S, kg ha^{-1}) of a soil layer from simulations of water and salt added to, and lost from the specific layer. Thus, the salt content of a specific layer was expressed at a water content of saturation and a parameter (c_1) that convert electrical conductivity (EC) to salt content (kg salt ha^{-1} mm^{-1} water added or lost from the layer) used. The input variables that will be required are electrical conductivity of a saturated extract at the start of the season (EC_e, mS m^{-1}), and mean electrical conductivity of the water table (EC_{WT}, mS m^{-1}) as well as the irrigation water (EC_I, mS m^{-1}) and rainfall (EC_R, mS m^{-1}) during the season.

The source of salt to the first soil layer are through irrigation and rain, while salt addition to the layer beneath will be equal to salt removed from the layer above until percolation to the layer beneath is zero. To determine the fraction of salt removed (DC) from a layer through miscible displacement as a function of percolation, leaching curves as described by Barnard et al. (2010) are used. For the layers in the capillary fringe an additional source of salt will be water table uptake through capillary rise from the water table. If this amount of salt added to the layers in the capillary fringe exceeds removal through percolation, salt will accumulate within the capillary fringe. When salt removal from the last layer just above the water table exceeds accumulation, it is assumed that salt from this layer will be removed through lateral flow of the saturated zone beneath the water table to lower laying fields.

As mentioned in the previous section SWAMP computes the water supply of a rooted soil layer, which will decrease as the soil dries (matric stress) until the requirement of the crop cannot be satisfied. Bennie et al. (1988) derived Eq. (4.1), which is the layer water supply rate (LWSR, mm d^{-1}), from Richards partial differential equation for water movement in an unsaturated non-swelling soil. Where Ψ_m is the matric potential (-kPa), F_{sr} the soil root conductance coefficient (mm^2 d^{-1} kPa^{-1}), Lv the root density (mm roots mm^{-3} soil) and Ψ_p the critical leaf water potential where plant water stress sets in (-kPa). θ is the simulated volumetric soil water content (mm mm^{-1}) and θ_o the volumetric soil water content (mm mm^{-1}) where $\Psi_m = \Psi_p$ (volumetric lower limit of plant available water under matric stress). Richards's equation was applied to the concept of a soil profile consisting of a network of concentric root-soil cylinders. It was assumed that water within a root-soil cylinder would move through the root xylem due to a hydraulic gradient (Gardner, 1960), i.e. the difference in total potential over a specific distance. In non-saline soils, the total potential is the sum of the negligible small gravitation head and matric potential. Thus, the hydraulic gradient was quantified by assuming that the root-xylem potential is equal to the leaf-xylem potential, with the outside border of the root-soil-cylinder determined by the average half distance between roots, calculated as the square root of 3.1428 (PI) times Lv (Barley, 1970). In addition, the hydraulic conductivity (K) in Richards equation was substituted with a combined soil-root conductivity (K_{sr}), which was related to the relative water content (θ/θ_o) and a specific soil-root conductance coefficient (F_{sr}).

$$LWSR_{k\ (d)} = F_{sr} \ln\left(\frac{\theta_{k\ (d)}}{\theta_{o\ (k)}}\right) \Pi Lv_{(k)}{}^{0.5} \left|\Psi_{m\ k\ (d)} - \Psi_p\right| z_{(k)} \quad (4.1)$$

However, in saline soils the difference in total potential over a specific distance (hydraulic gradient) must include both the difference in matric and osmotic potential. Hence, Ψ_m in Eq. (4.1) was replaced with the total soil water potential (Ψ_t, kPa), which is the sum of the matric and osmotic (Ψ_o) potentials. Ψ_o is calculated with Eq. (4.2), which shows that when θ decrease, salt will concentrate and the osmotic potential decrease. SWAMP simulates, therefore, the effect of osmotic stress (potential) at actual θ and not at saturation, where c_2 is a parameter used to convert EC (mS m^{-1}) to total dissolved salts (TDS, mg L^{-1}) and c_3 to convert TDS to Ψ_o. Furthermore, when salt accumulates the force (osmotic potential) with which the salt is attracting the water will increase, which will result in less water being available at higher water contents. Hence, θ_o in Eq. (4.1) was replaced with θ_t, which is the volumetric lower limit of plant available water under osmotic stress. Under non-saline conditions θ_o was obtained from the retention curve (Section 2.7) where $\Psi_m = \Psi_p$. For saline soils θ_t is the volumetric soil water content where $\Psi_m + \Psi_o = \Psi_p$. To determine θ_t for each layer on every day an arbitrary θ_t was incrementally reduced from saturation and the corresponding Ψ_m calculated from the retention curve. At the same time, these volumetric water contents were used together with the salt content of the layer on the specific day, to calculate the Ψ_o with Eq. (4.2). Hence, the Ψ_o will decrease as the layer becomes drier. The volumetric water content of the specific layer where $\Psi_m + \Psi_o = \Psi_p$ represent θ_t for the specific salinity of the layer on that day.

$$\left|\Psi_{o\ k\ (d)}\right| = \left[\frac{EC_{e\ (k)(d)}\ c_2\ c_3}{\theta_{k\ (d)}}\right] \theta_{s\ (k)} \quad (4.2)$$

With the above mentioned adaptations Eq. (4.1) was, therefore, changed to Eq. (4.3) to accommodate the effect of increasing salinity and decreasing osmotic potential on the water supply of a rooted soil layer. Water uptake or actual transpiration (T_A, mm) are determined with Eq. (4.4), where T_R is the transpiration requirement for day d (Section 2.7).

$$LWSR_{k\ (d)} = F_{sr} \ln\left(\frac{\theta_{k\ (d)}}{\theta_{t\ (k)}}\right) \Pi Lv_{(k)}^{\ 0.5} \left|\Psi_{t\ k\ (d)} - \Psi_p\right| z_{(k)} \qquad (4.3)$$

$$T_{A\ k\ (d)} = T_{R(d)} \left(\frac{LWSR_{k\ (d)}}{PWSR\ (d)}\right) \text{ where } PWSR_{(d)} = \sum_{k=1}^{n} LWSR_{(k)(d)} \qquad (4.4)$$

4.2.2 Lysimeter trial for model evaluation

Evaluation of SWAMP was based on data obtained from a lysimeter trial done by Ehlers et al. (2007). The trial investigated the effect of salt accumulation in the root zone on water uptake and yield of peas and maize grown on sand and sandy loam water table soils. The experiment was conducted at the lysimeter research facility (29˚01’00’’S, 26˚08’50’’E) near Bloemfontein, South Africa (Fig. 3.1). The facility consists of 30 round static lysimeters that are arranged in two parallel rows of 15 each, under a moveable rain shelter. The one row was filled with a sandy (Mean silt-plus-clay, SC = 8%) soil of the Clovelly form and the second row with a sandy loam (Mean SC = 18%) of the Bainsvlei form as listed (Soil Classification Working Group, 1991). According to the Soil Survey Staff (2003), the two soils qualify as a Quartzipsament and Plinthustalf, respectively.

Five different saline profiles were established by continuous leaching with different water quality treatments, which were replicated three times per soil type, before the start of the cropping seasons. The irrigation water qualities were prepared with sodium chloride (NaCl), calcium chloride ($CaCl_2$), magnesium sulphate ($MgSO_4$), sodium sulphate (Na_2SO_4), potassium chloride (KCl) and magnesium chloride ($MgCl_2$). The sodium adsorption ratio (SAR = 5) as well Ca/Mg (1.2) and SO_4/Cl_2 (1.6) ratio were based on long-term values of the Lower Vaal River and its tributaries (Du Preez et al., 2000). Peas were planted 21 July 2004 and irrigated with 25, 75, 150, 225 and 300 mS m^{-1} water, while maize was planted 17 December 2004 and irrigated with 25, 150, 300, 450 and 600 mS m^{-1} water.

The lysimeters had a diameter of 1800 mm and a depth of 2000 mm. The soil profile consisted of three zones. An upper unsaturated (0-600 mm zone), a capillary zone (600-1200 mm) and a saturated zone (water table between 1200 and 1800 mm from the surface). Each zone was subdivided into 300 mm thick layers. Water uptake from the 0-600 mm soil layers of each lysimeter 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 and applied as weekly irrigations (I, mm). Within each lysimeter a water table was maintained at a depth of 1200 mm with a constant head device. Capillary rise from the water table replaced the water uptake from the 600-1200 mm soil layer, and was recharged by applying water on a daily basis to the constant head device. The volume of water added to maintain a constant water level was converted to water depth, which represent water table uptake (WTU, mm), and had the same EC as the irrigation water. Salt accumulated, therefore, in the soil profiles due to salt additions through WTU recharge and irrigation because drainage from the lysimeters was zero. The EC_e for each layer was measured at the end of the growing season, on water samples obtained from ceramic cups that were installed in each layer.

The objective of the agronomic practices was to create optimal conditions for crop growth, allowing for maximum water uptake and yield. Cultivars, planting date, sowing density and fertilizer applications were based on widely used guidelines for central South Africa (Fertilizer Society of South Africa, 2007). The area surrounding the lysimeters was treated in the same manner. The soil water balance for each lysimeter was quantified on a weekly basis with measurements of soil water content (calibrated CPN neutron probe), irrigation and WTU, while rainfall (R, mm) was zero because the rain shelter was closed during rain events.

4.2.3 Input variables and model parameters

The input variables used in the simulations are listed in Table 4.1. The yield and harvest index of the control treatment for both crops grown on both soils were used as the target yield for all the simulations of the different treatments. This is required by SWAMP in order to determine the transpiration requirement under no matric or osmotic stress as discussed in Section 2.7.

Seven soil layers were selected and their measured SC, θ and EC_e at the start of the season entered. Table 4.2 provides the mean θ and EC_e of the soil profile for the different treatments. The water table was kept at a constant depth of 1200 mm, with EC's the same as the irrigation water quality treatments.

Table 4.1 Climate and crop input variables used in SWAMP to simulate the effect of osmotic stress on water uptake and yield of peas and maize

Input variables	Peas	Maize
Mean ET_o (mm day^{-1})	4.7	5.4
Planting date	20 July 2004	17 December 2004
Crop growth length (days)	130	140
Target seed yield (kg ha^{-1})	4743 ^{Cv}, 4578 ^{Bv}	14654 ^{Cv}, 12618 ^{Bv}
Harvest index	0.43 ^{Cv}, 0.45 ^{Bv}	0.47 ^{Cv}, 0.48 ^{Bv}

Cv = Clovelly soil; Bv = Bainsvlei soil

Table 4.2 Soil input variables used in SWAMP to simulate the effect of osmotic stress on water uptake and yield of peas and maize

Input parameters		Peas					Maize				
Soil	Treatment	1	2	3	4	5	1	2	3	4	5
Clovelly	$\theta_{start\ 0\text{-}2000\ mm}$ (mm mm^{-1})	0.266	0.267	0.262	0.260	0.261	0.297	0.292	0.298	0.293	0.292
	$EC_{e\ start\ 0\text{-}1200\ mm}$ (mS m^{-1})	33	74	78	159	252	39	78	107	161	279
	$EC_{I\ and\ WT}$ (mS m^{-1})	25	75	150	225	300	25	150	300	450	600
	Irrigation (mm)	453	486	435	408	431	463	445	386	380	368
Bainsvlei	$\theta_{start\ 0\text{-}2000\ mm}$ (mm mm^{-1})	0.263	0.264	0.263	0.261	0.262	0.295	0.297	0.293	0.289	0.289
	$EC_{e\ start\ 0\text{-}1200\ mm}$ (mS m^{-1})	50	130	224	326	421	56	155	265	383	533
	$EC_{I\ and\ WT}$ (mS m^{-1})	25	75	150	225	300	25	150	300	450	600
	Irrigation (mm)	400	363	283	271	236	361	348	267	259	272

Measured weekly irrigations during the growing season of peas and maize for all the treatments of both soils were used in the simulations, while rainfall was zero because of the presence of the moveable-rain shelter that covered the plots during rain events.

All the model parameters that were required to simulate evaporation, the transpiration requirement, capillary rise and water supply from the different soil layers of both crops were determined from input variables as shown in Section 2.7. The only exception was that the observed number of days for the different growth stages were used to describe crop growth. For the new c_1, c_2 and c_3 parameters that were added to the model, as explained in Section 4.2.1, a value of 0.075, 7.5 and 0.072 were used. The c_2 parameter is the conversion factor for EC to TDS (mg L^{-1}) that was obtained from Ehlers et al. (2007), while c_1 is used to convert EC to kg salt ha^{-1} mm^{-1} water. The relationship (c3) between soluble salt concentration and osmotic potential were derived as proposed by Borg (1989) with Eq. (4.5) from analyses of soil water sample data of Ehlers et al. (2007) taken with ceramic suction cups at different soil depths. From all these data a mean of 0.072 were calculated, where x represents the ions Na^+, Ca^{2+},

Mg^{2+}, SO_4^{2-}, Cl^- and K^+. R is the gas constant (8.31 kPa L mol^{-1} K^{-1}), T the absolute temperature, taken as 298.15 K (25°C), n = 1 (all salts are assumed to be completely dissociated), m_m the molecular mass of component x (g mol^{-1}) and f the fraction of component x that contributes to the total mass of soluble salts in the solution.

$$c_2 = c_{Na^+} + c_{Ca^{++}} + c_{Mg^{++}} + c_{SO_4} + c_{Cl^-} + c_{K^+} \text{ where } c_x = \left[\frac{R\ \ T}{1000}\right]\left[\frac{n\ \ f}{m_m}\right] \tag{4.5}$$

The parameter DC for every soil layer, which determines the fraction of salt removed as a function of percolation, was determined with Eq. (4.6), where P is die volume of water percolating from the specific layer and z the thickness of the layer.

$$DC_{k\,(d)} = 0.92\left(1 - \exp^{\,b\left(\frac{P_{(k)(d)}}{z_{(k)}}\right)}\right) \text{ where } b = 0.2673\ \ SC_k\ \ - 12.346 \tag{4.6}$$

4.2.4 Model performance

Ten simulations were done in total, one per treatment for both soils. These simulations were statistically analyzed by comparing crop water uptake values obtained by simulation to measured values using the approach of Bellocchi et al. (2002). With this approach, various statistical indices and tests were aggregated into three modules, i.e. accuracy, correlation and pattern according to a fuzzy-logic based expert system. These modules were then aggregated into a single indicator module, I_{SWAMP}, which represents the aggregated accuracy, correlation and pattern performance of SWAMP. The statistical indices and test that were used in the accuracy module are relative median absolute error (RMdAE, Eq. (4.7)), relative modeling efficiency (REF, Eq. (4.8)) and the Kolmogorov-Smirnov (KS) test of which the probability value was used and not the KS value. For the correlation module Spearman's rank correlation coefficient (r_s) was used, and pattern of residuals (crop water uptake simulations minus measurements) against independent variables days after plant (PI_{DAP}) and EC_e (PI_{ECe}) for the pattern module. It was decided to use these indices and test because the data do not represent populations with normal distributions (Donatelli et al., 2004b). Despite of the fact that these statistics are less powerful to detect differences that are present, it seems the most logical choice (Townend, 2009). This is because transformation of data did not achieve the desired normal distribution that is required for parametric statistics.

$$RMdAE = median_{i=1,...,n} \left| Ms_i - Sm_i \right| \frac{100}{\overline{M}} \tag{4.7}$$

$$REF = median_{i=1,...,n} \left(\frac{median_{i=1,...,n} \left| Ms_i - \overline{O} \right| - median_{i=1,...,n} \left| Ms_i - Sm_i \right|}{median_{i=1,...,n} \left| Ms_i - \overline{O} \right|} \right) \tag{4.8}$$

The mean of the three measured (Ms) replications were used and compared against the simulations (Sm), because no significant difference between the measured values of the replications were observed, where i is the ith value, n the number of data pairs and $\bar{O}$ the mean of the measurements. The KS test determines the probability that the measurements and simulations have the same distribution, while r_s is a measure of association between Ms and Sm. Computation of PI_{DAP} and PI_{ECe} were done by dividing the residuals in four and five groups, respectively, and calculate the pair-wise differences between average residuals of the groups (Donatelli et al., 2004a). Four and five groups were selected because it corresponds to the growth stages and number of water quality treatments, respectively. It was decided to use range-based fixed pattern index (PI) for the independent variable DAP and EC_e.

Fig. 3.2 shows the expert weights that were used to aggregate the different statistics, according to the relative importance of the statistic, into the three modules and I_{SWAMP}. The three membership classes, viz. favorable (F), unfavorable (U) and partially (Fuzzy), and the decision criteria to determine when the index is favorable or unfavorable, are also included. From the decision criteria and expert weights (Fig. 3.2) a dimensionless value of the module that range between 0 (best model performance) and 1 (poor model performance) were calculated (Bellocchi et al., 2002). The data analysis software Integrated Resources for Evaluating Numerical Estimates, IRENE (Fila et al., 2003), was used to aggregate the different statistics into I_{SWAMP} and the Statistics/Data Analysis software STATA 11.0 to determine KS and r_s (StataCorp, 2009).

4.3 Results

4.3.1 Salt accumulation and yield

Fig. 4.1 presents the measured response of relative yield, for both crops grown on the two soils, due to increasing soil salinity. Clearly, the two crops did not respond the same to osmotic stress, with a threshold of 105 mS m^{-1} and slope of 18% for peas and a threshold of 250 mS m^{-1} and a slope of 12% for maize.

As shown in Fig. 4.2, SWAMP was able to simulate these osmotic conditions during the growing season of the two crops well, i.e. the accumulation of salt caused by deteriorating water quality. Additionally, the buildup of salt in the root zone was fairly well translated to a reduction in yield of both crops by SWAMP, which was achieved despite of the fact that the two crops differs in their sensitivity to salinity. With a unit decrease in water quality SWAMP simulated an increase in EC_e of 1.9 mS m^{-1} compared to the measured value of 1.84 mS m^{-1}, while SWAMP simulated a relative decrease of 0.0011, compared to the 0.0013 that was measured.

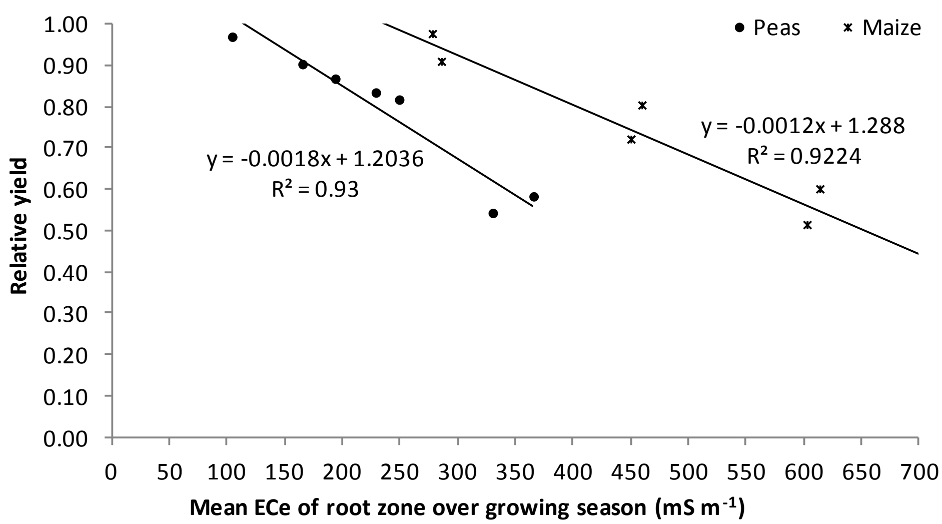


Fig. 4.1 Measured mean salinity of the soil above the water table (root zone) over the growing season, expressed as electrical conductivity of a saturated extract (EC_e), and relative yield of peas and maize grown on the Clovelly and Bainsvlei soils.

Thus, from a cumulative or seasonal perspective, SWAMP performed well under conditions of salt accumulation. The data set is, therefore, sufficient to characterize the performance of SWAMP when simulating water uptake of these two crops under osmotic stress.

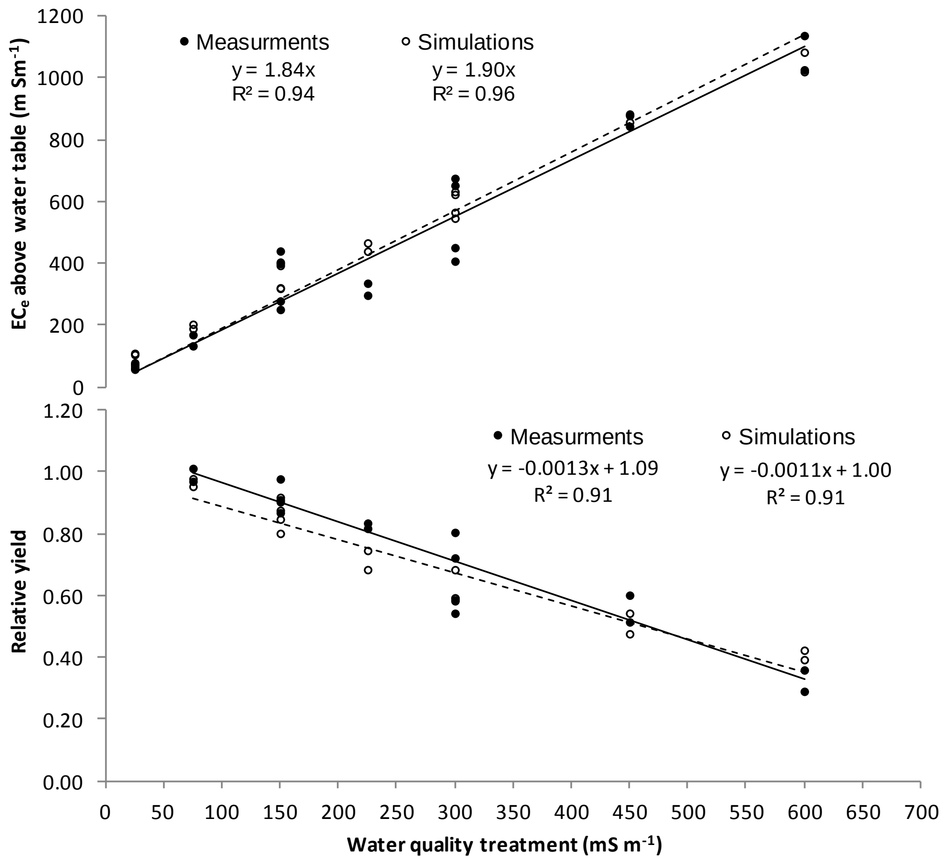


Fig. 4.2 Measured and simulated salinity of the soil above the water table (root zone), expressed as electrical conductivity of a saturated extract (EC_e), and relative yield of peas and maize plotted against water quality treatment.

4.3.2 Soil water potential and impact on water uptake

To understand how SWAMP simulated yield losses caused by salt buildup, two treatments were selected, i.e. a control and high salinity treatment (treatment 5) for both the Clovelly and Bainsvlei soils cultivated with peas and maize. Hence, Fig. 4.3 presents the simulated mean matric and osmotic potential of the root zone for both soils and the simulated and measured water uptake during the growing season of peas and maize. Additionally, Fig. 4.4 shows the water uptake residuals (simulations minus measurements) during the growing season against independent variables days after plant and EC_e. The statistical indices that were used to evaluate the performance of SWAMP are presented in Table 4.3. It was decided to use data from all five treatments and group the data of the two soils to provide a comprehensive dataset for characterizing the performance of SWAMP.

4.3.2.1 Peas

Considering the control treatment, the matric potential in both soils were relative constant during the growing season, while the osmotic potential remained above -150 kPa. No matric or osmotic stress occurred, therefore, during the growing season as a yield of 4500 kg ha^{-1} was simulated. For treatment 5, the matric potential of both soils also remained constant during the growing season. In contrast to the control treatment, the osmotic potential decreased considerably in both soils as the growing season progressed.

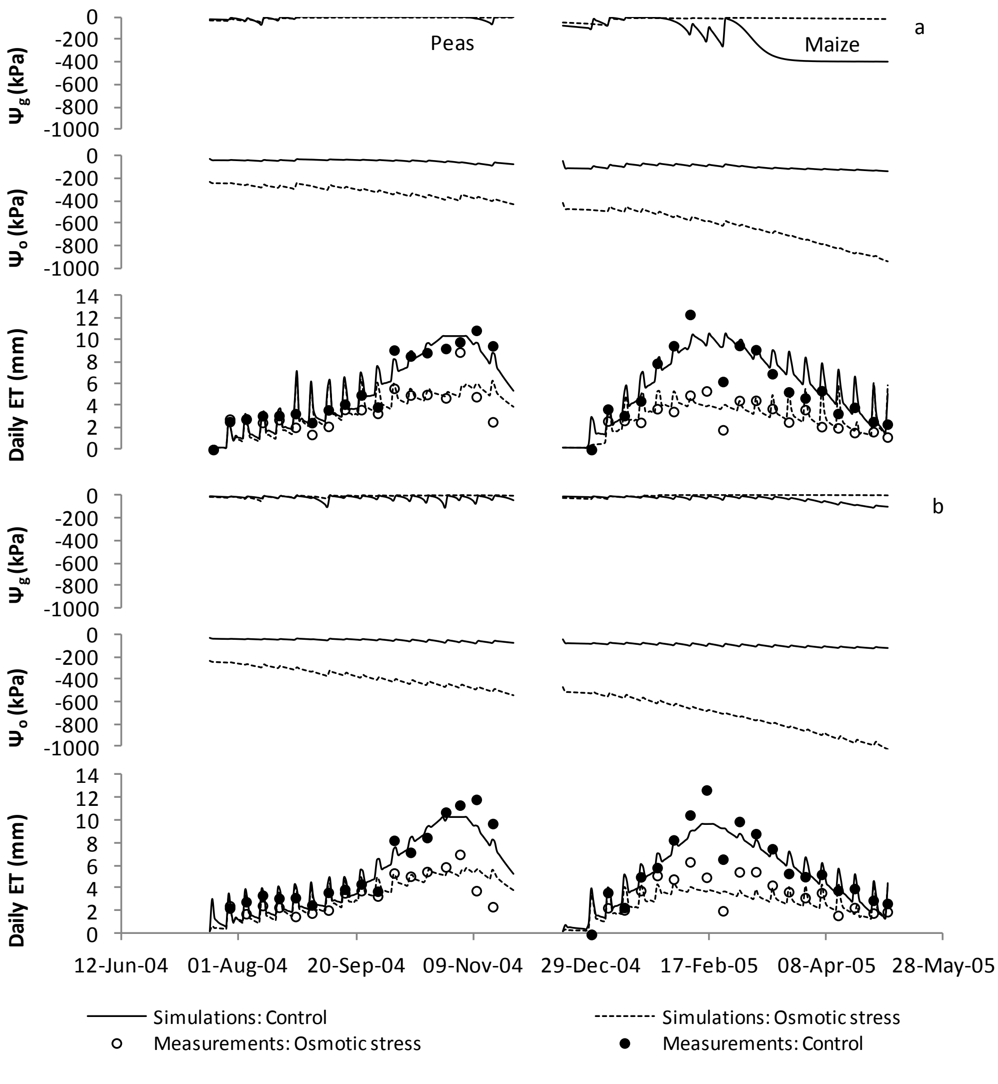


Fig. 4.3 Simulated mean matric (Ψ_g) and osmotic (Ψ_o) potential of the root zone during the growing season of peas (July 2004-November 2004) and maize (December 2004-May 2005) grown on the Clovelly (a) and Bainsvlei (b) soils for the control and treatment 5 (osmotic stress), together with the measured and simulated daily evapotranspiration (ET).

The simulations illustrate how osmotic stress developed during the growing season. As shown in Fig. 4.3, this caused a reduction in water uptake when compared to the control treatment. SWAMP was, therefore, able to partition soil water potential into its components of matric and osmotic potential in both soils. In addition, SWAMP was able to reduce water uptake during the growing season reasonably well under conditions of osmotic stress, which caused a reduction in relative yield (Fig. 4.2).

To investigate how well this was accomplished by SWAMP, the simulated water uptake during the growing season were compared with their corresponding measured values (Table 4.3). The following could be deducted from the three modules, i.e. correlation, accuracy and pattern (Section 4.2.4), which were used to evaluate SWAMP.

According to the correlation module, the extent with which water uptake simulations correlate with measurements was high (correlation < 0.1). The accuracy with which SWAMP simulated water uptake was good with a value of 0.30. Conversely, the value of the pattern module was elevated (> 0.5), which indicate the presence of macro-patterns. This elevated value was largely due to the higher PI_{DAP} value compared to PI_{ECe} (Table 4.3). A plot of the water uptake residuals against DAP and EC_e confirmed this as shown in Fig. 4.4.

Table 4.3 Statistical indices and test that were used to evaluate the simulations of weekly evapotranspiration and water table uptake of peas and maize by SWAMP

Simulation	Evapotranspiration	
Crop	Peas	Maize
n	170	180
RMdAE	19	18
REF	0.49	0.46
KS: D (*P*-value)	0.13 (0.116)	0.09 (0.398)
r_s	0.82	0.87
$PI_{v\ DAP}$	7.6	11.4
$PI_{v\ ECe}$	4.0	4.0
Accuracy	0.30	0.30
Correlation	0.06	0.03
Pattern	0.51	0.51
I_{SWAMP}	0.25	0.25

Water uptake was over-simulated during the early part of the season (30-70 days after plant) and under-simulated during the latter part (70-130 days after plant). In contrast, the water uptake residuals were more uniformly (PI_{ECe}< 5 mm) distributed with an increase in soil salinity (EC_e) as shown in Fig. 4.4. Salt accumulation had, therefore, no substantial influence on the quality of water-uptake simulations. In general, when the aggregated accuracy, correlation and pattern performance of SWAMP was considered it can be deducted that water uptake of a salt sensitive crop like peas was simulated reasonably well under relatively high salinity conditions (I_{SWAMP} = 0.25).

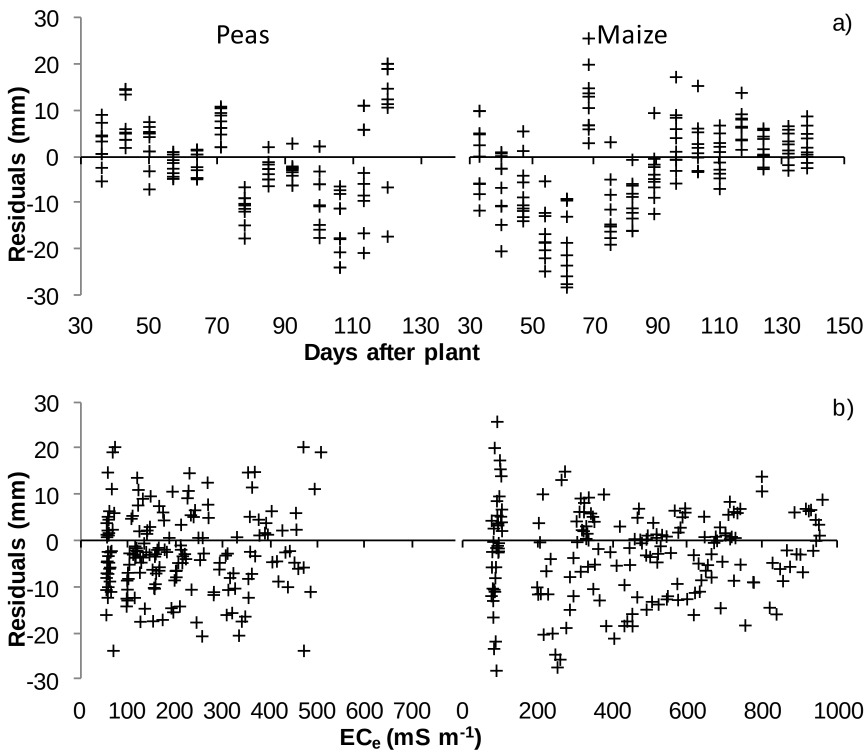


Fig. 4.4 Water uptake residuals (simulations minus measurements) during the growing season of peas and maize against independent variables days after plant (a) and soil salinity (b), expressed as electrical conductivity of a saturated extract (EC_e).

4.3.2.2 Maize

Like with peas during the maize-growing season, the soils were kept wet for the control treatment. The matric potential remained relatively constant until the end of the season when it decreased to -400 kPa, while the osmotic potential remained above approximately -150 kPa during the entire season. Thus, no matric or osmotic stress occurred and a yield of 14 000 kg ha^{-1} was simulated. For the salinity treatment 5, salt accumulation caused a decrease in the osmotic potential, i.e. approximately -1000 kPa at the end of the season. As shown in Fig. 4.3, this caused a reduction in water uptake when compared to the control treatment. This reduction was reflected in the lower grain yield (5000 kg ha^{-1}) resulting from osmotic induced water stress. SWAMP, therefore, also successfully reduced water uptake of maize during the growing season under conditions of osmotic stress.

The statistics in Table 4.3 show that these reductions in water uptake caused by osmotic stress were like peas simulated reasonable well by SWAMP. The correlation module was slightly lower than for peas, with a value of 0.03, while the accuracy (0.30) module was the same. Again, the value of the pattern module was higher (> 0.5), largely due to the higher PI_{DAP} value compared to PI_{ECe} (Table 4.4). A plot of the water uptake residuals against DAP showed that water uptake was, in contrast to peas, largely under-simulated during the early part (30-90 days after plant) of the season and over-simulated during the latter part (90-130 days after plant). Salt accumulation during the growing season of maize, like for peas, had no substantial influence on the quality of water uptake simulations, with uniformly distributed residuals with an increase in EC_e. According to the aggregated accuracy, correlation and pattern performance of SWAMP, water uptake simulations of maize compared well to peas under conditions of osmotic stress (I_{SWAMP} = 0.25).

4.4 Discussion

The results revealed that it was possible to simulate the accumulation of salt in the root zone during the growing season of peas and maize grown in sand to sandy loam soils, due to irrigation and capillary rise from a constant water table, reasonably accurately with SWAMP. This was done according to standard theory where evapotranspiration acts as a semi-permeable membrane (Hillel, 2000). Under these osmotic stress conditions, a decline in crop yield of both crops was simulated well, which was possible because SWAMP was able to simulate a reduction in water uptake of both crops reasonable accurately (I_{SWAMP} > 75%) with the layer water supply rate algorithm.

No macro-pattern was observed in simulating water uptake of both crops with an increase in soil salinity (osmotic stress), which means that the water uptake residuals contain no structure that is not accounted for in the adaptations to the layer water supply rate algorithm and parameters. SWAMP contains, however, some macro-patterns in simulating water uptake of both crops with an increase in days after plant (growing season). The water uptake residuals contain, therefore, structure not accounted for in the model. The structure was attributed to the assumption of a fitted ET_o over the growing season and not because of the adaptations to the layer water supply algorithm. SWAMP uses an average crop specific factor (m) over the growing season to relate the transpiration requirement (potential transpiration) to maximum biomass yield. An improvement might be to determine m for each growth phase as suggested by Haka (2010) and Barnard et al. (2013) to improve the distribution of the transpiration requirement during the growing season.

It can be concluded, therefore, that with SWAMP an alternative model are provided to simulate the effect of osmotic stress on water uptake and yield of peas and maize grown on sand to sandy loam water table soils. This can be accomplished under these conditions without the difficulty of determining the numerical parameters to solve the Richards and convection-dispersion equations to simulate water and salt flow. Furthermore, the problem of determining parameters for the commonly employed piecewise linear and S-shaped functions, to simulate water uptake under osmotic stress, from literature as suggested by Skaggs et al. (2006) does not exist. The model parameters required by SWAMP under these conditions are determined successfully from easily measured input variables.

Clearly, SWAMP provides an improvement in root water uptake modeling under osmotic stress, through a more dynamic layer water supply algorithm. Although not tested in this chapter, but due to the nature of the algorithm (Section 4.2.1), it is anticipated that SWAMP will be able to simulate compensated water uptake, where water uptake is increased in the part of the root zone with more favorable conditions. Additionally, SWAMP will be able to incorporate the combined effect of matric and osmotic potential on water uptake without the additional additive and multiplicative assumptions. This is important because, as De Jong van Lier et al. (2009) showed, the detrimental effects of osmotic stress on water uptake increase as the soil becomes drier. The approach in which fixed reduction factors is based on salinity threshold and slope is, therefore, refined with the approach adopted by SWAMP. The consequence is that SWAMP simulates the change in osmotic stress with changing water content, which is not possible with the salinity threshold and slope analysis. However, water and salt flow simulations in water table soils with SWAMP can be improved by using Richards and the convection-dispersion equations.

4.5 Conclusions

This chapter dealt with the inclusion of a new salinity subroutine in SWAMP which was evaluated under controlled saline conditions by using data from a lysimeter trial. Adaptations to the algorithms was made to simulate salt transport in saline water table soils and include the effect of osmotic potential on root water uptake.

It was concluded that SWAMP could simulate the accumulation of salt within the root zone of sand to sandy loam water table soils well. The subsequent detrimental osmotic effect on the yield of salt sensitive and moderately salt sensitive crops (peas and maize) was simulated reasonably accurately. This was accomplished because the modified root water uptake subroutine used by SWAMP was able to reduce water uptake during the growing season under osmotic stress fairly well.

Hence, this chapter provides an alternative model that do not require the numerical parameters to solve the Richards and convection-dispersion equations and the piecewise linear and S-shaped functions, where determination and calibration of the parameters is difficult. This is because SWAMP was able to determine the model parameters that are required for peas and maize grown in sand to sandy loam water table soils successfully from input variables. It is anticipated that a combination of the layer water supply algorithm used by SWAMP, with the Richards and convection-dispersion equations for water and salt flow, will contribute towards further improvements in modeling the dynamic detrimental effect of water and salt stress.

CHAPTER 5

EVALUATION OF ON-FARM WATER AND SALT MANAGEMENT FOR IRRIGATED FIELD CROPS GROWN ON WATER TABLE SOILS: CASE STUDIES AT ORANGE-RIET AND VAALHARTS

5.1 Introduction

In central South Africa, like most irrigation regions throughout the world, on-farm water and salt management must be continually evaluated and improved. This is because salt tends to accumulate in poorly drained soils under irrigation, where poor water and salt management practices exist (Le Roux et al., 2007). The opposite is also true where excessive leaching due to poor irrigation scheduling is inclined to deteriorate the quality of water resources because of salt pollution resulting from drainage effluent (Van Rensburg et al., 2008; Van Rensburg et al., 2011). The days where the sole purpose of irrigation was to increase crop production are long gone. Farmers are under increasing pressure to specifically prevent the degradation of water resources, and above that, they need to produce higher yields with less water (Hillel and Vlek, 2005; Pott et al., 2009; Kijne, 2011). Advocates for a more sustainable irrigation sector, therefore, attempt to empower farmers and encourage them to continually evaluate and improve on-farm water and salt management (Kijne, 2006).

Research over the past few decades has contributed tremendously to the advancement of on-farm water and salt management (Oster and Wichelns, 2003; Hillel and Vlek, 2005; Kijne, 2006; Kijne, 2011). Scientist have learned, for example, how to utilize rainfall and shallow water tables as a water source for crop water requirements, which would otherwise be lost (Ayars et al., 2006; Jhorar et al., 2009; Isidoro and Grattan, 2011; Singh, 2013). Theory and practices for the reduction of drainage water and subsequent use for crop production is better understood than ever before (Rhoades et al., 1992; Singh, 2004; Malash et al., 2005; Sharma and Minhas, 2005). Advances in soil water measuring technology has made soil water monitoring convenient and affordable for farmers and service providers (Van der Westhuizen and Van Rensburg, 2011), which is a breakthrough in irrigation scheduling (Van Rensburg, 2010; Annandale et al., 2011).

Despite this tremendous progress, excessive drainage, leaching, soil salinization and water logging still occur and even expand annually in irrigation schemes over the world (Heuperman et al., 2002). This is also the case in central South Africa, within the Vaalharts and Orange-Riet Irrigation Schemes which cover 34 000 and 15 000 ha, respectively. Both these schemes are half a century old. Vaalharts on the one hand has an extensive, permanent shallow water table (Verwey and Vermeulen, 2011), while Orange-Riet experiences periodic episodes of shallow water tables (Van Dyk et al., 1997). Given that, 50% of the soils irrigated in Vaalharts are artificially drained and 70% under center pivot irrigation systems, farmers in this region should have a good control over water and salt management. The latest generation of center pivots can apply the desired amount of water uniformly over a field, at the precise time, with the smallest amount of non-beneficial water consumption (Reinders et al., 2010). Against this background, an investigation was conducted to determine how farmers managed their irrigation and the impact thereof.

This study focused, therefore, on how farmers with the latest generation of center pivots managed water and salt in soils with water tables within or just below the potential root zone. Sound decisions on when and how much to irrigate should, however, be based on scientific knowledge and measurements (scientific or objective scheduling), as opposed to decisions based on intuition (subjective scheduling). The objective was to determine on-farm water and salt management practices of two farmers in central South Africa. Their practices were evaluated with regard to water conservation by using rainfall and shallow water tables as sources, minimization of irrigation-induced drainage, leaching and salt additions, as well as management of plant available water to maintain optimum yields. This was done to investigate the associated benefits of objective scheduling compared to subjective scheduling under water table conditions, because 80% of South African (Stevens et al., 2005) and 67% of Australian (Montagu and Stirzaker, 2008) irrigators do not use scientific irrigation scheduling.

5.2 Methodology

The water and salt balances of two irrigated fields during four growing seasons as influenced by different irrigation scheduling scenarios were compared. The objective scheduling method represented a popular approach where soil water content was measured weekly with capacitance probes (WIN) installed to a depth of 600 mm. Irrigations were calculated as the deficit between these measurements and a predetermined drained upper limited. With the subjective scheduling method irrigation was based entirely on intuition and experience, hence no technology was introduced to facilitate the decisions on when and how much to irrigate.

5.2.1 Location and description of fields

The research was conducted in the central part of South Africa on two farms of which one was located within the Orange-Riet and the other within the Vaalharts Irrigation Scheme (Fig. 5.1). Orange-Riet is situated between the Orange River and the Riet River in the Free State, with a small area in the Northern Cape (Fig. 5.2). North of Orange-Riet and situated between the Harts River and the Vaal River in the Northern Cape lies Vaalharts (Fig. 5.2). Orange-Riet and Vaalharts have a semi-arid climate, i.e. rainfall is 397 and 427 mm per year respectively, and the atmospheric evaporative demand of 1740 and 1647 mm respectively (Van Rensburg et al., 2012). Rainfall mainly occurs in the form of thundershowers 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. Fig. 5.3 shows the two irrigated fields where the subjective (field 1) and objective (field 2) scheduling methods were applied. Field 1 consisted of a 30 ha center pivot located at Orange-Riet and field 2 of a 50 ha center pivot located at Vaalharts.

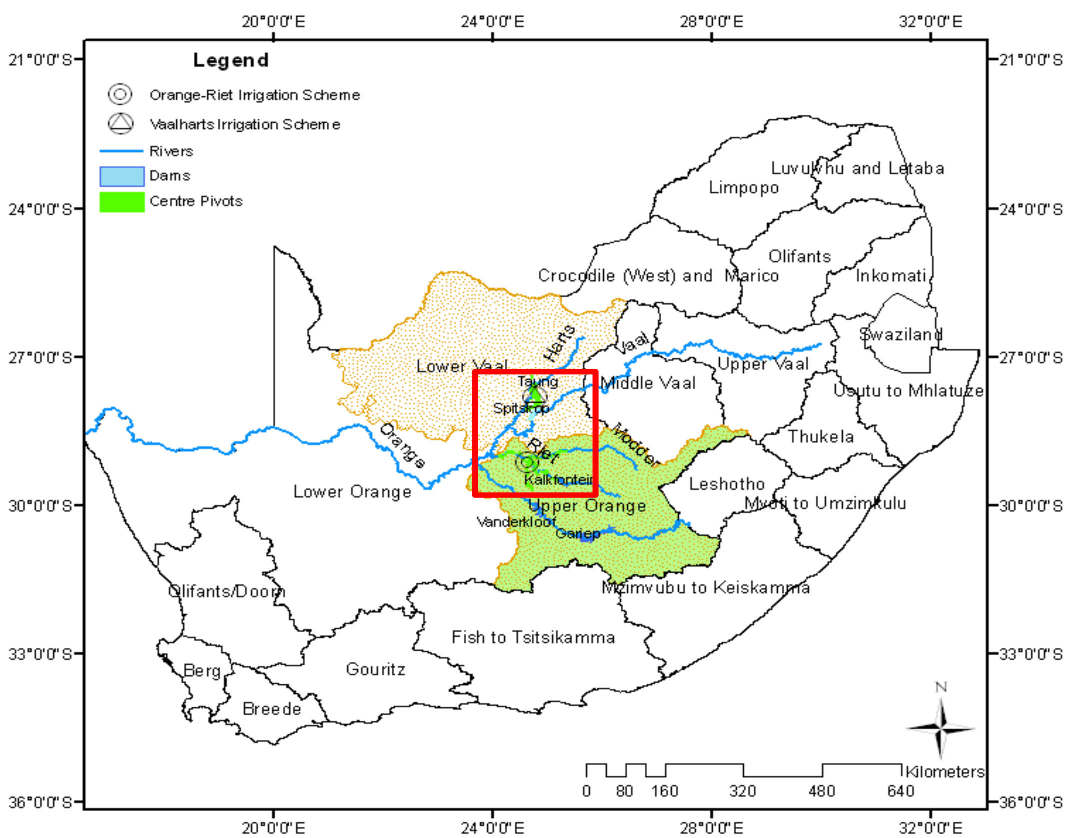


Fig. 5.1 Geographical position of the Orange-Riet and Vaalharts Irrigation Schemes and catchment water management areas in South Africa.

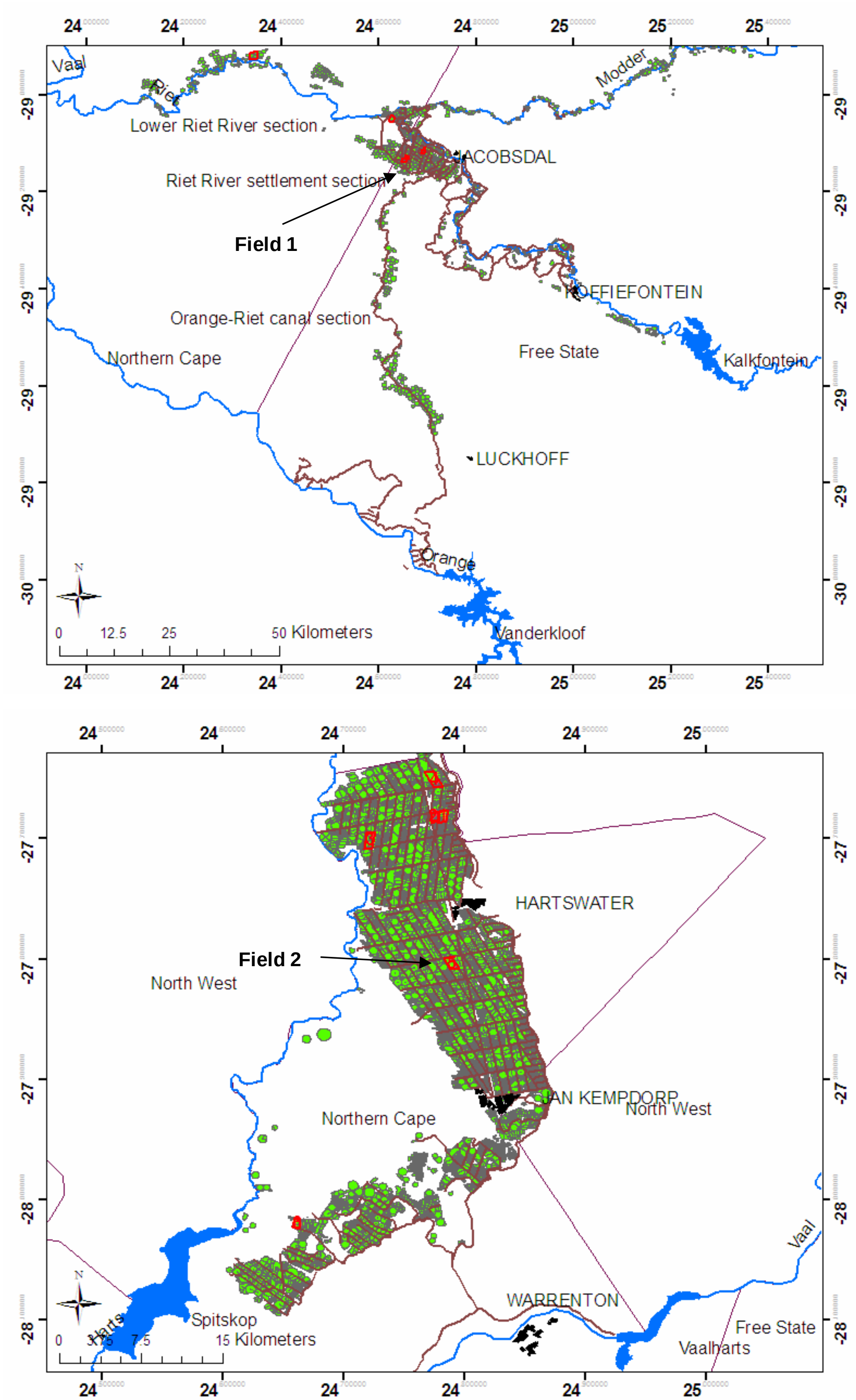


Fig. 5.2 Geographical position of field 1 and field 2 at the Settlement section and the F-block section of the Orange-Riet and Vaalharts Irrigation Schemes, respectively.

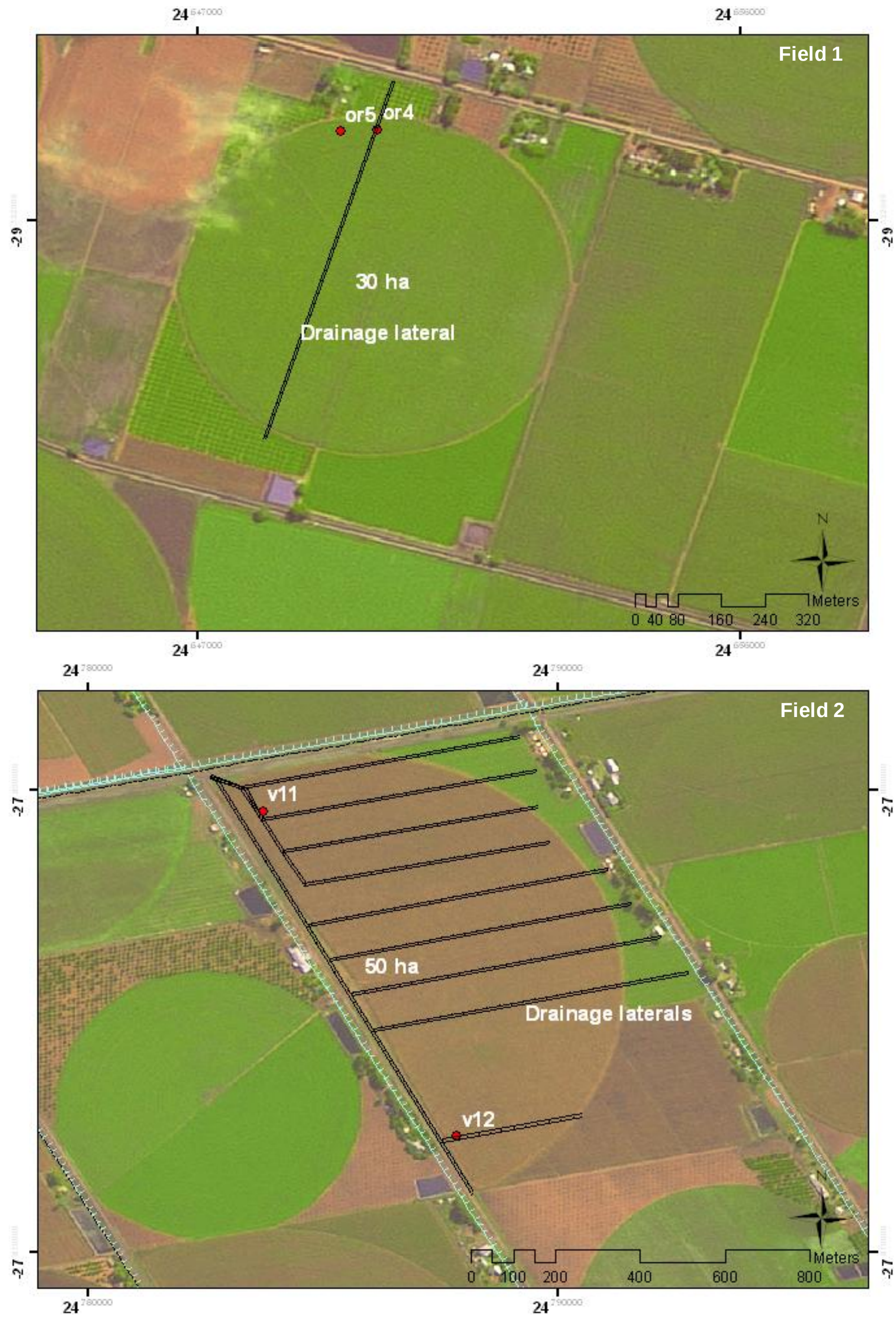


Fig. 5.3 Location of measuring points or4 and or5 at field 1 (representing subjective irrigation scheduling) and v11 and v12 at field 2 (representing objective irrigation scheduling), within the Orange-Riet and Vaalharts Irrigation Schemes, respectively.

The soil of field 1 comprises aeolian sandy deposit on lime and was classified as a Hutton form and Ventersdorp family (Soil Classification Working Group 1991). The A and B1 horizons fall in the fine sandy textural class and the B2 and C horizons in the fine loamy sand textural class, all exhibiting an apedal massive structure. This soil has a water table that fluctuates between 1600 and 1900 mm. The soil of field 2 is for all practical purposes the same as the one of field 1. The only difference is 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 form and Roodeplaat family (Soil Classification Working Group 1991). The internal drainage system at field 1 consisted of a single 650 m long lateral, installed at a depth of 1800 mm through the middle of the field, in order to remove sub-surface drainage water. This lateral was 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 water logging (Fig. 5.3). In contrast to field 1, field 2 was completely drained and the internal drainage system was already installed when the farm was purchased.

5.2.2 Agronomic practices

The farmer at field 1 followed a winter wheat- summer maize crop rotation during the measuring period of two years, while the farmer at field 2 also used a wheat-maize crop rotation during the first year, followed by a barley-maize cycle during the second year. A slight reduction in wheat yield during the first year at field 2 was attributed to infection by 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 agronomic practices for the two fields are summarized in Table 5.1. These practices are conventional for the two irrigation schemes where two cereal crops are planted annually. Conventional land preparation practices were followed, which consisted of burning or baling and removing the crop residue, followed by a disk and/or mould board plough, and/or deep ripping before planting.

5.2.3 Data acquisition

Two measuring points, or4 and or5 in field 1 and v11 and v12 in field 2, each with dimensions of 4 m x 4 m were set up per crop field (Fig. 5.3). Two neutron access tubes (2000 mm long), one observation well (perforated 63 mm PVC tubes and 3000 mm deep) and a rain gauge were installed at each measuring point.

Table 5.1 Summary of agronomic practices followed during the four cropping seasons at field 1 (or4 and or5) and field 2 (v11 and v12)

Field 1

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

Field 2

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

Weekly measurements consisted of rainfall (R, mm), irrigation (I, mm), soil water content (W_{Soil}, mm), water table depth (Z_{WT}, mm), artificial drainage (AD, mm), electrical conductivity of the irrigation water (EC_I, mS m^{-1}), water table (EC_{WT}, mS m^{-1}) and drainage water (EC_{AD}, mS m^{-1}). R and I were measured with rain gauges placed on the soil surface. An area of 6 m^2 was cleared around each rain gauge, which was placed several meters from where the soil water content was measured, to prevent crop interference.

W_{Soil} was measured with a calibrated neutron probe. Z_{WT} was measured manually by using an electronic device and AD, the discharge rate from the drainage tube with a bucket and stop watch, which was converted to mm AD by taking the area that was drained into account. EC_I, EC_{WT} and EC_{AD} were measured with a calibrated handheld Ecoscan (Con6) Electrical Conductivity Meter.

At every measuring point, subsamples of the unsaturated soil above the water table were taken per 300 mm depth interval at the start and end of each growing season, using a 75 mm diameter auger. These samples were dried at 40°C, passed through a 2 mm sieve, and then thoroughly mixed to prepare representative samples for the determination of electrical conductivity of a saturated extract (EC_e, mS m^{-1}) with a standard procedure (The Non-Affiliated Soil Analysis Work Committee, 1990). The different crops within the experimental area were harvested at maturity from a 16 m^2 area, dried, weighed and threshed to determine the seed mass and total above-ground biomass.

The efficiency of each center pivot was evaluated by placing 30 rain gauges evenly apart. The amount of irrigation water in the rain gauges was determined at a low (20%) and high (100%) speed. The Heermann and Hein uniformity coefficient (CU_H, %) and distribution uniformity (DU_{lg}, %) were calculated with Eq. (5.1) and Eq. (5.2), respectively, where R_i is the distance (m) of rain gauge at point i from the center, y_i the application depth (mm) at point i as collected in the rain gauge, y_g the weighted average application of the total system (mm), and A the weighted average application of the lowest 25%. In addition, the application efficiency (AE, mm) and system efficiency (SE, mm) were calculated with Eq. (5.3) and Eq. (5.4) respectively, where GA is the gross application (mm), Q the center pivot flow rate (m^3 $hour^{-1}$), t the rotation time (hours) and A the total wetted area of center pivot (ha).

$$CU_H = 100\left(1 \frac{\Sigma y_i - y_g}{R_i y_i}\right) \tag{5.1}$$

$$DU_{Ig} = \frac{A}{y_g}100 \tag{5.2}$$

$$AE = \frac{y_g}{GA}100 \quad where \;\; GA = \frac{Qt}{10A} \tag{5.3}$$

$$SE = \frac{AE \quad DU_{Ig}}{100} \tag{5.4}$$

5.2.4 Solving the soil water and salt balance

To solve the water balance of the potential root zone (prz) at each measuring point under fluctuating water table conditions, the approach as described in Chapter 3 was used (Eq. (5.5) or Eq. (5.6)). With this approach field measurements (m) of ΔW_{Soil}, R, I and AD were combined with simulations (s) of evaporation (E, mm), transpiration (T, mm), percolation (P, mm) and water table uptake (WTU, mm) to calculate the net amount of water entering (+D, mm) or leaving (-D, mm) the potential root zone through the saturated zone just below the water table, where arz is the actual root zone (Eq. (5.7)). The calibrated and validated SWAMP model (Chapter 3 and Chapter 4) was used for the simulations. Table 5.2 provides the input variables that were used at field 1 and field 2.

The same approach was used to solve the salt balance of the potential root zone (Eq. (5.8) or Eq. (5.9)), where S represents the salt content (kg ha^{-1}) of the specific component and F the net amount of salts remaining in the soil from fertilizer application; the amount removed by the crop yield was subtracted from the total amount applied (Van Rensburg et al., 2012).

$$\pm D_{(c)} = WTU_{(s)} - P_{(s)} + AD_{(m)} - \Delta W_{prz(m)} - \Delta W_{arz(s)} \quad \text{where } Z_{WT} \text{ fluctuate} \tag{5.5}$$

$$\pm D_{(c)} = \Delta W_{prz\ (m)} - R_{(m)} - I_{(m)} + E_{(s)} + T_{(s)} + AD_{(m)} \tag{5.6}$$

$$\pm D_{(c)} = WTU_{(s)} - P_{(s)} + AD_{(m)} \quad \text{when } Z_{WT} \text{ remain constant}$$

$$\Delta W_{arz\ (s)} = R_{(m)} + I_{(m)} + WTU_{(s)} - E_{(s)} - T_{(s)} - P_{(s)} \tag{5.7}$$

$$S_{\pm D(c)} = S_{WTU(s)} - S_{P(s)} + S_{AD(m)} - \Delta S_{prz(m)} - \Delta S_{arz(s)} \quad \text{where } Z_{WT} \text{ fluctuate} \tag{5.8}$$

$$S_{\pm D(c)} = \Delta S_{prz(m)} - S_{R(m)} - S_{I(m)} - S_{F(s)} + S_{AD(m)} \tag{5.9}$$

$$S_{\pm D(c)} = S_{WTU(s)} - S_{P(s)} + S_{AD(m)} \quad \text{when } Z_{WT} \text{ remain constant}$$

$$\Delta S_{arz(s)} = S_{R(m)} + S_{I(m)} + S_{WTU(s)} + S_{F(s)} - S_{P(s)}$$

Table 5.2 Climate, crop, soil and water **i**nput variables used by the model SWAMP to simulate the soil water and salt balance at field 1 and field 2

Field 1: Subjective scheduling									
Measuring point		or4				or5			
		Wheat	Maize	Wheat	Maize	Wheat	Maize	Wheat	Maize
Climate	ET_o (mm day^{-1})	5.4	6.1	5.3	4.7	5.5	6	5.3	4.7
Crop	Planting date	Table 5.1							
	GSL (days)	148	131	148	131	148	131	148	131
	Yield (kg ha^{-1})	7334	15892	6172	16510	6400	14758	6178	18297
	HI	0.48	0.60	0.43	0.60	0.46	0.58	0.43	0.58
	AFA (kg ha^{-1})	Table 5.1							
Soil	*z (mm)	300							
	*S+C (%)	11							
	*θ (mm mm^{-1})	0.21	0.23	0.25	0.22	0.22	0.26	0.27	0.25
	*EC_e (mS m^{-1})	88	75	58	69	65	79	56	73
	Z_{WT} (mm)	1900	1895	1711	1895	1900	1663	1513	1788
	EC_{WT}, (mS m^{-1})	110	101	115	124	120	106	103	122
	DC	0.85	0.7	0.7	0.6	0.7	0.8	0.65	0.6
Water	R (mm)	Fig. 5.4							
	I (mm)								
	EC_I (mS m^{-1})	22	21	21	20	24	21	21	20
Field 2: Objective scheduling									
Measuring point		v11				v12			
		Wheat	Maize	Barley	Maize	Wheat	Maize	Barley	Maize
Climate	ET_o (mm day^{-1})	4.9	5.6	4.5	5.1	4.9	5.7	4.5	5.1
Crop	Planting date	Table 5.1							
	GSL (days)	145	131	145	131	148	131	147	131
	Yield (kg ha^{-1})	6549	13586	6134	12983	4927	13101	6025	11536
	HI	0.38	0.6	0.47	0.6	0.29	0.57	0.45	0.6
	AFA (kg ha^{-1})	Table 5.1							
Soil	*z (mm)	300							
	*S+C (%)	11							
	*θ (mm mm^{-1})	0.23	0.24	0.24	0.26	0.26	0.27	0.28	0.28
	*EC_e (mS m^{-1})	88	115	54	103	143	165	98	139
	Z_{WT} (mm)	1754	1494	1632	1516	1426	1185	1143	1142
	EC_{WT}, (mS m^{-1})	125	132	134	140	182	163	157	114
	DC	0.75	0.9	0.85	0.64	0.69	0.83	0.62	0.6
Water	R (mm)	Fig. 5.4							
	I (mm)								
	EC_I (mS m^{-1})	61	65	63	71	61	65	67	71

ETo = Mean atmospheric evaporative demand, GSL = growing season length, HI = harvest index, AFA = Amount of fertilizer applied, z = soil layer thickness, S+C = Silt-plus-clay fraction ((<0.05 mm) of each layer, θ = volumetric soil water content of each layer at the start of season, ECe = electrical conductivity of a saturated extract for every layer at the start, ZWT = mean water table depth during the season, ECWT = mean electrical conductivity of water table during the season, DC = distribution coefficient, R = rainfall, I = irrigation, ECI = Mean electrical conductivity of irrigation during the season, * = represents the mean value of the soil profile, although the value of each soil layer was used in SWAMP

5.3 Results and discussion

5.3.1 Irrigation system efficiency

The results of the different efficiency measurements for the center pivots at field 1 and field 2 are listed in Table 5.3. It was found that the irrigation uniformity of both center pivots was generally good (CU > 90%), but the center pivot at field 2 was less efficient. The type of sprinklers and the spacing of sprinklers were, therefore, sufficient to deliver the desired uniformity at both fields. However, according to the application efficiency the center pivot at field 2 was less efficient than the one at field 1 in applying the desired amount of water, probably because field 2 was 20 ha smaller than field 1. It is well established that the area covered by individual systems play a significant role in their efficiency. Overall, the risk for crop water stress due to poor irrigation water application at both fields was low, because the center pivots can apply between 11 and 14 mm day^{-1}. This is equal to or higher than the water use of any of the crops grown during the study. Both center pivots were, therefore, reasonably efficient in their application of water.

Table 5.3 Efficiency measurements of the centre pivot at field 1 and field 2

Centre pivot	Irrigation system efficiency (%)				Area (hectare)	Design application rate (mm day^{-1})
	CU	DUlq	AE	SE		
Field 1	90	87	94	81	30	14
Field 2	93	84	74	62	51	11

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

5.3.2 Water management

Weekly measurements of R, I, W_{Soil} and Z_{WT} at field 1 and field 2 during the four cropping seasons are given in Fig. 5.4. The seasonal soil water balances for the two fields are provided in Table 5.4. The rainfall characteristics at the two fields were typical of a semi-arid climate zone: unpredictable, erratic and poorly distributed. This wide variety of weather conditions presented, therefore, a challenge to the farmers in terms of their irrigation scheduling. At both fields irrigation was less during the summer months because of higher R (Fig. 5.4). In addition, at both fields water was applied according to the specific growth stage of the crop, hence water applications increased when the crops reached their peak water demand.

At field 1, R and I had very little influence on Z_{WT} because the water table depth remained relatively constant (± 1800 mm). The water table was, therefore, deep enough to ensure sufficient storage in the unsaturated zone for R and I, or lateral movement of water from the saturated zone and artificial drainage was sufficient to remove excess water. During the early part of the second wheat season, the water table level increased sharply to 1500 mm, because of high rainfall (115 mm) that fell during the drying phase of the maize during the first season when ET was low. The slight delay in response of the water table level was probably due to lateral inflow of water in the saturated zone from higher lying fields that received the same amount of rain.

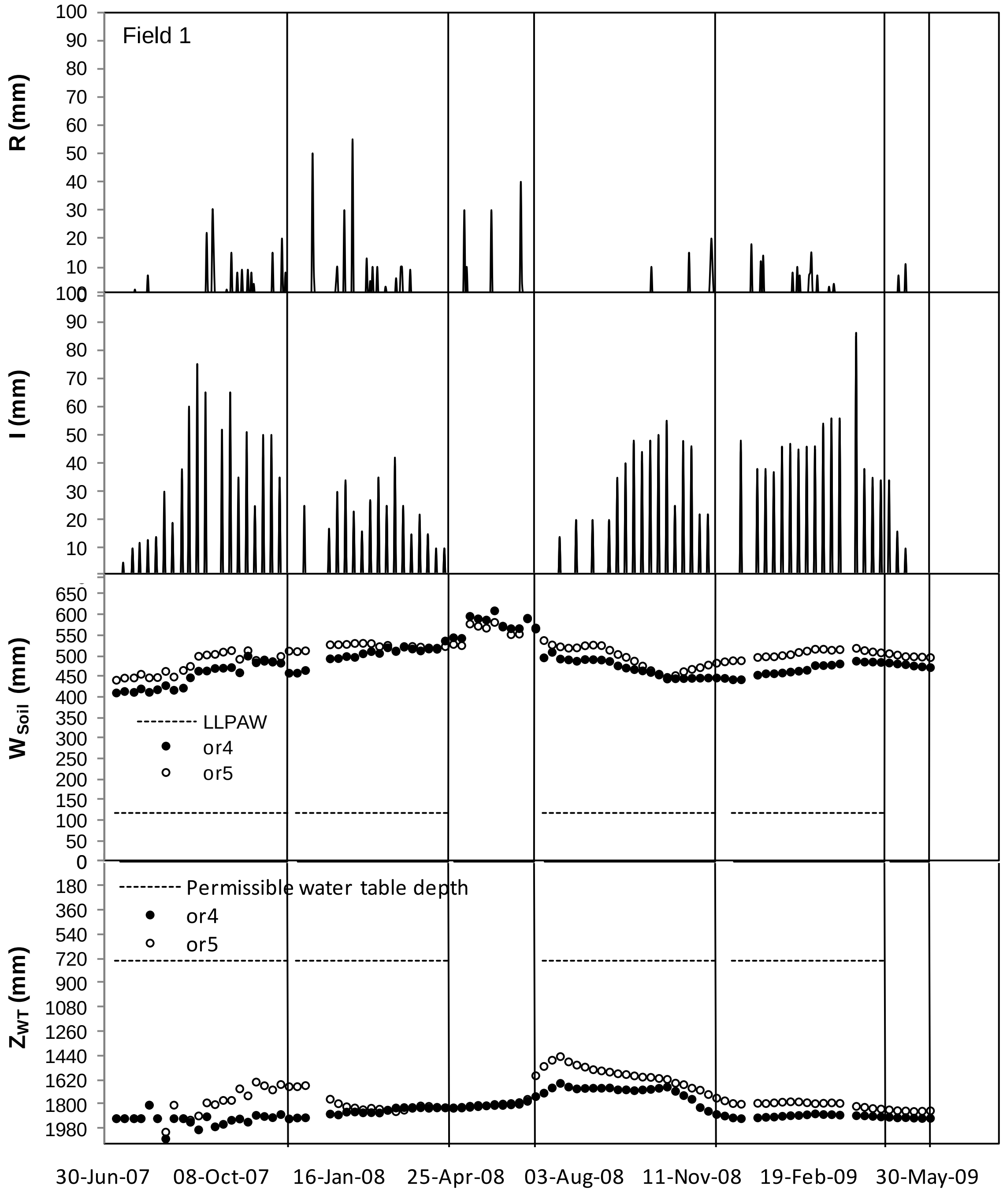


Fig. 5.4 Rainfall (R), irrigation (I), soil water content of a 2000 mm profile (W_{Soil}) and water table depth (Z_{WT}) for the measuring points at field 1 (or4 and or5) and field 2 (v11 and v12), together with the lower limit of plant available water (LLPAW) and permissible water table depth.

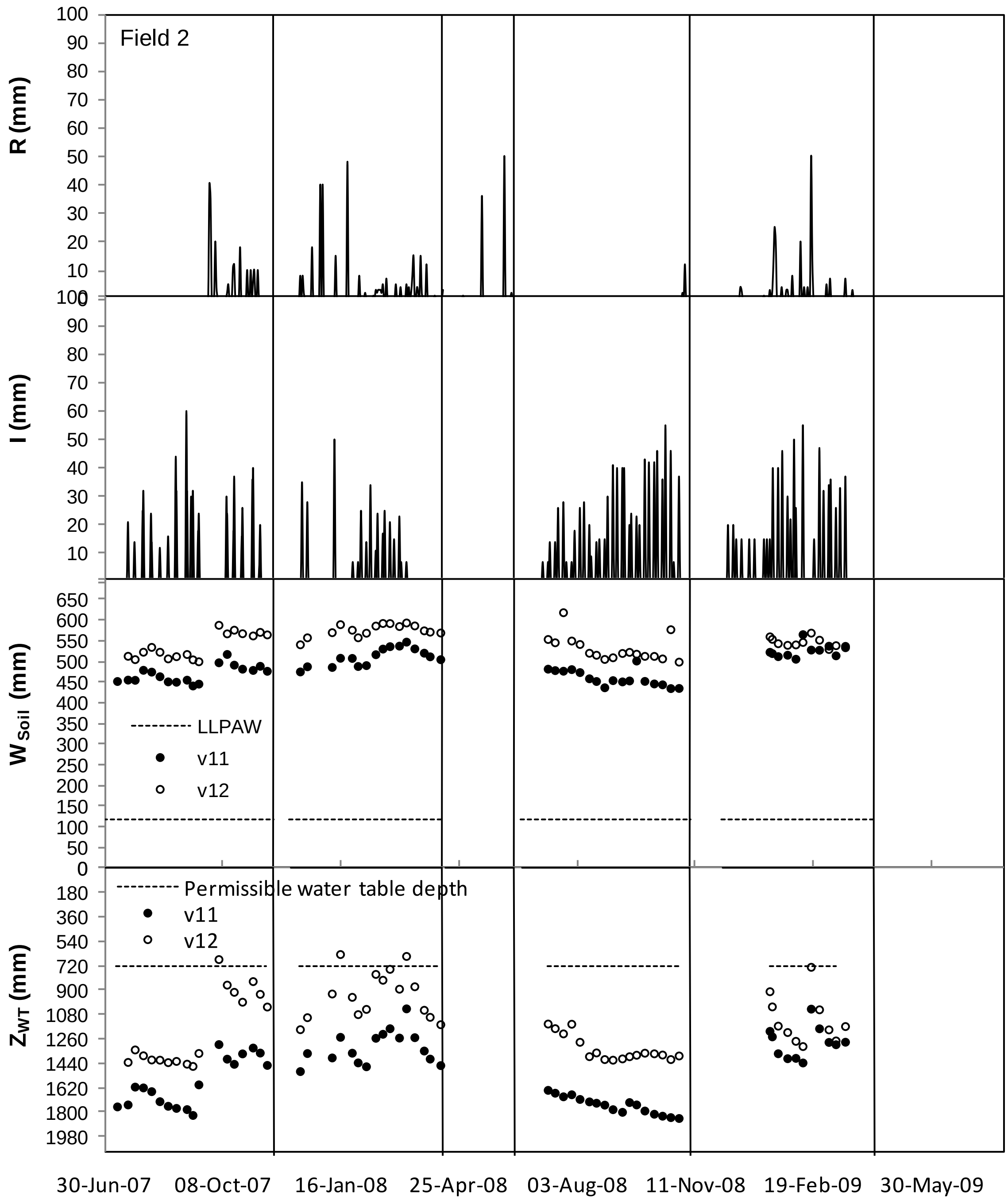


Fig. 5.4 continue

At field 2, high R and I events during the four cropping seasons correlated well with sharp increases in the level of the water table, because the water table was much shallower at field 2 compared to field 1. Storage by the unsaturated layer above the capillary fringe for R and I was less compared to field 1.

Table 5.4 Net gain (+D) or loss (-D) of water from the potential root zone (prz) through the saturated zone as calculated (c) from the measured (m) change in soil water content (ΔW) of the potential root zone, rainfall (R), irrigation (I) and artificial drainage (AD) together with simulations (s) of evaporation (E), transpiration (T), water table uptake (WTU) and percolation (P)

Crop	Measuring point	$\Delta W_{(prz)}$	$R_{(m)}$	$I_{(m)}$	$E_{(s)}$	$T_{(s)}$	$ET_{(s)}$	$AD_{(m)}$	$\pm D_{(c)}$	$WT_{Uptake\,(s)}$	$P_{(s)}$
		mm									
Field 1: Subjective scheduling											
1st Wheat	or4	48	177	561	61	569	631	10	-50	198	289
	or5	71		578	80	521	601	10	-74	178	301
	Mean	59		570	71	545	616	10	-62	188	295
1st Maize	or4	78	262	359	34	708	742	22	+203	265	224
	or5	11		359	61	677	738	22	+153	321	224
	Mean	45		344	47	693	740	22	+178	293	224
1st Maize drying	or4	21	115	0	56	0	56	16	-22	0	115
	or5	40		0	49	0	49	16	-11	0	107
	Mean	31		0	52	0	52	16	-17	0	111
2nd Wheat	or4	-49	65	550	48	516	564	23	-77	251	333
	or5	-55		552	67	517	584	23	-72	320	383
	Mean	-52		551	58	516	574	23	-75	286	358
2nd Maize	or4	42	115	739	39	565	604	10	-198	203	456
	or5	19		733	53	647	700	10	-119	236	382
	Mean	31		736	46	606	652	10	-159	220	419
2nd Maize drying	or4	-11	18	26	29	0	29	3	-23	0	44
	or5	-9		56	35	0	35	3	-45	0	74
	Mean	-10		41	32	0	32	3	-34	0	59
Field 2: Objective scheduling											
Wheat	v11	25	193	362	53	573	625	68	163	229	193
	v12	52		321	51	565	615	67	220	355	284
	Mean	38		342	52	569	620	68	192	292	239
1st Maize	v11	30	313	178	48	566	614	141	292	357	244
	v12	29		172	49	581	630	141	318	451	308
	Mean	29		175	49	573	622	141	305	404	276
1st Maize drying	v11	-23	90	0	31	0	31	34	-48	0	73
	v12	-15		0	30	0	30	34	-41	0	83
	Mean	-19		0	30	0	30	34	-44	0	78
Barley	v11	-47	14	459	57	524	581	90	152	290	202
	v12	-55		428	63	408	472	90	65	318	302
	Mean	-51		444	60	466	526	90	109	304	252
2nd Maize	v11	14	205	375	37	488	525	132	93	315	406
	v12	-26		339	36	429	465	132	25	334	432
	Mean	-6		357	37	459	495	132	59	324	419

Just after these high R and I events, the water table depth dropped sharply again. This showed that the drainage system at field 2 is in good working condition, which together with lateral water outflow quickly removes excess water. In general, the water table at measuring point v11 was deeper during the measuring period. This was because there were fewer drainage laterals present at the southern part of the field, where v2 was located (Fig. 5.4).

It was found that with subjective scheduling R was not sufficiently incorporated as a source of water (Field 1). During three of the four cropping seasons more water were applied (R+I) than required by the crops (ET), i.e. 21, 7 and 31% during the first wheat, second wheat and second maize seasons, respectively. During the first maize season, 18% less R+I were applied than required by the crop. Thus, in total over the four cropping seasons when R+I was compared to ET an over-supply of 9% occurred. This over-supply resulted in 65 mm of artificial drainage and a net loss of 118 mm through lateral outflow through the saturated zone. It was also found that in general with the subjective scheduling method the saturated zone below the water table was not utilized as a source of water. Net lateral inflow of water from this zone into the potential root zone contributed 24% towards ET only during the first maize season.

With the objective scheduling method (Field 2), R was better incorporated into the schedule compared to subjective scheduling. During three of the four seasons less R+I was applied than ET. The deficits amounted to 85, 134 and 68 mm per season, respectively. The difference between R+I and ET were supplied by capillary rise in the soil profile. A respective net gain of water to the potential root zone through lateral movement of water in the saturated zone below the water table of 192, 305 and 109 mm per season was recorded (Table 5.4). With the objective scheduling method it was possible to conserve irrigation water by integrating rainfall intelligently, and also by using the water table as a source of water for crop water uptake.

5.3.3 Salt management

Fig. 5.5 shows the salt distribution within the soil profiles taken 5 times during the measuring period at fields 1 and 2. The seasonal salt balances of the two fields are given in Table 5.5. The comparison of EC_e values during the measuring period indicated no obvious accumulation of salt at either field. In addition, the salinity of the water table remained relatively constant. This showed that salt was sufficiently leached into the water table and removed laterally through water movement below the water table to lower lying fields and/or artificial drainage. In field 1 with subjective scheduling, there was a net loss of salt from the potential root zone during all the seasons, except the first maize season (226 kg ha^{-1}). The same trend was observed in field 2 with objective scheduling, where a net gain of salt occurred during the barley season (703 kg ha^{-1}). Thus, it is confirmed that the water table was not a significant source of salt, but acted as a sink. The major sources of salt in the potential root zone were fertilizers and irrigation water, i.e. 5238 and 8084 kg ha^{-1} in total for field 1 and field 2 over the four cropping seasons, respectively.

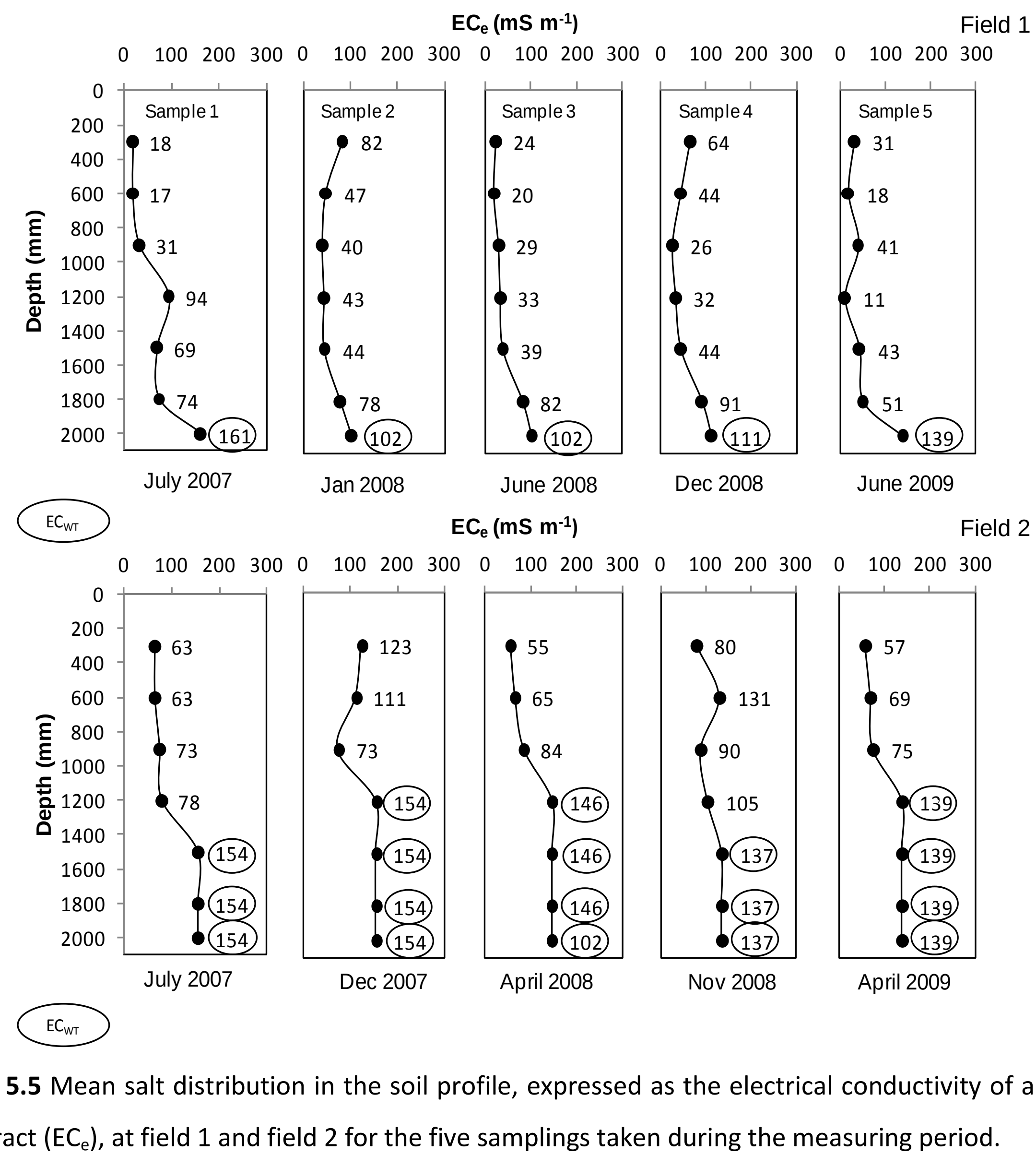


Fig. 5.5 Mean salt distribution in the soil profile, expressed as the electrical conductivity of a saturated extract (EC_e), at field 1 and field 2 for the five samplings taken during the measuring period.

Table 5.5 Net gain (+S_D) or loss (-S_D) of salt from the potential root zone (prz) through the saturated zone as calculated (c) from the measured (m) change in salt content (ΔS) of the potential root zone, salt added through rainfall (S_R) and irrigation (S_I) and salt last through artificial drainage (S_{AD}) together with simulations of upward salt flow through capillary rise (S_{WTU}) and downward salt leaching through percolation (S_P)

Field 1: Subjective scheduling									
Crop	Measuring point	kg ha^{-1}							
		$\Delta S_{(prz)}$	$S_{F\,(s)}$	$S_{R\,(m)}$	$S_{I\,(m)}$	$S_{AD\,(m)}$	$\pm S_{D\,(c)}$	$S_{WTU\,(s)}$	$S_{P\,(s)}$
1st Wheat	or4	-781	387	27	926	87	-2034	1633	3753
	or5	607			1040	87	-760	1599	2446
	Mean	-87			983	87	-1397	1616	3100
1st Maize	or4	1151	448	39	565	225	324	2004	1953
	or5	955			565	225	128	2552	2649
	Mean	1053			565	225	226	2278	2301
1st Maize drying	or4	-1730	0	17	0	154	-1593	0	1747
	or5	-1841			0	154	-1704	0	1858
	Mean	-1786			0	154	-1649	0	1803
2nd Wheat	or4	281	286	11	866	223	-659	2161	3042
	or5	672			869	223	-271	2470	2964
	Mean	477			867	223	-464	2316	3003
2nd Maize	or4	186	419	17	1109	96	-1263	1887	3246
	or5	108			1100	96	-1332	2157	3585
	Mean	147			1104	96	-1297	2022	3415
2nd Maize drying	or4	-225	0	3	41	29	-240	0	268
	or5	-514			88	29	-576	0	605
	Mean	-370			65	29	-409	0	437
Field 2: Objective scheduling									
1st Wheat	v11	1437	419	29	1656	728	60	2147	2814
	v12	1168			1469	715	-34	4850	5599
	Mean	1302			1562	722	13	3498	4206
1st Maize	v11	-121	419	47	868	1465	10	3534	4989
	v12	-1259			839	1465	-1098	5517	8080
	Mean	-690			853	1465	-545	4525	6534
1st Maize drying	v11	-2205	0	14	0	461	-1758	0	2219
	v12	-1988			0	461	-1540	0	2001
	Mean	-2097			0	461	-1649	0	2110
Barley	v11	2442	286	2	2169	947	933	2918	2932
	v12	1965			2151	947	504	3774	4217
	Mean	2204			2160	947	703	3331	3575
2nd Maize	v11	216	362	30	1997	1388	-786	3304	5477
	v12	-844			1805	1388	-1655	2853	5896
	Mean	-314			1901	1388	-1221	3078	5686

Of this, fertilizers added 29 and 23%, respectively, and irrigation 68 and 80%, respectively. The higher salt additions at field 2 was because poorer quality water was used compared to field 1, viz. 21 and 68 mS m^{-1} for field 1 and field 2, respectively.

If it is assumed that at both fields the salinity of the irrigation water was 68 mS m^{-1}, then the more accurate objective scheduling method reduced salt additions by 4749 kg ha^{-1} over the four cropping seasons compared to the subjective scheduling method, which resulted in over-irrigation. Care should, therefore, be taken to apply more accurate irrigation scheduling technology with poorer quality irrigation water.

With over-irrigation by the subjective scheduling method, approximately 10% more salt was removed from the potential root zone than added, implying that the soil quality had improved over the measuring period (Fig. 5.5). There was a slight build-up of salts in the profile, about 5% of the total salt additions where the more accurate objective scheduling method was used. However, with neither scheduling methods there was any risk of impairing crop growth due to salinity. Soil salinity was actually very low for both scheduling methods and a considerable amount of salt was discharged to lower lying areas. At field 1, 16% of the total salt added was removed by artificial drainage, while the rest (84%) drained laterally to lower lying fields. For field 2 this amounted to 62% and 33%, respectively. This way of salt leaching was the subject of many research projects conducted in the two irrigation schemes (Du Preez et al., 2000; Viljoen et al., 2006; Van Rensburg et al., 2012).

5.3.4 Synopsis of applied management practices

The mean water use efficiency for both fields was above 9, 13 and 23 kg grain ha^{-1} mm^{-1} water applied for wheat, barley and maize, respectively. This can be expected due to the design and ease of management of the center pivot irrigation systems (Reinders et al., 2010) and its direct impact on avoiding crop water stress, because the design application exceeds the water requirements of most crops at any specific time. Yields cannot be used as a sole indicator to assess the sustainability of irrigation practices. All water and salt gains and losses need to be considered during the evaluation (Hillel, 2004). When this was done for the two irrigation-scheduling strategies, the associated benefits of more accurate scheduling in terms of water and salt management were substantial.

The more accurate objective scheduling conserved 20% more water over the four cropping seasons compared to subjective scheduling. This was possible because rainfall and capillary influx from the water table were better incorporated as sources of water for crop water requirements. Thus, drainage from the potential root zone, which led to lateral water movement to lower lying fields and/or artificial drains, was 417 mm less over the four cropping seasons when compared with the subjective scheduling. With objective scheduling soil water content can be measured on an hourly basis. Hence, prior to irrigation the deficit to fill the soil profile to the drained upper limit minus rainfall storage can be calculated and irrigations adjusted accordingly. The capillary contribution from a shallow water table can also be taken into account, which can be simulated with SWAMP amongst other models. Unfortunately at field 2 the farmer monitored soil water content only in the top 600 mm or 30% of the root zone while the water table oscillated beyond this depth during the four cropping seasons. The results showed that the total inflow (621 mm) of water into the potential root zone through lateral movement of water in the saturated zone below the water table, expressed as a percentage of evapotranspiration (2293 mm), amounted to a total of 27% over the four cropping seasons. This is an indication of the water tables contribution to the water requirements of the four crops. According to Ehlers et al., (2003) and Ayars et al., (2006), the water table can supply up to 60% of crop water requirements. Thus, irrigations could have been reduced further by forcing the crop to use more water from the shallow water table. In practice, this means that farmers should use longer probes for measuring soil water content, or the probes should be used in conjunction with water table observation wells installed at critical points in the field, in order to improve irrigation scheduling and adjust the amount of water that is applied.

The benefit of more accurate objective irrigation scheduling in terms of reducing salt addition and leaching was substantial, i.e. over four cropping season's 4749 kg ha^{-1} less salt was added, while 15% less salt were removed from the potential root zone. Although less compared to over-irrigation by the subjective scheduling, leaching was unfortunately still substantial when objective scheduling was used (95% of total salt additions). This phenomenon was ascribed to the presence of a water table within or just below the root zone that changes the hydraulic properties of the soil. Water drains much faster through the capillary zone above the water table (Ehlers et al., 2003). Hence, storage for soil water in this nearly saturated capillary zone is limited due to the shallow water table depth (1400 mm). Under these conditions leaching into the water table occurs frequently when irrigation and/or rainfall exceeds the available storage. The artificial drains and water tables are linked to rivers (Ellington et al., 2004), which mean users downstream are the recipients of the salt. Thus, discharge of salt from the potential root zone needs to be managed in a sustainable way. At both fields the low salt content of the soil is an indication of effective (even excessive) leaching. General recommendations are that periodic leaching should be applied the threshold salinity of the crop is reached, because the efficiency of leaching (mm drainage per kg salt removed) will improve with increasing soil salinity (Monteleone et al., 2004; Barnard et al., 2010). It is anticipated that in these shallow water table soils irrigation can be significantly reduced to decrease leaching. Because storage for soil water is limited in these soils, rain events above 40 mm will contribute significantly to salt leaching. 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.

5.4 Conclusions

In this paper, an investigation was conducted on how farmers with the latest generation of center pivot irrigation systems managed water and salt in soils with shallow water tables in or just below the potential rooting depth. A water and salt balance approach was used to evaluate subjective and objective scheduling methods in two fields (central South Africa) for four cropping seasons.

It was concluded that irrespective of the scheduling method for center pivot use, farmers obtained comparable yields at both fields. The center pivots allowed the farmers to irrigate more accurately by controlling the amount of water applied and intervals between irrigations. Crop water stress was, therefore, prevented apparently detracting from the merits of irrigation scheduling. Shallow water tables that were present within or just below the potential root zone contributed considerable towards crop water uptake. Water and salt balance estimations over the potential rooting depth of 2000 mm showed that it was possible to conserve in excess of 20% irrigation water using scientific based, objective scheduling, compared to intuitive, subjective scheduling, consequently also reducing salt additions. Despite applying less irrigation with objective scheduling, almost all of the applied salt was still leached into the water table. The salts that were leached into the water table was partly removed by artificial drains and discharged into rivers. It was determined that the water in the saturated zone below the water table level, at both fields, were not stagnant but drained laterally or downwards towards lower lying areas. This lateral flux of water through the saturated zone was responsible for the removal of the rest of the salts. The continuous removal of salt is generally not considered good practice, because ideally salt should be accumulated and periodically leached during high rainfall events and/or fallow periods. The results also suggest that it will be worthwhile for farmers to invest in long soil water monitoring probes (at least 1500 mm) to take the capillary contribution from the water table into account. Furthermore, models like SWAMP can be used to determine the contribution from water tables to crop water requirements, which can be subtracted from irrigation requirements.

Although both scheduling approaches resulted in similar yields, better on-farm water and salt management is possible by monitoring the soil water deficit and irrigating accordingly. It would also be advisable to manage the plant available water deficit of the root zone of deep soils as such to make provision for rain that falls within two to three days after an irrigation thereby creating a rain storage capacity equivalent to 2-3 days crop water use. In doing so, farmers can address the environmental problems associated with irrigation, i.e. degradation of water resources, and produce similar yields as with subjective scheduling methods but with less water.

CHAPTER 6
SUMMARY AND RECOMMENDATIONS

6.1 Introduction

In the past irrigation farmers have played a key role in feeding South Africa and are expected to play a still greater role in future. This is because 30% of the country's food is produced on 1.5% of the cultivated land using 63% of the available surface water, with limited potential for expansion in terms of land and water availability. However, although irrigation is associated with increased crop production, which results in lower food prices, higher employment and more rapid agricultural and economical development, like most technologies it has a down side as well, i.e. soil and water salinization. Similar to most large irrigation regions throughout the world this salinization is a major obstacle for farmers in the Orange-Riet and Vaalharts Irrigation Schemes. To ensure sustainable production in the region, salt concentrations in the root zone must be managed within limits that will not significantly influence crop growth and yield as well as degrade soils and water resources, due to the migration of salts through lateral water table movement and/or drainage effluents. Water and salt management under water table conditions by farmers at Orange-Riet and Vaalharts must, therefore, be evaluated and/or improved on a continuous basis.

The aim of this study was, therefore, to understand the dynamics of water and salt flow through water table soils in the region as influenced by water and salt management practices. This would assist farmers and policy makers towards improved water and salt management and help to reduce crop failure and environmental degradation.

To accomplish this aim the approach was to synthesize current knowledge on how to manage the salt load associated with irrigation at farm level in order to formulate best water and salt management practices. Some of these practices were then evaluated on a case study basis at two farms located in the region by comparing them to current water and salt management practices. Evaluating water and salt management under fluctuating water table conditions in the field without the aid of mathematical models is, however, difficult. This is because of the difficulty to quantify water and salt transport in water table soils and the subsequent effect of matric and osmotic stress on crop growth and yield as influenced by rainfall, irrigation, evaporation, transpiration, capillary rise, lateral water table movement and artificial drainage. From the multitude of available models it was decided to use the **S**oil **W**ater

Management **P**rogram, SWAMP, which together with the research approach led to the following research questions.

i) Which strategies are suggested in the literature to manage the salt load associated with irrigation at farm level?
ii) How credible is the model SWAMP when used to assess current water management practices under water table conditions by farmers in semi-arid regions?
iii) Will the model SWAMP be able to simulate salt flow in water table soils and the subsequent effect of osmotic stress on water uptake and yield satisfactorily?
iv) Do farmers with the latest generation of centre pivots employ best water and salt management practices in water table soils, using different irrigation scheduling approaches?

In this chapter the findings of the previous chapters are summarized to address the research questions and present the recommendations.

6.2 Summary

6.2.1 Research question I

From the literature that was consulted in Chapter 2 it was evident that an integrated holistic approach is needed to conserve water, prevent soil salinization and water logging and to protect the environment and ecology. It was found that ultimately the different irrigation, drainage and salinity/sodicity strategies can be encapsulated by the following best on-farm water and salt management practices:

- Selection of crops with salt tolerances adapted to the situation.
  Purpose: To enhance crop production and ensure optimal water use.
- The use of efficient irrigation systems and irrigation scheduling aimed at minimizing water application and reducing deep percolation.
  Purpose: Even distribution of water over fields to avoid unnecessary deep percolation in patches receiving over-irrigation. By minimizing the amount of applied water less salts are added to the root zone. Proper irrigation scheduling should reduce deep percolation and thus drainage outflow. A disadvantage of this practice is that gradual salt accumulation will take place in the root zone during periods of low rainfall.

- On-farm interception, isolation and reuse of unavoidable drainage water by irrigating a succession of crops with increasing salt tolerances.

  Purpose: Drainage water still contains water that can be used for crop production. The rationale behind this practice is to consume most of the water, not adsorbed by salt ions (hydration), to produce crops. It can be adopted during drought periods with a restriction on water supply, or on a continuous basis by cultivating a succession of crops with increasing salt tolerances. Another option is to irrigate with high quality irrigation water early in the growing season to ensure good emergence and initial crop establishment, and to change to irrigating with drainage water later in the growing season when the crop is more tolerant.
- Utilization of shallow water tables to supplement the crop water requirement and reduce the irrigation requirement.

  Purpose: Shallow water tables, within or just below the potential rooting depth, can contribute between 30 and 60% towards the crop water demand, depending on the depth of the water table, crop and soil type. In such cases less irrigation and hence salts will be added to the root zone.
- Monitoring the root zone salinity in order to decide when to apply controlled leaching for removal of the excess salts by drainage or when to employ chemical or bioremediation.

  Purpose: Implementation of the above mentioned practices all have the inherent danger of gradual salinization of the root zone when periods of low rainfall, especially in arid climates, generate insufficient leaching of salts. Under these conditions controlled leaching of salts from the root zone becomes necessary through over-irrigation.

6.2.2 Research question II

Mathematical models are invaluable tools for irrigation farmers in semi-arid regions to assess and/or improve their water management practices under water table conditions. The application of complex numerical models remains a challenge, because determination of input variables and model parameters are tedious and complicated. Thus, the credibility of SWAMP to assess on-farm management practices was investigated in Chapter 3. This was done by determining how accurately SWAMP simulates water use of field crops from shallow water tables and how the model can be applied to assess current water management practices by farmers, when model parameters were determined from easily measured input variables. Hence, no calibration of model parameters was done.

To accomplish the objectives two data sets were used, i.e. data from a lysimeter experiment of Ehlers et al., (2007) and from a case study conducted on an irrigated field located within the Orange-Riet Irrigation Scheme.

SWAMP was evaluated with a fuzzy-logic based expert system, which aggregates various statistical metrics into a single indicator module (I_{SWAMP}) that represents the model's aggregated accuracy, correlation and pattern performance. According to I_{SWAMP} weekly evapotranspiration (I_{SWAMP} = 70%) and water tale uptake (I_{SWAMP} = 90%) of wheat, peas and maize grown on sand to sandy loam water table soils were simulated well. The success was attributed to the fact that the model parameters required by the various algorithms were accurately determined by SWAMP from easily measured input variables.

Because the osmotic potential at this stage cannot be considered by the model, SWAMP was only applied where the effect of irrigation and water table salinity on crop water use was negligible. Under these conditions field measurements were successfully combined with simulations by SWAMP to solve the soil water balance under fluctuating water table conditions at field level. Compared to studies where complex models were used this was achieved with easily obtainable input variables. The variables consists of planting date, length of growing season, seed yield, mean atmospheric evaporative demand, mean water table depth over the season, silt-plus-clay content and volumetric soil water content at the start of the season. SWAMP optimized, therefore, in situ field observations of rainfall, irrigation, fluctuation in water table depth, change in soil water content and artificial drainage, all of which are easily measured. This is vital considering that farmers cannot adopt alternative management practices if their current practices cannot be measured. Due to these strengths, i.e. user- and data-friendly, SWAMP should, therefore, be readily adopted by irrigation farmers and agricultural advisers to ensure efficient water use.

6.2.3 Research question III

Successful revision of on-farm water and salt management practices for subsequent improvement depends heavily on mathematical models that can simulate the dynamic response of crops to both water (matric) and osmotic stress. The determination of parameters for the water stress (matric and osmotic) response function, which models like SWAP, HYDRUS and SALTMED use to simulate macroscopic water uptake presents a challenge. As a solution to this problem a salinity subroutine for SWAMP was developed. This subroutine is introduced in Chapter 4. Adaptations to the models algorithms were made to simulate the upward and downward movement of salt in water table soils. In addition the function responsible for simulating the water supply rate of a specific soil layer, and hence matric stress, was adapted to also accommodate osmotic stress. These adaptations to SWAMP were evaluated by using data from a lysimeter trial of Ehlers et al., (2007). This was accomplished by comparing measured and simulated water uptake and yield of peas and maize, grown in saline sandy to sandy loam water table soils.

SWAMP successfully simulated the accumulation of salt within the root zone above the water table due to irrigation and capillary rise. This was done employing standard theory where whereby the evapotranspiration process acts as a semi-permeable membrane, leaving the salts behind in the soil. The corresponding reduction in crop yield of peas and maize was simulated successfully. The model was able to simulate reduced water uptake as a result of osmotic stress during the growing season and performed well regarding aggregated accuracy, correlation and pattern analysis; I_{SWAMP} was 75%.. Thus, SWAMP provides an alternative to the generally applied models that simulate solute transport in water table soils and the effect of salinity on water uptake and crop yield. No numerical parameters to solve the Richards and convection-dispersion equations for solute transport are required by SWAMP. In addition, parameters for the commonly employed piecewise linear and S-shaped functions to simulate water uptake under osmotic stress are not necessary. SWAMP will determine the model parameters that are required to simulate water uptake of peas and maize grown in sand to sandy loam water table soils under osmotic stress successfully from input variables.

6.2.4 Research question IV

In Orange-Riet and Vaalharts, like most of the irrigation schemes throughout the world, water and salt management need continuous evaluation at farm level in order to improve the sustainability of the irrigation sector. This is especially applicable to conditions where water tables are present within or just below the potential root zone. Thus, in Chapter 5 an investigation was conducted to determine how two farmers in this region, that use the latest generation of centre pivots, manage water and salt in water table soils. The soil water and salt balance of two irrigated fields (two different farmers) were quantified over four growing seasons with the help of SWAMP. The farmers used different irrigation scheduling methods, *viz.* an objective (scientific) and a subjective (intuition) scheduling method.

During the four cropping seasons it was found that both scheduling methods were efficient in converting irrigation water into yield. It seems, therefore, that both farmers, irrespective of their scheduling preferences, are schooled in irrigation scheduling with the aim of achieving high yields and applied water use efficiencies. This may appear to be confirmation of a general perception that objective scheduling is not superior to subjective scheduling. However, when all water and salt gains and losses were considered in the analysis the opposite conclusion was reached, i.e. objective scheduling saved 20% more water by better utilizing rainfall and the water table as sources of water for transpiration, compared to subjective scheduling. It was also found that with objective scheduling the farmer could have saved even more water if the soil water content of the deeper subsoil was monitored. The farmer measured only the top 600 mm of soil instead of at least 1500 mm.

The presence of a water table within or just below the potential root zone generally induced wetter conditions in the capillary zone, with limited storage capacity for rainfall and/or irrigation available above the capillary fringe. This caused uncontrolled drainage and leaching with both scheduling methods, although considerably more losses were experienced with subjective scheduling compared to objective scheduling. Thus, for farmers to address the environmental problems associated with water tables, i.e. uncontrolled leaching of salts, improved or appropriate objective scheduling methods are required in order to implement best on-farm water and salt management practices. Considering all water losses and gains it is clear that objective scheduling is superior to subjective scheduling.

6.3 Recommendations

The research findings are applicable to irrigated fields located in semi-arid regions where water tables, within or just below the potential root zone of sand to sandy loam soils, can flow laterally to lower lying fields and/or through artificial drainage systems. Where drainage and leaching of salt from the potential root zone are restricted by a stagnant water table care should be taken when interpreting the recommendations provided below.

6.3.1 Farmers

To manage water and salt under the above mentioned conditions farmers should use the most appropriate scientific (objective) scheduling method to determine the irrigation requirement, i.e. atmospheric-based quantification of evapotranspiration, soil water content measurement, crop-based monitoring and an integrated soil water balance approach. The latter class encompasses both real time and pre-programmed methods. Clearly no single method to suit 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 and fluctuations in water table depths.

Rainfall should be managed and taken into consideration by these objective scheduling methods. This can be done by not wetting the soil to the drained upper limit or by subtracting rain that fell during the previous irrigation cycle from the irrigation requirement of the present cycle. In addition water table uptake should be subtracted from the irrigation requirement. This can be determined with SWAMP or by measuring the soil water content of the entire potential root zone (2000 mm).

With these practices unnecessary drainage and leaching from irrigated fields will be reduced, without a significant danger of salt accumulating to levels that can harm most field crops. This is because it was shown that leaching as a result of high rainfall events is extremely effective in wet soils with shallow water tables. Once water table depths in these soils are below 2500 mm from the soil surface and/or when poorer irrigation water quality (>75 mS m^{-1}) are used, rainfall should not be taken into consideration when determining the irrigation requirement. This practice can be combined with irrigation induced leaching by multiplying the irrigation requirement with a leaching factor. It is generally suggested however that irrigation induced leaching should only be applied when salt accumulates to levels that will harm the crop.

It is recommended that farmers use the model SWAMP to plan and/or monitor their practices in order to implement these best water and salt management practices. Water and salt gains and losses to and from the potential root zone can be successfully quantified with limited climatic, soil, crop and water input variables as listed in Table 2.4. This is possible without the determination of unambiguous numerical model parameters and crop- and site-specific calibration exercises. When SWAMP is applied in conditions other than this, the determination and calibration of model parameters remains essential.

6.3.2 Agricultural advisors and managers

Decisions by agricultural advisors and managers of Water User Associations (WUA) on whether water is fit for irrigation use are generally based on the electrical conductivity (EC) of the water. From the findings of this study it is recommended that a more dynamic approach should be followed, where the water and salt management practices that are adopted by the farmer and the environmental factors affecting yield (different ecotopes) are taken into account. For example the United States Salinity laboratory Staff (1954) classifies water with an EC between 25 and 75 mS m^{-1} as medium salinity water (class C2), i.e. the water can be used if moderate amount of leaching occurs. Crops with moderate salt tolerance can be grown in most cases without special practices for salinity control. However, when it is considered that such water will be used in a semi-arid region on a sandy loam soil, with a shallow water table that is not stagnant, and where the farmer adopts subjective irrigation scheduling methods, the water can actually be regarded as equivalent to a S1 class (low salinity water). This would be possible because leaching under these conditions is extremely efficient, as shown by the results (Chapter 5). In these soils the storage capacity above the capillary fringe is limited, which causes excessive leaching of salt into the water table that is easily removed through lateral movement of the saturated zone below the water table, especially where subjective scheduling is applied. Hence, salt sensitive crops can be grown when this water is used under these conditions because the danger of excessive salt accumulation is low.

A similar more dynamic approach should also be adopted by WUAs with regard to billing water use of farmers in semi-arid regions where sandy to sandy loam water table soils are irrigated. Under these conditions there should be an incentive for irrigators to use less water. Currently at Orange-Riet and Vaalharts there are incentives since farmers are allowed 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. However, a problem might arise when all irrigators with shallow water table soils use less water. 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. 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.

6.3.3 Researchers

In this study it was shown that the model SWAMP can be used with confidence to simulate water and salt transport in water table soils in semi-arid regions and to predict the subsequent effect of matric (drought) and osmotic (salinity) stress on water uptake and yield of field crops. Additionally valuable insight, with the help of SWAMP, was gained into the dynamics of water and salt flow through water table soils under field conditions as influenced by best on-farm water and salt management practices. To enhance this knowledge the following additional research will be invaluable.

- The effect of fertilizer management (type, amount and stage of application) on salt additions to the root zone must be quantified. This will help improve the algorithm used by SWAMP to simulate salt additions through fertilization.
- For improved modeling with the model SWAMP the effect of rhizosphere salinity on water uptake needs to be quantified. Additionally, the use of mean seasonal atmospheric evaporative demand (ET_o) to determine the daily evapotranspiration requirement (potential) needs attention.
- The modeling interface of SWAMP must be changed in order to accommodate a management and research option. For the management option the interface must be simple, i.e. model parameters need only be accessed and changed with the research option.
- Temporal and spatial characterizing of water table depths at field and scheme level.
- An economic environmental tradeoff assessment of the best water and salt management practices must be done. This will aid the development of policy measures for water and salt management at farm level.

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