KTH Architecture and the Built Environment

IRRIGATION WITH SALINE WATER USING LOW-COST DRIP-IRRIGATION SYSTEMS IN SUB-SAHARAN AFRICA

Louise Karlberg

April 2005

TRITA-LWR PhD Thesis 1020
ISSN 1650-8602
ISRN KTH/LWR/PHD 1020-SE
ISBN 91-7178-063-7

PREFACE AND ACKNOWLEDGEMENTS

Water is truly an intriguing topic to study. It moves around in the ecosystem in many forms, like rain, snow, vapour and ice. Sometimes it is visible in lakes and rivers, whereas most of the time it is hidden under the soil surface or in the vegetation. Water has the potential to make deserts bloom and to cloth the landscape in white frost on cold winter mornings. All people have a relationship to water in one way or another. We use it for drinking, swimming in, sailing on, watering our plants, washing our cloths and even for skiing on. This fascinating nature of water has been the well of inspiration to this thesis.

This research would never have been completed if it weren't for the input from so many people. First, I would like to thank Per-Erik Jansson, my main supervisor, both for coming up with the original idea behind this work and for all the support provided, in particular during the last hectic months. It took some linguistic skills to learn to interpret your sometimes very abstract Greek in five dimensions, but once I got past that stage, I believe that we had many fruitful discussions. Secondly, my gratitude goes to my co-supervisor Johan Rockström. Thank you Johan for fitting me into your tight schedule. Your brief commenting on a mutual publication given over the phone while standing in a ski-lift is definitely a classic. I truly appreciate your down-to-earth constructive comments and the help in finding the forest amongst way too many trees. Furthermore, I am grateful to Uri Shani (co-supervisor) and Alon Ben-Gal, from the Hebrew University of Jerusalem, Israel, for productive co-operation at the start of this project. Thank you also Uri for giving me the opportunity to visit Israel.

Furthermore, I am grateful to the Swedish International Development Cooperation Agency (Sida) for providing the funding for this work.

During my period at the International Water Management Institute (IWMI), South Africa, in 2003, an infinite number of people helped me in many ways. Frits Penning de Vries, IWMI, not only provided me with many ideas in the area of saline water use for irrigation, but was also an invaluable help concerning discussions on photosynthesis modelling. The rest of the staff at IWMI is also acknowledged for their support, hospitality and friendship shown. John Annandale and Martin Steyn, University of Pretoria, were instrumental in the initiation and completion of the field experiment. Thanks for all the help with contacts, climatic data collection, but maybe most of all, for your general advice and support when I was at the depth of despair in trying to handle my 2000 tomato babies. Maintaining this experiment would never have been possible if it hadn't been for the kind help of many people. Wayne Truter was not only the best possible of friends (you are my favourite South African friend, you know) but he also helped me out with so many practical issues that I eventually gave up counting. Eyob, Yacob, Tsedal and the rest of the students that assisted in the experiment; you are the most hardworking people I've ever come across. I am very impressed and so grateful, both for your help and for your friendship. Furthermore, what would life have been like if it wasn't for the nice, friendly, competent and helpful staff at the experimental farm? Thank you all.

In Sweden, I've also had the pleasure of working with many great people. Magnus Svensson has spent many long hours listening to my unending complaints about the extent of my uselessness, and still managed to provide me with constructive comments and new energy to continue the struggle. I hope we can continue this co-operation in the future. David Gustafsson has been very helpful, both with technical issues such as getting reluctant models to work, and also with 'straightening' many question marks on water and heat related processes. To the rest of the staff at the Department of Land and Water Resources Engineering: what I will miss the most about my PhD work will, without doubt, be the pleasant coffee breaks shared with you!

Finally, I would like to express my sincere gratitude towards my friends and my family. I am deeply sorry for neglecting you the last couple of months. As you all know, words cannot describe how important you are to me. Lastly, and most importantly: Duncan. How can I ever thank you enough? You have been instrumental to the completion of this work in so many ways that I do not even know where to begin. Thanks for helping me make the map in Paper I (for which you so far have not been acknowledged), for linguistic corrections of all papers and the thesis (except for this last paragraph), for building brick stands for irrigation tanks, for fixing leaking pipes, for sucking out clay in clogged drippers, for harvesing loads of tomatoes in the blazing South African sun, for drying many tears, for encouragement and critisism, for maintaining the household these last couple of months, for believing in this work even when I did not, and most of all, for just being there. I could never have asked for a better husband.

Louise Karlberg
Stockholm, April 2005.

ABSTRACT

In the scope of future population support, agricultural productivity, in particular in sub-Saharan Africa, has to increase drastically to meet the UN's millennium development goals of eradicating extreme poverty and hunger by 2015. Water availability in the root-zone limits crop production in large parts of the developing world. As competition for fresh water increases, water of lower quality, for example saline or polluted water, is often used for irrigation. Low-cost drip systems are suitable for saline water irrigation because they effectuate a minimisation of salt accumulation, leaf burn and peaks in salt concentration. Nonetheless, all types of saline water irrigation contain the risk for causing soil salinisation. Thus, in order to achieve long-term sustainability of these systems, appropriate management strategies are needed. The choice of management practices may be influenced by local conditions such as climate, soil and irrigation water salinity. A literature review showed that there is a potential for saline water irrigation in sub-Saharan Africa in water scarce areas. Low-cost drip irrigation with saline water (6 dS m^{-1}) was successfully used to irrigate two consecutive crops of tomato in semi-arid South Africa. An integrated ecosystems model was developed to simulate long-term yield and salt accumulation in a drip-irrigated agricultural system for a range of salinities, climates and management techniques. Crop, salt and water balance data from two field experiments conducted in Israel and South Africa, respectively, were used to parameterise and test the model. Emphasis was placed on testing the usability of the model as a tool for evaluating the importance of certain plausible management options of low-cost, drip-irrigation systems. Therefore, particular focus was directed towards correctly describing soil salinity stress on plant growth and soil evaporation from a distributed (wetted and dry) surface. In addition, the model was developed to function for different climates without having to change any other parameters or variables except for the actual climatic data. Simulations were subsequently run over a 30-year period to study long-term yield and salt accumulation in the soil profile for two sites in South Africa, demonstrating the applicability of the model. Model simulations showed that high soil salinities reduced crop growth and thus increased both drainage and soil evaporation. Further, covering the soil with a plastic sheet led to a reduction of soil evaporation and a subsequent increase in both transpiration and drainage. Rainfall was crucial for the leaching of salts from the soil, and thus in regions with low levels of rainfall, a higher leaching fraction of supplied saline irrigation water has to compensate for the lack of rain. However, a high leaching fraction also causes large amounts of salt leaching, which could potentially pollute underlying groundwater and downstream ecosystems. This risk can be mitigated using mulching, which minimises non-productive water losses, thereby lowering irrigation water needs. The choice of irrigation water salinity, frequency of irrigation and soil coverage may differ between the farmer and the regional water manager due to different preferences. Furthermore, the study highlighted how environmental variables such as water use efficiency and radiation use efficiency can be used as indicators of system performance. Whereas the latter is first and foremost a general stress indicator, water use efficiency more precisely describes specific factors such as plant size, allocation patterns and evaporative demand, which will affect the exchange of carbon dioxide and water through the stomata.

Keywords: Water use efficiency; Radiation use efficiency; Management techniques; Modelling; Tomato

LIST OF PAPERS

This thesis is based on the following papers that are referred to by their corresponding Roman numerals and can be found in appendix 1-4.

I. Karlberg, L. and Penning de Vries, F.W.T., 2004: Exploring potentials and constraints of low-cost drip irrigation with saline water in sub-Saharan Africa. Physics and Chemistry of the Earth, 29:1035-1042.

II. Karlberg, L., Rockström, J., Annandale, J.G. and Steyn, J.M.: Low-cost drip irrigation of tomatoes using saline water: a suitable technology for southern Africa? Submitted to Agricultural Water Management.

III. Karlberg, L., Ben-Gal, A., Jansson, P-E. and Shani, U., 2005: Modelling transpiration and growth in salinity-stressed tomato under different climatic conditions. Accepted for publication in Ecological Modelling.

IV. Karlberg, L., Jansson, P-E. and Gustafsson, D.: Modelling management strategies for low-cost drip-irrigation systems using saline water. Submitted to Irrigation Science.

V. Karlberg, L., Annandale, J.G., Jansson, P-E., Rockström, J. and Steyn, J.M.: Long-term impact of different management strategies for low-cost drip-irrigation systems using saline water – modelling two hypothetical agricultural systems in South Africa. Submitted to Agricultural and Forest Meteorology.

Table of Content

INTRODUCTION

Thomas Robert Malthus (1766-1834) posited the hypothesis that unchecked population growth always exceeded the growth of the means of subsistence. Region after region has disproved this assumption, mainly because Malthus grossly underestimated the potential of productivity increasing technology. However, in Sub-Saharan Africa the population growth rate has exceeded the rate of growth in food production since the early 1970's, and what is worse, the gap continues to widen, resulting in a decreased per capita food production (Pinstrup-Andersen *et al.*, 1997). The Millennium Development Goals (MDGs) declared by the United Nations in 2000 aim at eradicating extreme poverty and hunger by 2015. Three-quarters of the world's poor live in rural areas and depend largely on agriculture as their main source of income, and in sub-Saharan Africa that figure is as high as 80% (IFPRI, 2004). Unfortunately, agricultural productivity in the area remains very low; below 1 Mg ha^{-1} for many crops. It is estimated that a 10% increase in agricultural productivity is associated with a 7.2% reduction in poverty (IFPRI, 2004). Water availability in the root-zone has been shown to be the most limiting factor for crop production in semi-arid regions (Falkenmark & Rockström, 1993). Unfavourable agricultural conditions such as erratic rainfall, high evaporative demand and the inherently low fertility of soils constrain agriculture in the region. With secure access to irrigation water, crop productivity could be substantially increased by supplementary irrigation to bridge dry spells (Fox & Rockström, 2003; Barron, 2004). However, competition from households, industries and ecosystems limits the amount of water from rivers, streams and groundwater that can be allocated to agriculture. It is estimated that approximately 80% of current fresh water withdrawals are used in irrigated agriculture in Africa and western Asia (UNEP, 1999). Water scarcity is becoming one of the major limiting factors to economic development and welfare in large parts of the semi-arid regions of the world. About one-third of the world's population live in countries with moderate to high water stress, i.e. in areas where the withdrawal of fresh water exceeds 10% of accessible runoff (UNEP, 1999, 2002). Constantly increasing populations aggravate the problem of access to fresh water. The worst situation is found in Africa and western Asia. It has been estimated that an additional 5600 km^3 yr^{-1} of fresh water is required to eradicate malnutrition and feed the human population in 2050 in addition to the 7000 km^3 yr^{-1} that is used currently for food production from land (Falkenmark & Rockström, 2004).

If the possibility of allocating more water to agriculture is limited, then the efficiency with which water is presently being consumed for crop production has to increase. Water productivity (WP), defined as yield per unit consumptive water (i.e. total evapotranspiration), varies substantially between crops, climates and regions. Whereas the productive flow component of total consumptive water is rather non-negotiable, agricultural management techniques can have large impacts on the non-productive water flow. Thus, several management strategies to improve water productivity exist, such as mulching, drip irrigation, intercropping, agroforestry, soil fertility management, rainwater harvesting, soil and water conservation, and improved crop varieties (Falkenmark & Rockström, 2004). For example, by shifting from conventional surface irrigation to drip irrigation in India, yields increased by up to approximately 50%, whereas water productivity increases ranged from 40-250%, depending on the crop grown (Postel *et al.*, 2001).

In addition, as competition for fresh water increases, water of better quality is primarily used for domestic purposes, whereas water of lower quality is often used for irrigation (Khroda, 1996). Therefore, one challenge for the future will be to maintain or even increase crop production with less water that may often be of poor quality, for example saline water. Saline water irrigation is practiced in several regions of the world (Rhoades *et al.*, 1992), where water scarcity prevents the use of freshwater for irrigation. Despite the fact that yield is lower when salts accumulate in the root-zone (Bernstein, 1964) and that leached salts may pollute groundwater and downstream ecosystems, there are still several benefits with saline water irrigation that may outweigh these drawbacks. By using low quality water for irrigation, it would for example be possible to extend the normal growing season, thus targeting markets when the demand is especially high. Saline water irrigation could also be used to bridge dry-spells for crops that are normally rainfed, therefore increasing yield. In irrigated agriculture, any shift from freshwater to saline water irrigation incurs a yield reduction, but enables more freshwater to be allocated to other purposes.

The greatest risk for the farmer with using saline water is that of salinisation, which may lead to crop failure. Careful management of these systems is therefore required. Drip irrigation has been shown to be the most useful irrigation technique when irrigating with saline water (Dasberg & Or, 1999). Low-cost drip-irrigation has recently been implemented in several countries in sub-Saharan Africa (e.g. du Plessis & van der Stoep, 2000; Kabutha *et al.*, 2000; Sijali, 2001; Chitsiko & Mudima, 2002). Apart from the overriding question of the general feasibility of saline-water, low-cost, drip irrigation, there are several management issues, such as the amount of irrigation water that should be used, irrigation frequency, emitter discharge rate and mulching, which should be tested. The effect of these management approaches on plant growth depends on climate. In order to evaluate the impact of various management techniques, as well as the sustainability of the system, the interactions between soil salinity, soil evaporation and climate, and their impacts on growth and transpiration, need to be understood and analysed in an integrated manner. A simulation model is a suitable tool for incorporating these processes and their interactions. Rhoades *et al.* (1992) conclude that there is a lack of information on how crops respond to time and space varying osmotic and matric potential, as well as ion-toxicity levels as a function of irrigation management, soil water retentivity characteristics and atmospheric conditions.

In summary, if Malthus' theory is to be proved wrong for sub-Saharan Africa, it is essential to increase not only agricultural productivity, but also water productivity in the region. The use of saline water drip-irrigation becomes an interesting technique since it may imply that a higher yield can be produced per unit freshwater input, thus enabling a reallocation of freshwater from agriculture to other uses or an expansion of irrigated agriculture. However, management of these systems is crucial to achieve long-term sustainability, and requires an integrated approach in which the influence of climate and management on growth and transpiration is addressed in an ecosystems perspective.

AIMS AND OBJECTIVES

The aim of the thesis is to evaluate different irrigation management techniques for low-cost drip irrigation systems with saline water, and the feasibility of saline water irrigation in general, with special focus on sub-Saharan Africa. More specifically, the following objectives were addressed in the thesis:

1. To explore the potentials and constraints of low-cost drip-irrigation systems in sub-Saharan Africa (Paper I).
2. To investigate yield from low-cost drip irrigation systems with different discharge rates, mulching and irrigation water with different salinities, in field experiments under semi-arid conditions (Paper II).
3. To develop an integrated ecosystems model for the study of crop yield and long-term sustainability in a drip irrigation system with saline water (Paper III and IV).
4. To test the usability of the model on data from field experiments (Paper II) in order to evaluate the importance of specific management options in a drip irrigation system with saline water, focusing particularly on the effect of salinity stress on plant growth (Paper III), soil evaporation from a distrib-

uted (wetted and dry) surface (Paper IV) and climatic influence on transpiration and growth (Paper III and IV).

5. To demonstrate the applicability of the model by evaluating the impact of management approaches on long-term sustainability, in terms of crop yield, salt accumulation in the soil and leaching (Paper V).

BACKGROUND

Irrigation with saline water

Irrigation of agricultural land is an ancient agricultural practice. The Old World Mesopotamian civilisation was built upon a prosperous agricultural sector that was supplied with water from the Euphrates and Tigris rivers. The Nile Valley is yet another recent example of an area dependent on irrigation water. Globally, the area under irrigation is five times larger today than what it was a hundred years ago (Rosegrant *et al*., 2002). Without irrigation, increases in agriculture to feed the world's growing population would not have been possible. However, there are two major undesirable environmental effects of irrigation, which are believed to have caused the destruction of the glorious Mesopotamian civilisation (Tanji, 1990). When irrigation water is allowed to infiltrate into the soil, the ground water table starts to rise and may, in time, bring the zone of saturation close to the surface; a phenomenon called waterlogging. The other side effect is salinisation, caused by an accumulation of salts in the root-zone. In areas where the climate is hot and dry, for example the Sahel region, irrigated lands are subject to substantial water losses through evapotranspiration. Salts contained in irrigation water remain in the soil and increase in concentration when the water evaporates from the soil or when the plants take up water for transpiration. If the salt is not leached from the soil, the salt concentration constantly increases. This process is called secondary salinisation. Nearly 10% of the earth's total land surface is covered with saline soils (Szabolcs, 1994). High salt concentrations in the soil leads to low crop yields (Bernstein, 1964) and can also cause soil permeability problems (e.g. Bresler *et al*., 1982). If the process of salinisation is allowed to continue, agricultural land might eventually have to be abandoned. To avoid salinisation, additional irrigation water has to be applied to the field in order to leach the salt from the root-zone.

The basic principle behind a sustainable agricultural system based on irrigation with saline waters in terms of long term crop yield, is that the salt concentration in the root-zone has to be kept below a certain threshold level. These levels are specific for each crop species (Maas & Hoffman, 1977). To some extent this is a self-regulatory process by the plant (Shani & Dudley, 2001). When the soil salinity increases, the plant responds by decreasing water uptake. Thus, more water is available for leaching of salts from the soil, removing more salt from the root-zone. Soil salinity can be kept at the same concentration as the irrigation water, if soil evaporation can be minimised and sufficient water is added to provide for leaching. The Food and Agriculture Organisation of the United Nations (FAO) has developed guidelines for an evaluation of the suitability of water for irrigation (Ayers & Westcot, 1985).

By applying saline water with appropriate irrigation management techniques, long-term sustainability in agricultural systems can be achieved (Rhoades *et al*., 1992). One such irrigation technique is drip-irrigation, which has been successfully used in combination with saline waters (e.g. Shalhevet, 1994). Saline water (up to 11 dS m^{-1}) has been used successfully in combination with commercial irrigation to irrigate a number of crops globally (Paper I). Several characteristics make drip irrigation suitable for irrigation with low-quality water. One benefit of drip irrigation is its high water application efficiency, which can potentially reach values as high as 90%, although 80% is practicable (FAO, 1997). This can be compared with surface irrigation schemes, which normally have an efficiency of around 50%. Thus, less water and therefore less salt, is added to the soil. Secondly, the salt tends to accumulate away from the active root-zone at the wetting front close to the soil surface (Dasberg & Or, 1999; Shalhevet, 1994). These salts can be leached out of the root-zone by heavy rainfall. Due to the low discharge rates of drip irrigation systems, a more even soil water content can be maintained in the soil, and therefore peaks and drops in salt concentration are avoided. Finally, foliar absorption of salts and leaf burn are averted as the irrigation water is applied below the canopy, as opposed to sprinkler irrigation.

There seems to be a general lack of information on the prevalence and composition of saline aquifers in sub-Saharan Africa (Paper I). Nevertheless, some countries, such as South Africa, Botswana and Zimbabwe, have documented the presence of saline aquifers. Information concerning the extent of usage of saline water for irrigation in the rest of sub-Saharan Africa, however, is largely missing (Paper I). Simplified drip irrigation systems that depend less on spare parts and involve lower initial costs have been developed for small-scale farmers (FAO, 1997), and are being used by farmers in, for example Kenya, Tanzania, Malawi, Zambia, Uganda, Zimbabwe and South Africa (du Plessis & van der Stoep, 2000; Kabutha *et al.*, 2000; Sijali, 2001; Chitsiko & Mudima, 2002). In sub-Saharan Africa one of the most common low-cost drip irrigation systems is the bucket and drum kit. These systems can irrigate an area the size of a small vegetable garden. Since drip irrigation involves high initial investment costs, cash crops, such as various types of vegetables, are often grown. Many of these systems are managed by women; in Kenya, 70-80% of the drip kit users are women (Kabutha *et al.*, 2000).

As stated above, all saline water irrigation systems require careful management to prevent escalating soil salinisation. Several management strategies and techniques are available to achieve the goal of long-term sustainability in the saline water irrigated system with low-cost drip irrigation. Emitter discharge rates vary between 0.2-3.0 $l\,h^{-1}$, depending on the type of drip system and the head of the water (Chigerwe *et al.*, 2004). Compared with flow rates under conventional drip of approximately 2.0-8.0 $l\,h^{-1}$, these values are relatively low (Dasberg & Or, 1999). A lower emitter discharge results in longer irrigation application periods, and potentially higher soil evaporation. However, a lower discharge rate creates a more vertical wetting pattern than a high discharge rate, which results in a smaller wetted soil surface area and thus less soil evaporation (Dasberg & Or, 1999). The choice of drip irrigation system will in this case depend on the relative importance of these two processes. By reducing soil evaporation, the efficiency of the system can be increased further and thus even less saline water will have to be added to the farmer's field. Applying mulch to cover the soil might be an interesting option in this respect. Other management issues and technological aspects that need to be considered are, for example, irrigation scheduling, emitter spacing and irrigation water amounts. These factors will vary between regions and crops. In addition, problems related to the equipment, such as the risk for emitters clogging, the effectiveness of simple filters, in-line drip emitter systems performance versus micro-tube systems, and rusting of the equipment caused by the saline water, remain to be evaluated for low-cost drip systems.

Effects of soil salinisation on growth

Increased soil salinity leads to reduced transpiration and growth, and subsequent reductions in yield (Bernstein, 1964). However, the mechanisms behind salinity stress are not yet fully understood (Rhoades *et al.*, 1992; Shalhevet, 1994). Growth reductions are normally ascribed either to an osmotic or an ion toxicity effect (Lagerwerff & Eagle, 1961; Epstein 1980; Bresler *et al.*, 1982). Accumulation of salts in the soil results in higher osmotic potential, thus binding the water more tightly to the soil and limiting plant water uptake. Plants respond by adjusting the internal osmotic potential by compartmentation of either synthesised organic solutes in the cytoplasm or of inorganic ions in the vacuole, thus sustaining water uptake at least partially (Greenway & Munns, 1980, 1983; Läuchli & Epstein, 1990; Jacoby, 1994; Katerji *et al*., 1997, 1998). Compartmentation of ions in the vacuole has a dual function in that it also removes toxic ions from the cytoplasm. In addition, ion toxicity is avoided by active exclusion of ions from the tissues.

Crop tolerance to salinity varies between crops. Maas and Hoffman (1977) developed a function for salt tolerance in terms of relative crop yield, Y_r, as a function of a threshold salinity level, *a*, and a percentage decrement value per unit increase of soil salinity in excess of the threshold, *b*, according to:

$$Y_r = 100 - b\left(EC_e - a\right)$$

where EC_e is the soil salinity expressed in terms of electrical conductivity (dS m^{-1}). Data on crop salt tolerances has been summarised by Maas (1986). However, it is important to bear in mind that such salt tolerance data is only a rough estimate of crop production, since plant growth is influenced by other environmental factors such as climate and irrigation management practices.

An ecosystems model of a saline-water drip-irrigated crop

Some of the most important features of the saline-water drip-irrigation system are depicted in the conceptual model (Fig. 1). The figure illustrates how several environmental and climatic factors, such as radiation, affect the system, how water and carbon flows through the ecosystem and how these fluxes are linked. Considering the water flows (blue), two sources of water can be identified, namely irrigation water and precipitation (i.e. rain). In this case we assume that the drip emitter is placed next to the stem, and thus only the area surrounding the stem is wetted. Water is stored in the soil, from where it can be extracted by the plant's roots and can leave the plant in the form of transpiration. From the surface, water evaporates both from the wetted area next to the stem, and from the soil patches in between irrigation points. Soil evaporation and transpiration are driven by several climatic variables such as radiation, wind speed and humidity. The prevailing climate gives rise to a potential evapotranspiration, which together with the access to water in the plant and soil determines actual evapotranspiration. Looking specifically at transpiration, there are several plant characteristics that influence potential transpiration. The plant height affects the turbulence around the plant and thus the transport of water vapour, stomatal conductance is a measure of how open the stomata are and therefore how much water that can leave the plant, and leaf area affects, for example how much radiation that is absorbed by the plant canopy. In addition, root depth will affect the availability of soil water and consequently plant water uptake and transpiration. If the soil moisture content in the root-zone exceeds field capacity, some water will drain to lower soil horizons.

Carbon fluxes (green) are generated by photosynthesis in the leaves of the plant. In Figure 1 this is represented only as an influx of matter from the assimilation process. Photosynthesis is primarily a function of radiation and carbon dioxide content in the sub-stomatal cavity in the leaf. The availability of carbon dioxide is dependent on the ease of transport of the gas from the atmosphere to the chloroplasts inside the leaf, and therefore stomatal conductance is imperative for the determination of photosynthesis. In addition, water stress, measured for example as the ratio between actual and potential transpiration, can limit photosynthesis. Assimilates are allocated to the leaves, stem and roots. Plant carbon content determines plant characteristics such as plant height, leaf area and root depth. Thus, plant water and carbon flows are not only linked through stomatal functions, but also from the relationships between the size of different organs and the physical plant characteristics. This is clearly seen in Figure 1 by following the arrows from assimilation to any of the influencing variables, to potential evapotranspiration, to transpiration and then back again to assimilation.

Salts enter the system via the irrigation water and accumulate gradually in the root-zone.

Each rainfall event brings fresh water to the soil, which dilutes the salt concentration. If drainage occurs, salts will be leached from the root-zone to underlying soil horizons. Plant uptake of salts is negligible, and therefore both plant water uptake and soil evaporation result in an increase of salt concentration in the root-zone. This increased concentration has to be balanced by leaching. However, since salinity stress causes a reduction in growth, which in turn will lead to a smaller root system and lower water uptake, relatively more water is available for leaching (positive feedback) or for soil evaporation (negative feedback). Salinity stress can either be considered as an increased plant metabolism (No. 1 in Fig. 1), or as reduced water uptake (No. 2 in Fig. 1). In the former case the high metabolism results in a higher respiration and thus a lower net assimilation.

The impact of climate on both transpiration and photosynthesis was highlighted above. Humidity and radiation influence the degree of opening of the stomata, and hence both the inflow of carbon dioxide and the outflow of water vapour. Radiation also drives transpiration and is central in the photosynthesis process. Finally, wind speed affects the turbulence around the plant, and therefore the transport of water vapour from the plant and carbon dioxide to the plant. In conclusion, it is clear that a change in climate can affect transpiration and photosynthesis differently. Additionally, precipitation may be imperative for the leaching of salts from the root-zone.

As has been indicated indirectly, soil evaporation is a key process in saline water irrigation, since it is a non-productive water loss that leads to salt accumulation in the root-zone. This means that the lower the soil evaporation, the less salts will accumulate in the root-zone. Soil evaporation under drip irrigation is determined by the size of the wetted surface as well as the location of the surface. At the end of the growing season the plant canopy will shadow most of this area, thus resulting in lower evaporation. Time is another important factor. Since potential evaporation is lower at night, a wetted surface at night will have lower soil evaporation than a wetted surface during the day.

Management can affect several variables in the system. The discharge rate of the drip system may affect infiltration time, and consequently soil evaporation, and it may further affect the shape of the wetted sphere around the dripper. Secondly, the amount of water per irrigation event, as well as the irrigation frequency, is likely to affect both the leaching of salts and soil evaporation. Covering the soil with plastic mulch will significantly reduce soil evaporation, but may on the other hand decrease the infiltration of precipitation. Using organic mulch instead may not be as efficient in terms of preventing soil evaporation, but on the other hand does not affect infiltration. Finally, salt accumulation in the root-zone, and thus growth, is dependent on the salinity of the irrigation water. Therefore, irrigation water salinity will affect all the management issues mentioned above.

Limitations of the project

Accumulation of salts can affect the physico-chemical properties of the soil, and thus the suitability of the soil as a medium for plant growth (Bresler *et al.*, 1982; Szabolcs, 1994; Rhoades *et al.*, 1992). Dispersion of clays leads to a loss of porosity and permeability, as well as crust formation. Many studies have been conducted on the suitability of different soils for saline water irrigation, and the mechanisms behind soil and salt interactions are well understood (e.g. Szabolcs, 1994). The largest problems are found in soils with a high sodium absorption ratio (SAR). It is crucial to evaluate the suitability of a soil before starting a saline water irrigation project. In this study we have used soils that are not prone to dispersion, and the effect of salt on the physico-chemical properties of the soil is not dealt with further.

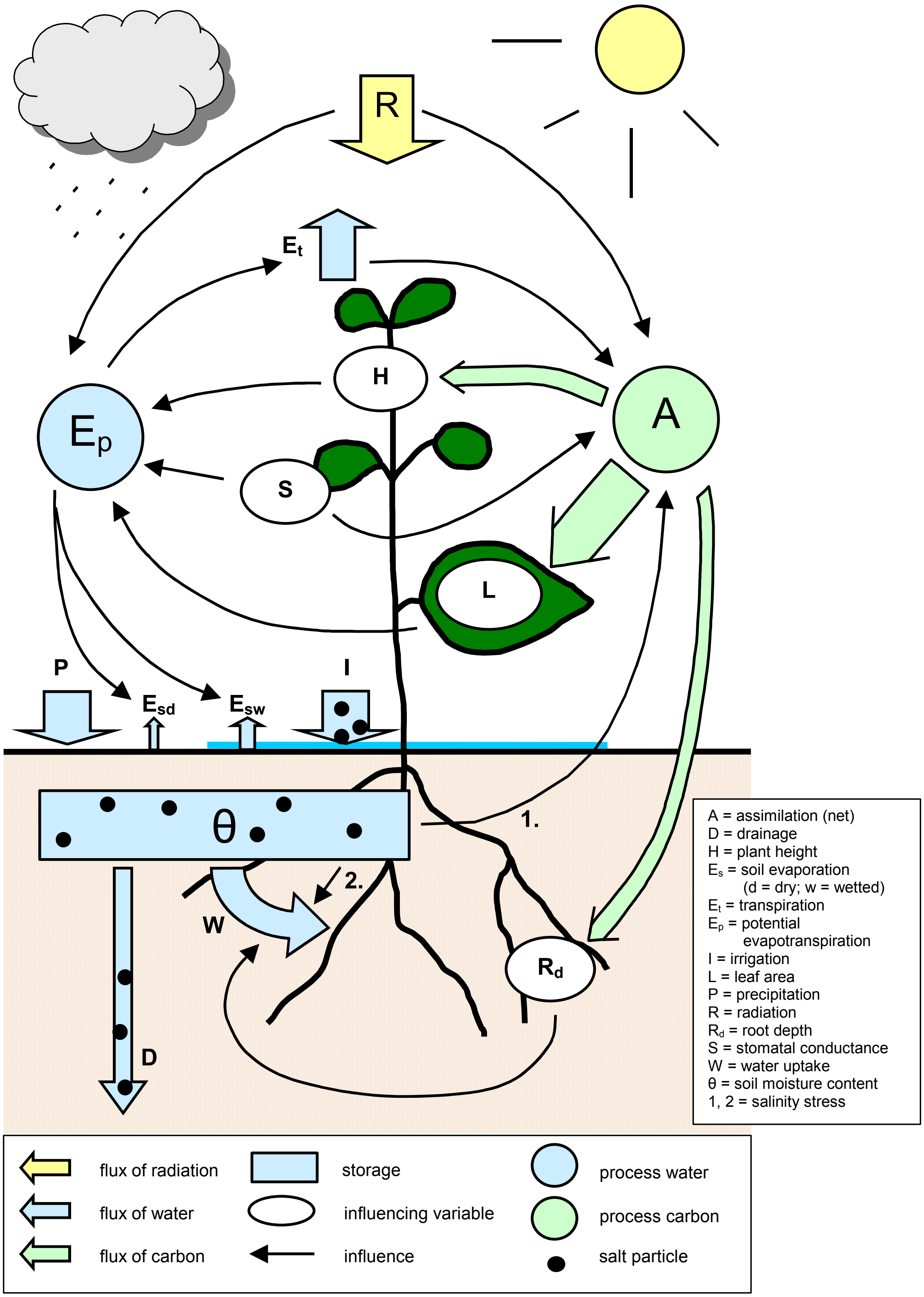

Figure 1. Conceptual model for some of the major biophysical processes in a drip-irrigated system using saline water.

The sensitivity to salinity stress is believed to vary between different growth stages (Abel & MacKenzie, 1964; Maas *et al*., 1983; Al-Tahir & Al-Abdulsalam, 1997; Hussain *et al*., 1997; Zeng *et al*., 2001). For example, to ensure the proper establishment of a crop it is essential to keep salt concentrations at a minimum during germination and seedling stages. If flower formation is affected by salinity, plant resource allocation patterns can be altered. It has been shown that some plants actually respond to high levels of soil salinity by increasing the amount of resources allocated to roots (Brugnoli & Björkman, 1992; Fung *et al*., 1998). Soil salinity can also affect the quality of the produce. For example, it has been showed that the fresh weight of tomatoes, as well as the fraction of marketable harvest, is reduced under saline conditions (Li *et al*., 2001), whereas the amount of soluble solids showed a marked increase (Vinten *et al*., 1986). The latter is an important quality criterion for tomato juice production. Interestingly, high vapour pressure deficits have also been shown to increase the amount of soluble solids in tomato (Leonardi *et al*., 2000). Although the importance of these aspects of salinity stress on crop growth and yield is recognised, they have not been addressed in this thesis.

METHODS

Since agriculture in the semi-arid tropical regions in developing countries comprises predominantly small-scale subsistence farming, this project focuses on small-scale, simple, low-cost irrigation management techniques that are not heavily reliant on spare parts and technicians. Only drip irrigation equipment presently available on the market for smallholdings have been used. All management options studied were simple, affordable and could easily have been carried out by the farmers themselves. In order to retrieve the money invested in irrigation techniques, the crop intended for irrigation has to be a cash crop. This study uses tomatoes, which is a common cash crop throughout Africa.

Literature reviews

Literature reviews were conducted in several fields of research to establish the state-of-the-art within each field. These reviews are summarised in Paper I and III and in the background description above, and cover the following topics: causes and impacts of salinisation; irrigation with saline water in developed countries; the availability of saline water in sub-Saharan Africa; the access to and implementation of low-cost drip irrigation systems and it's potential to be used in combination with saline water; the physiological effects on plant growth and transpiration of salinity and/or water stress; physiological characteristics of tomatoes; different models for simulating transpiration; and growth under salinity stress. In addition, data from literature on tomato characteristics was used in the parameterisation of the simulation model, as described below.

Field experiments

In order to study low-cost drip irrigation systems in semi-arid[1] South Africa, an on-station field experiment was designed in which different irrigation management techniques were compared. The field experiment was carried out from September 2003 to April 2004 at the Hatfield Experimental Station, Pretoria, South Africa (Paper II). Data on soil salinity, soil moisture content, and biomass growth and yield from two consecutive crops of tomato (*Lycopersicon esculentum* Mill. Cv. "*Daniella*"), as well as some other variables, was collected and subsequently analysed. The experiment consisted of twelve different treatments repeated on three adjacent fields i.e. three repetitions (Fig. 2). Two drip irrigation systems with low and high discharge rates (0.2 and 2.5 $l\ hr^{-1}$) were used to irrigate tomatoes with water of three different salinity levels (0, 3 and 6 $dS\ m^{-1}$). These treatments were repeated with plastic mulch and under bare soil conditions.

[1] mean annual rainfall of 668 mm

Figure 2. Field experiment at Hatfield Experimental Farm, Pretoria, South Africa, 2003-2004.

In this experiment a completely randomised block design was chosen. The number of repetitions was quite low, i.e. three, whereas the number of plants within each treatment was relatively high; 42 plants were planted for each treatment. This resulted in a rather low variation between samples from the same treatments, which to some extent compensated for the small number of repetitions. The reason for choosing such as design was a practical one; it requires additional labour and money to irrigate more treatments than to increase the number of plants per treatment, since each treatment was irrigated from a separate drip-kit on separate production beds. Nonetheless, three repetitions are sufficient to perform an analysis of variance on the collected data, and thus to draw conclusions on differences between the various management techniques.

Together with data from a second field experiment on saline water irrigated tomatoes (*Lycopersicon esculentum* Mill. Cv. "*Daniella*" and "*5656*") grown in weighing lysimeters from the Arava desert, Israel, the field data from South Africa provided input to the modelling studies of these systems. The Israeli data was useful for the first parameterisation and testing of the model. Using weighing lysimeters provided a good estimation of daily transpiration, and destructive sampling at the end of the experiment provided an estimate of plant allocation patterns, growth and leaf area index. However, this dataset could not be used to capture the water balance of the low-cost drip irrigation system when used on production beds. Thus, the South African experiment was designed particularly to estimate soil evaporation and soil moisture content in the wetted area close to the drippers, and in the dry area in the middle of the production beds. An attempt was also made to describe soil salinity levels at different distances from the drippers and at different depths by taking soil water samples and analysing the electrical conductivity (EC) of those.

Modelling

Crop growth and yield under saline conditions is affected not only by soil salinity but also by numerous environmental variables, such as soil type, potential evaporation, precipitation and irrigation management techniques. Consequently, the choice of irrigation management strategies with saline waters is a complex issue, especially in combination with drought and nutrient stress. A large number of experiments on crop tolerance to salinity and effects on yield have been carried out in laboratories (Shalhevet, 1994). In addition, a smaller number of experiments have been carried out in the field, but this procedure is both time-consuming and expensive. Field data can be studied and the underlying processes of the agricultural system can be efficiently analysed by incorporating the data into models. Furthermore, these models can be used as operational tools to transfer knowledge between localities. An advantage with using such models is that complex and dynamic systems, such as the soil-plant-atmosphere-continuum, can be understood as an integrated system and at the same time at a very detailed scale. Models also allow one to transfer and test the applicability of empirical data between different sites, an issue that has been problematic for scientists to date. Finally, models are cheap compared to field experiments and may sometimes be the only feasible option for that reason. For example, a field experiment on the sustainability of systems using low-cost drip irrigation with saline water requires a study that will stretch over many seasons, and will thus become both labour consuming and costly.

Several models that simulate flows of water, energy, carbon and nutrients through the soil-plant-atmosphere system have been developed. Within the realm of soil sciences, several transient models that use numerical solutions to compute water and solute flow and consider heterogeneous soil profile conditions in detail, were being created as computer processing capacities grew in the 1970s (e.g. Nimah & Hanks, 1973; Feddes *et al*., 1978; Jansson & Halldin, 1979; Belmans *et al*. 1983; Letey *et al*., 1985). Some of these models, such as the one by Nimah and Hanks (1973) and Letey *et al*. (1985) describe crop production under salinity stress. Although different functions for salinity stress are sometimes used, common to all these models is that soil salinity reduces growth through decreased water uptake. The degree of detail in the descriptions concerning the coupling between the ecosystem and the atmosphere, such as radiation interception, aerodynamic resistance and evapotranspiration, vary between models. An evaluation of the effect of climate on plant growth requires that these processes are explicitly expressed. Many of the first models used the concept of water use efficiency to estimate growth (de Wit, 1958), and this concept was gradually developed as the soil water balance models evolved towards more detailed estimations of crop growth (e.g. Feddes, 1988). Recent developments in advanced growth models have led to the incorporation of more detailed growth functions into transient models (Smets *et al*. 1997; van Dam *et al*. 1997; Annandale *et al*., 1999; Ferrer-Alegre & Stöckle, 1999), in which growth is commonly calculated as a function of radiation according to the concept of radiation use efficiency (Monteith, 1977). Parallel to the development within soil science, plant physiologists started to develop models for growth. The commonly used biochemical model by Farquhar *et al*. (1980) has been incorporated into several recent models, which has a strong emphasis on the exchange of water and carbon dioxide between the plant and the atmosphere (Sellers *et al*., 1996; Dai *et al*., 2004). In order to simulate transpiration and growth under salinity stress and the influence of climate, there is a need for models that bridge these two disciplines and thus incorporate detailed descriptions of the soil, the plant and their coupling to the atmosphere.

This project used and further developed a physically based, transient, integrated ecosystems model, the CoupModel (Jansson & Karlberg, 2004). The objective with the development of the CoupModel to simulate growth and transpiration under saline conditions has not been to suggest new functions, but rather to combine available modules for different processes in the system that have been successfully tested and previously used. It might be appropriate at this stage to clarify what the word *model* means in this context. A comprehensive eco-systems model like the CoupModel, consists of several *modules* for the calculation of different processes, such as soil evaporation, photosynthesis and heat transfer. These modules are often linked and are dependent on each other. However, these modules are often referred to as models at a different level, namely when one describes the functions that make up these modules. In the text that follows the double meaning of the word model has often been used. Drawing from this discussion, it is possible to make a general conclusion about the choice of models.

Since many models have grown to incorporate a rather large number of modules, the choice of a certain *model* becomes less important than choosing the correct *modules*.

The CoupModel simulates a one-dimensional soil profile and the vegetation cover above. Therefore, certain modifications were made to account for the two dimensional nature of drip-irrigation. In the model, water enters the system either as precipitation or as irrigation. Irrigation water is added to an area around the stem, whereas precipitation, on the other hand, is evenly distributed over the soil surface. Thus, in the CoupModel, the soil surface is divided into an irrigated (wet) and a non-irrigated (dry) section, whereas soil moisture in the lower soil layers is assumed to be evenly distributed vertically. Soil evaporation is calculated independently from the irrigated and the non-irrigated surface, using a surface energy balance approach. Water uptake is assumed to be equal to transpiration, and is a function of potential transpiration, soil moisture and root distribution (Jansson & Halldin, 1979). Furthermore, water can drain from the soil profile or leave the surface as surface runoff. Potential transpiration is calculated using the Penman combination equation modified by Monteith (1965), in which potential transpiration is a function of radiation, wind speed, air humidity, plant height, leaf area and stomatal conductance.

The bio-chemical photosynthesis model developed by Farquhar *et al.* (1980) estimates gross photosynthesis as a function of radiation, transpiration, leaf nitrogen content and temperature, and carbon dioxide availability. The latter is regulated by the stomatal conductance, as well as the exchange capacity of carbon dioxide between the leaf surface and the atmosphere. Assimilates are allocated to leaves, stem and roots, and also to fruits after flowering. Carbon is lost from the plant again through growth and maintenance respiration.

Both photosynthesis and transpiration depend on the opening and closing of stomata. Stomatal conductance is calculated using the Lohammar model (Lohammar *et al.*, 1980; Lindroth 1985), in which the conductance is a function of radiation and humidity. When calculating carbon dioxide exchange, this model is modified slightly to include a function for plant water stress (i.e. the ratio between actual and potential transpiration). Not only does transpiration influence photosynthesis, but photosynthesis also affects transpiration through a number of plant characteristics. Leaf area, plant height and root depth are all functions of the carbon content in the leaf, stem and roots respectively. These plant characteristics are subsequently used to estimate either potential or actual transpiration.

Salinity stress is calculated with the van Genuchten soil salinity reduction function (van Genuchten, 1983; van Genuchten & Hoffman, 1984; van Genuchten & Gupta, 1993). In the Coup Model this function can be used in different ways to determine the effect of soil salinity on plant growth. In the first approach, salinity stress reduces growth by increasing respiration. This approach corresponds to the interpretation of salinity stress as a toxicity effect or an increase in plant metabolism due compartmentation of osmoregulating compounds in the vacuole. Alternatively, salinity stress can be chosen to reduce water uptake and hence transpiration, thus corresponding to the osmotic stress theory for salinity stress.

The model was parameterised, calibrated and tested using two independent datasets from the Arava desert, Israel (Paper III). As a first step in the parameterisation process, measurements were used when possible. Secondly, literature values substituted missing measurements. Finally, only a small number of parameters remained unknown. These parameters were calibrated using the first dataset, and tested on the second. The modelling exercise focused primarily on correctly describing the impact of salinity stress and climate on growth and transpiration. Since the plants in the Israeli experiment were grown in lysimeters, it was not possible to test soil evaporation processes that are assumed to be crucial for the field situation. Therefore, the field experiment carried out in South Africa (Paper II) was designed to provide additional data for parameterising and testing the model on drip-irrigation in the field (Paper IV). The two independent datasets collected from this field experiment were used analogously to the Israeli data. Furthermore, the water balance and its effect on salt accumulation in the soil, and the concomitant effect on yield, was simulated for all salinity and management treatments tested in the field experiment in South Africa (Paper IV). Climatic data from a nearby meteorological station, together with soil data collected at the experimental station (Tesfamariam, 2004), formed inputs to the model.

After the model had been parameterised and tested, 30-year simulations, based on climatic data from 1975-2004 from two meteorological stations in South Africa, were conducted to evaluate the long-term crop yield and sustainability of the low-cost drip irrigation systems for various management techniques (Paper V). The first station, Keimoes, is located in the dry and hot Gordonia region in the south western part of the country alongside the Karoo semi-desert, and has an annual average rainfall of approximately 200 mm. Occasional night frost prevents cropping during the winter season. Therefore, at this station only one crop, tomato, was planted during the summer and supplementary irrigated with water of different salinities (0, 3, 6 and 12 dS m^{-1}). At the second station, Letaba, located in the Limpopo Province in northern South Africa, rainfall is higher (approximately 800 mm) and night-time temperatures do not fall below freezing. A hypothetical agricultural system consisting of one summer crop, maize, and one winter crop, tomato, was constructed. Similar to the tomato crop at Keimoes, this crop was supplementary irrigated with water of different salinities, whereas the maize was completely rainfed. Two leaching fractions (LF), as well as bare soil and plastic mulch treatments were compared at both sites. Since irrigation amounts and rates were considered fixed characteristics of the drip kits, different leaching fractions were assigned by changing the irrigation frequency and thus the amount of water used for irrigation. This was accomplished in the irrigation module by initiating irrigation every time the soil water content in the uppermost 15 cm of the soil was lower than specific threshold values. These were arbitrarily set to 35 and 50 mm for the low and the high leaching fraction, respectively. In this study, the low leaching fraction corresponded to about one or two irrigation events per day, whereas the high leaching fraction corresponded to approximately two or three irrigation events per day. For each irrigation event the plants received roughly 1.2 l of water per plant.

Evaluating ecosystem efficiency

To analyse the impact of different management approaches or the influence of climate, there are a number of other variables that can be used. One of the most common is water use efficiency (WUE), which in this thesis is defined as the ratio between net photosynthesis and transpiration. WUE is a measure of the combined impact of several plant and environmental variables on the relative size of carbon and water fluxes through stomata. For instance, WUE is known to vary between species with different photosynthetic pathways (e.g. Schulze et al., 2002). Most plants belong to a group normally defined as C_3 plants. The first step in the line of photosynthetic reaction is called carboxylation, and in these plants this step is catalysed by an enzyme called Rubisco. At low CO_2 concentrations in the sub-stomatal cavity, Rubisco's affinity for O_2 increases. Apart from the obvious disadvantage of spending the absorbed radiation on fixating the "wrong" gas (i.e. O_2), the process is also energy consuming and thus results in a loss of CO_2, termed photorespiration. Photorespiration occurs predominately at high rates of photosynthesis under optimal growing conditions, for example at midday in tropical regions with adequate water and nutrient supply. As the C_3 plant is spending energy on non-productive processes while maintaining transpiration, WUE will subsequently be reduced. A different group of plants, named C_4 plants, have developed a different kind of photosynthetic pathway that avoids competition between CO_2 and O_2 at low CO_2 concentrations. In these plants, an enzyme called PEP-carboxylase catalyses carboxylation. Compared with C_3 plants, this photosynthetic pathway is not as efficient under non-limiting CO_2 conditions, and thus C_4 plants are common only in tropical climates where high radiation levels causes CO_2 deficiencies under optimal growing conditions. In addition, stomatal conductance is generally higher for C_3 plants compared with C_4 plants, which also contributes to the higher WUE in the C_4 crops.

As a more general indicator of water, salt and atmospheric stress in the ecosystem, the ratio between net photosynthesis and absorbed radiation, in this thesis called the radiation use efficiency (RUE), is a helpful variable. From an ecohydrological point of view, freshwater productivity, which relates yield to the amount of freshwater supplied to the system, is a measure of how much produce that can be derived from a certain input of water. This measure is based on the assumption that saline water is unsuitable for anything but for irrigation purposes. Unfortunately, this variable is slightly misleading, since it does not say anything about the partitioning into consumptive flows on the one hand, and drainage and runoff formation on the other. It is however difficult to calculate a relevant index for water productivity of saline water irrigation on the drainage basin scale, since the blue water flow from the farmer's field may be polluted with salts that may have a negative impact on water productivity for downstream farmers.

RESULTS AND DISCUSSION

Is there a potential for saline water irrigation in sub-Saharan Africa?

By correlating electrical conductivity in the uppermost aquifer with annual average rainfall in South Africa, two regions, the Limpopo Province in the north, and the Karoo in the central western part of the country, were identified as regions with a potential for saline water irrigation (Paper I). In the Limpopo Province, salinities range from 1-4 dS m^{-1} and the average annual rainfall is between 500-650 mm in large parts of the province. Supplementary irrigation of vegetable crops grown during the dry winter season is a common practice by the small-scale farmers in the region using either river water, which in some cases is slightly saline, or freshwater collected from roofs in large water tanks. Using saline groundwater that could be pumped using a simple treadle pump would save precious freshwater for the farmers and decrease the time spent on fetching irrigation water from the river. The Karoo semi-desert has higher groundwater salinity, with values up to 10 dS m^{-1} or more in some areas. While rainwater levels are generally too low to maintain crop production, supplementary irrigation with saline groundwater irrigation water might enable the farmers to produce one crop per year. Even though these systems may possibly require more elaborate management practices to achieve sustainability when compared to the Limpopo province, due to the thirsty atmosphere in the region, the problem of polluting downstream ecosystems and underlying aquifers is smaller if these water bodies are already saline.

Yields from tomato irrigated with low-cost drip systems using saline water

Yield (i.e. total fruit wet weight) from tomato irrigated with low-cost drip systems was above the average marketable yield in South Africa of 31.5 Mg ha^{-1} (FAO, 2004), for the first and the second growing season using saline water (6 dS m^{-1}) (Paper II). Plastic mulch improved yield by, on average, 10 Mg ha^{-1} for both saline and non-saline treatments, whereas yield was not affected by the discharge rate of the drip systems. Salt accumulation in the root-zone seemed to be strongly dependent on rainfall. During drier periods salts began to build up, but were subsequently leached again during periods of higher rainfall. A decrease in average soil salinity of 3-5 dS m^{-1}, depending on the treatment, was estimated for a four-week period of heavy rainfall during autumn, which can be compared with maximum soil salinity concentrations of approximately 15 dS m^{-1}.

Developing and testing an integrated ecosystems model

Plant response to high concentrations of salts in the soil was simulated both as a reduction in water uptake and as an increase in plant respiration. When applying the model to the dataset collected during the autumn in Israel, the first approach gave the best correlation with measured photosynthesis and transpiration (Paper III). On the other hand, during spring, the increased respiration approach showed better agreement with measurements. Interestingly, the underlying assumptions about WUE differ between approaches. In the former case, WUE is unaffected by irrigation water salinity, whereas for the latter approach, WUE is lower at high soil salinity concentrations. Most likely, a combination of these two approaches will probably describe plant response to soil salinity levels most accurately; however, this may vary between plant species.

Secondly, photosynthesis and transpiration was modelled for different climates. High levels of radiation and vapour pressure deficit, as well as extreme air temperatures, affected both photosynthesis and transpiration, and thus WUE (Paper III and IV). Generally, a dry and hot climate leads to temperature stress, high levels of transpiration and radiation saturation, resulting in low WUE. It was found that WUE could differ by a factor two between seasons.

Finally, soil evaporation in a drip-irrigated system was studied using microlysimeter measurements from the field-grown tomato trial conducted in South Africa. The partially wetted surface characteristic of drip irrigation, in combination with relatively low radiation absorption of the wetted area due to shadowing of the plant canopy, results in relatively low levels of soil evaporation in comparison with rainfed systems (Paper IV). The CoupModel was developed to account for both the distributed surface and the shadowing of the plant in relation to that surface, and was found to accurately estimate transpiration and photosynthesis for saline conditions under different climates (Paper III and IV).

Impact of management

The water balance for saline-water drip-irrigation systems varied with different management approaches (Paper IV and V). In the dry and hot climate at Keimoes, transpiration constituted almost 60% of the total amount of water added when a low irrigation frequency with fresh water was applied. The corresponding figure for soil evaporation was approximately 40% and surface runoff and drainage was negligible. Using saline irrigation water (9 dS m^{-1}), which is commonly found in the uppermost aquifer in this region, the figure for soil evaporation exceeds 90% of the total amount of water added to the system. Low transpiration levels also caused an increase in drainage, creating a positive feedback on growth by increasing the leaching of salts from the root-zone. Furthermore, the water balance is affected by the leaching fraction; at high leaching fractions a substantial amount of water is lost as drainage from the system. It was also found that using mulch to cover the soil leads to a decrease in soil evaporation. In the milder climate at Letaba, management practices affected the water balance of the system in a similar way, although the impact was not as large as at Keimoes. The biggest difference between the two sites was that more water was lost as drainage and runoff at Letaba compared with Keimoes. Finally, the drip-system discharge rate was found not to influence the water flows in the system. It is commonly assumed that the wetting pattern varies with discharge rate (Dasberg & Or, 1999); however, in a recent study by Li *et al.* (2004), it was shown that the ratio between wetted radius and wetted depth between systems with different discharge rates was rather small after twelve hours. Since irrigation took place at sunset, this might explain why there was no difference between systems.

Predictions of sustainability and yield

Yield of drip-irrigated tomatoes at Keimoes was above the average marketable yield for all salinity treatments when irrigating with a high leaching fraction (Paper V). Between seasons all salts were leached out from the soil profile. On the contrary, at the lower leaching fraction salts built up in the soil during dry years, causing a significant reduction of yield to levels below the average marketable yield even at low salinity levels (3 dS m^{-1}). Apart from increasing the amount of time spent on irrigation per day, a higher leaching fraction also resulted in a greater salt load to the groundwater and/or downstream ecosystems, as well as an increased risk for waterlogging. By covering the soil with a plastic mulch to further minimise soil evaporation, the irrigation amount is lowered and thus leaching is slightly reduced.

At the Letaba site the importance of leaching was smaller due to the milder climate and higher rainfall (Paper V). Therefore, even at the lower irrigation frequency an estimated yield above 100 Mg ha^{-1} was obtained for the high irrigation water salinity treatment (9 dS m^{-1}). At high irrigation water salinities, the treatments with a high leaching fraction performed worse than those with a low leaching fraction due to the higher salt load in the soil. At both irrigation leaching fractions, most of the salt was leached from the uppermost soil profile after each cropping season with saline irrigation; however, at the lower leaching fraction, high salinity levels still remained in the soil when the second crop was planted, thus causing yield reductions. The latter problem could be avoided if the leaching fraction was temporarily increased before planting of the second crop to provide sufficient leaching.

One aspect of saline water irrigation that was not accounted for in the modelling approach is the potential formation of a salt crust at the soil surface. This salt might dissolve and leach down into the root-zone in the case of an irrigation event, thus causing plant stress and subsequent yield reductions. In this context, the reduction of soil evaporation using mulch is therefore of importance since it would minimise the likelihood of salt crust formation.

Ecosystem analysis

WUE depends on several environmental factors; some of which are non-negotiable and some that are affected by management approaches (Paper III and V). Different types of climatic stress can lead to reduced WUE as shown in Figure 3, in which a supplementary irrigated tomato crop grown in the summer at Letaba (L) is compared with the same crop from Keimoes (K). Due to higher temperature stress, a "thirstier" atmosphere (high VPD) and a greater degree of radiation saturation, WUE for the Keimoes plant was half that of the plant grown at Letaba. WUE also varies substantially between seasons, as demonstrated in the field experiment simulations from South Africa (Fig. 3). The drier and hotter climate during spring (S) resulted in a lower WUE compared with autumn (A). As stated previously, the photosynthetic pathway of the plant can affect WUE. In this study, the tomato represents C_3 plants, whereas maize represents a C_4 plant. Surprisingly, simulations of supplementary irrigation of maize (M) and tomato (T) grown during summer at Letaba show a similar WUE for both crops (Fig. 3). Even though maize, being a C_4 plant, could have been expected to have a higher WUE compared to the tomato plant, the tomato's WUE is high due to the large allocation of assimilates to fruits, which has a low maintenance respiration. In addition, stomatal conductance was not adjusted for maize, which may partly explain the lack of any difference between the two types of crops. Furthermore, it was shown that salinity stress could influence WUE; however, it remains unclear to what degree different salinity response processes influence the relationship between transpiration and net photosynthesis (Paper III). If the reduced growth of the plant subject to high soil salinity concentrations is caused by a lower water uptake, WUE is unaffected by the stress. On the other hand, if high levels of maintenance respiration are instead responsible for reduced growth, WUE can be expected to be lower at high salinities. In the simulations of the tomatoes grown in Israel during autumn, WUE was higher at high irrigation water salinity compared with at low salinity (N), when the first approach (W) was incorporated in the model (Fig. 3). The reason for this was that the stressed plants were smaller than the non-stressed plants. Thus, plant size has an important impact on WUE, as confirmed in field experiments (de Soyza et al., 1996; Marler & Mickelbart, 1998). For the second approach (Re), simulated WUE was lower compared with N (Fig. 3). Finally, plant allocation patterns affect WUE to some degree. An increased allocation of assimilates to roots (Ro) and fruits (F) of 10% compared to normal (N), both resulted in a higher WUE due to lower maintenance respiration in roots and fruits compared with other plant organs (Fig. 3).

RUE is a general indicator of the level of stress in the ecosystem and can thus be expected to vary between regions and with different management approaches (Paper V). For a supplementary irrigated tomato crop grown during summer at Letaba, RUE was higher than for the same plant grown at Keimoes, where plants are subject to higher temperature stress, radiation saturation and high VPD (Fig. 4). When the Keimoes plant was irrigated with saline water (9 dS m^{-1}), RUE decreased even further.

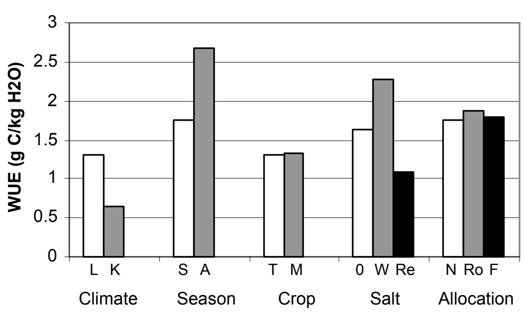

Figure 3. Comparison between water use efficiency for different climates, seasons, crops, irrigation water salinities and allocation patterns. L = Letaba; K = Keimoes; S = Spring; A = Autumn; T = Tomato; M = Maize; 0 = no salt in irrigation water; W = water uptake approach for salinity stress; Re = respiration approach for salinity stress; N = normal allocation pattern; Ro = increased allocation to roots; F = increased allocation to fruits.

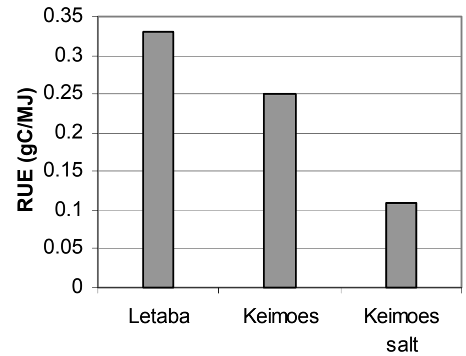

Figure 4. Radiation use efficiency for a supplementary irrigated tomato crop grown during summer at two different sites, Letaba and Keimoes. A comparison between freshwater and saline water (9 dS m^{-1}) irrigation at Keimoes is also made.

While WUE is a measure of the potential biomass growth per transpiration unit under certain conditions and for particular crops, it does not adequately capture the total amount of water use per unit crop produce. Thus, in the latter case, water productivity, i.e. net photosynthesis per unit consumptive water flow, is a much more appropriate measure. Water productivity includes both soil and interception evaporation, while excluding water loss from the system that can be extracted by down-stream water users. In tropical ecosystems with ample radiation levels, growing conditions are often far from optimal, high temperatures regularly cause plant stress, and CO_2 concentrations limit midday photosynthesis. RUE is a very good measure of the combined impact of these limiting factors on growth. Therefore, the variable is of less value in temperate ecosystems, where radiation itself is often the main determinant of growth. The modelling approach applied in the thesis accounted for growth reduction due to both stomatal closure at high VPD, as well as CO_2 limitation in C_3 plants, in a physiologically based manner. Disregarding these two important processes in tropical ecosystems will lead to an overestimation of growth, or alternatively they would have to be accounted for in an empirical way in more simple growth models.

Implications of the findings for the farmer

From a farmer's perspective, long-term yield, the time spent on irrigation and water availability will determine the choice of irrigation method and management technique, whereas factors such as downstream effects might be of minor importance. In dry and hot regions, such as the Gordonia region in which Keimoes is situated, it can be assumed that farmers would prefer higher leaching fractions, since lower leaching fractions did not prove sustainable when using saline water irrigation. It could further be assumed that the farmers would choose not to include mulch in the system, since the gains in yield are only small and mulch is costly and requires more labour. Figure 5a depicts this scenario using a range of fresh and saline water inputs. Not surprisingly, the highest yield is achieved when using fresh water irrigation, but this assumes a substantial allocation of fresh water to irrigation purposes. On the other hand, if the crop is only rainfed, harvest is predicted to fail in most years. By irrigating with water of a salinity level up to 9 dS m^{-1}, yields are expected to be lower than when fresh water is used, while still reaching an above average marketable yield. The farmer must in each case balance the reduction in yield against the gain in freshwater savings to decide upon the optimum use of saline water. In addition, the time spent irrigating every day and the amount of water needed for irrigation, are both quite high, which is likely to be an important constraint for the farmer.

In wetter areas, such as at Letaba, rainfall is large enough to provide for sufficient leaching even at the lower leaching fraction. Since the aspect of time, water and cost saving is important to farmers, it can be assumed that they would choose the lower leaching fractions that only requires one or two irrigation events per day, and that they would choose not to use mulch. In this region it is possible to obtain a crop yield above average marketable yield for most years, even without irrigation (Fig. 5b). Nonetheless, yield is improved by irrigating the crop either with saline or fresh water. Just like in the previous example, the gains in freshwater savings must be balanced against yield loss for each salinity level. Finally, if a salt crust at the soil surface starts developing, the farmer may want to consider using mulch at both locations.

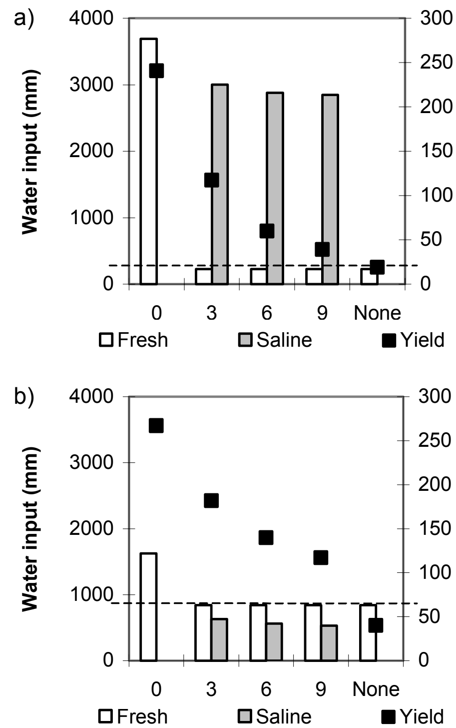

Figure 5. Water input and yield for a range of irrigation options at a) Keimoes and b) Letaba. None = no irrigation; 0 = 0 dS m^{-1} in irrigation water; 3 = 3 dS m^{-1} in irrigation water; 6 = 6 dS m^{-1} in irrigation water; 9 = 9 dS m^{-1} in irrigation water. The dashed line indicates the annual average rainfall level at each site.

Implications of the findings for the ecohydrologist

From an ecohydrologist's point of view, not only will long-term yield be of interest, but also fresh water productivity and leaching of salts. In the Keimoes region the high load of salts to the groundwater and downstream aquifers has been identified as significant when using a high leaching fraction. Since saline water irrigated agriculture is not feasible without the appropriate leaching of salts, the only possibility to minimise leaching is to reduce the non-productive evaporative flows from the system and in doing so, lowering irrigation requirements. Assuming that farmers are willing and able to apply mulch to their fields, soil evaporation can be minimised. As shown in Figure 6a, the amount of yield per unit of freshwater input (i.e. freshwater productivity) is highest at the lowest irrigation water salinity level and decreases with increasing salinity. The lowest water productivity is found when freshwater is used for irrigation. However, the latter value is slightly misleading since the creation of drainage and runoff has a value for downstream users and ecosystems. On the contrary, the creation of runoff and drainage when saline irrigation water is used is a potential pollutant rather than a resource. Figure 6a illustrates this trade-off by showing gains in freshwater productivity against potential pollution of downstream ecosystems, exemplified in this case by the amount of salts in the drainage water for a range of irrigation options. Thus, for each irrigation project the gains in fresh water productivity from saline water irrigation have to be balanced against the leaching of salts. In this context, it is worth noting that apart from the amount of salts leaving the root-zone, the salt concentration of the drainage water also has to be considered.

In more humid regions, in this case represented by the Letaba station in the Limpopo Province, fresh water productivity is higher when using irrigation compared to without (Fig. 6b). The highest fresh water productivity is found at low irrigation water salinities (3 dS m^{-1}), but already at intermediate salinity levels (6 dS m^{-1}) water productivity equals that of fresh water productivity. In addition, fresh water irrigation is likely to generate beneficial drainage water and runoff. Thus, from an ecohydrological perspective, it is better to choose fresh water for irrigation purposes rather than water of a higher salinity, i.e. greater than 4 dS m^{-1}. However, all irrigation treatments, irrespective of salinity, generated a higher freshwater productivity compared to the rainfed crop. Similarly to drier regions, the gains in water productivity therefore need to be related to the impacts of leaching.

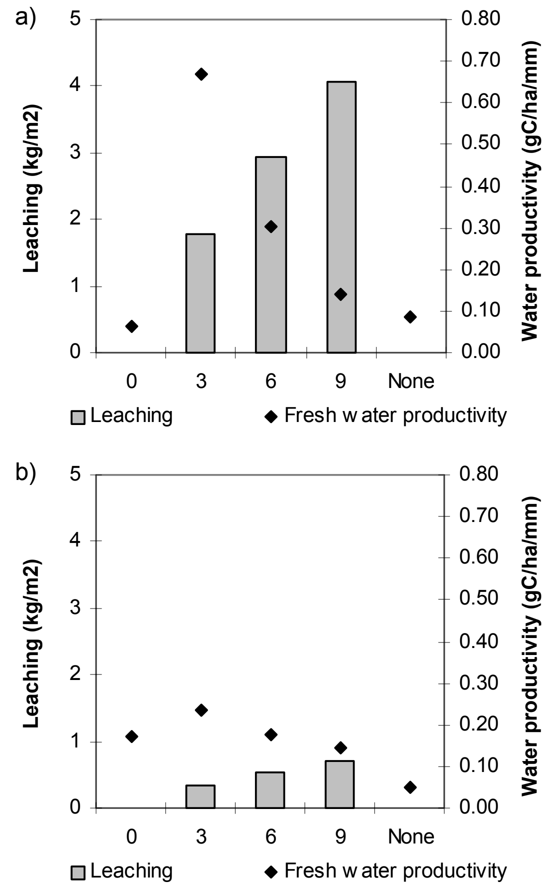

Figure 6. Fresh water productivity and leaching for a range of irrigation options at a) Keimoes and b) Letaba. None = no irrigation; 0 = 0 dS m^{-1} in irrigation water; 3 = 3 dS m^{-1} in irrigation water; 6 = 6 dS m^{-1} in irrigation water; 9 = 9 dS m^{-1} in irrigation water.

GENERAL CONSIDERATIONS CONCERNING IMPLEMENTATION

No irrigation system can be successfully implemented if it is done without considering social implications. A prerequisite for farmers to adopt saline-water drip-irrigation is that there has to be apparent benefits from using the technology. Reduced water costs and labour, the potential to target off-season markets and the bridging of dry-spells are obvious incentives. While acknowledging the vital importance of these factors, it has not been the focus of this project to study them further. However, the management techniques and equipment (i.e. drip-irrigation kits, mulching, etc.) studied in this project have been chosen to resemble the farmers' situation as far as possible. Several factors external to households, such as access to markets to sell produce and buy fertiliser and equipment, access to micro-finance, technologies, infrastructure, institutions, land entitlements, the level and distribution of community wealth, and population growth, influence the success of an irrigation project (Reardon & Vosti, 1995; Scherr, 2000). In addition, a lack of reliable and affordable transportation to market places is a common constraint to farmers in many rural areas in sub-Saharan Africa. Marketing of agricultural produce is difficult for the small-scale farmers and results in lower competition and hence lower prices for the produce. National legislation, for example concerning water pricing, will have a direct impact on economic benefits derived by farmers. The introduction of drip irrigation, which is traditionally perceived as a complex, high technology technique, to rural farmers requires particular sensitivity. More often than not these rural farmers are illiterate and may have faced several hardships, such a crop failure and the inability to meet their own and their family's basic food requirements (de Lange *et al.*, 2000). In this context, the training of farmers has to be adapted to fit their special needs and must incorporate and respect the indigenous knowledge and traditions present in the local community. Extension officers need to acquire sufficient knowledge to take over the role of the irrigation expert after the training programme and the implementation of the techniques are completed.

Irrigation with saline water may pose a threat to sustainable development and cause severe environmental impacts (Beltrán, 1999). Sustainable agricultural development is a broad concept that has been defined as "…a system that can evolve indefinitely toward greater human utility, greater efficiency of resource use and a balance with the environment which is favourable to humans and most other species" (Harwood, 1990). Sustainable irrigation with saline water requires that some additional water, above what is needed for evapotranspiration, is added to the soil to remove the salts from the root-zone, i.e. a leaching fraction (Meiri, 1984; Rhoades *et al.*, 1992). As was shown in this study, the size of the leaching fraction depends on several factors, such as crop salt tolerance, climate, irrigation practices, soil type and mulching. In addition, appropriate drainage of the leaching fraction is required to avoid encountering problems with water-logging. This drainage water may in turn have an environmental impact on down-stream areas, the groundwater and/or the surrounding surface water. One example of an irrigation project that has had a detrimental effect on surrounding ecosystems is the San Joaquin Valley in California, U.S.A. (Rhoades *et al.*, 1992). Once a lush patch-work of aquatic wetland, riparian forest and valley savannah with a teeming biological diversity, a hundred and fifty years of irrigation in the valley has resulted in tremendous losses in native habitat, and fish and wildlife populations are a fraction of what they used to be. A thorough assessment of potential environmental consequences is thus crucial before adopting an irrigation scheme with saline waters. These side effects have not been addressed within this project, and the term sustainability was only used to refer to sustainable crop yield from the farmer's field.

RECOMMENDATIONS ON MANAGEMENT STRATEGIES

In order to achieve sustainability when irrigating with saline water, management strategies must aim to achieve two things: to minimise soil evaporation from the surface and to apply enough water to the field to ensure leaching of excess salt ions from the root-zone. Low-cost drip irrigation is suitable to use for irrigation with saline water, since it minimises salt accumulation in the soil, leaves are not subject to leaf burn, and peaks in salt concentrations are avoided. Even though discharge rates vary substantially between different systems and with the height of the water tank, this does not seem to have any significant importance for the water balance and the concomitant salt accumulation and crop yield. Water with a salinity of up to at least 9 dS m^{-1} can be successfully used for the irrigation of vegetables, depending on the salinity tolerance of the crop and the average marketable yield. However, yield and salt accumulation is strongly dependent on climate and management approach. In dry and hot climates with low annual precipitation, a high leaching fraction is needed to provide sufficient leaching of salts in order to prevent salt accumulation in the uppermost part of the soil. For a small garden irrigated from a 25 l bag or tank, this could mean two to three irrigation events per day, depending on the climate. A side effect of increasing the leaching fraction is that more salts are introduced into the system, causing large transfers of salts to underlying aquifers and downstream ecosystems. By further minimising soil evaporation, for example by covering the soil with mulch, less water is needed for satisfying the leaching requirements and thus the amount of salts leaving the system will be lower. In addition, mulching will help to prevent the formation of a salt crust on the surface. In hot and more humid climates with higher annual precipitation, less water is needed for leaching. Thus, in the case of the small garden, irrigating once or twice per day would be sufficient to achieve adequate leaching and hence sustainability. However, at the end of the growing season it might be wise to increase the leaching fraction slightly to leach out remaining salts in order to prevent yield loss from subsequent crops.

FUTURE RESEARCH

Despite the fact that the model was successful in simulating long-term yield and sustainability for a number of management options in a saline-water drip-irrigated agro-ecological system, it contains some very simplified descriptions for parts of the system. Soil water content and salt accumulation in the root-zone are typically two-dimensional characteristics in drip-irrigation systems, a fact not taken into consideration by the model. The latter characteristic can be beneficial, as salt accumulates away from the roots of the plant; however, it can also be problematic, if this causes a large salt load in the root-zone in the event of rainfall. Not accounting for these phenomena may have generated errors in the simulations, and there is thus a need to further develop the model in these respects.

Furthermore, the irrigation module could easily be refined to allow for more sophisticated irrigation scheduling. For example, the automatic irrigation approach used for the 30-year simulations, in which irrigation is governed by soil water content in the root-zone, could lead to a sub-optimisation of irrigation if the event takes place during midday, or could be unrealistic if irrigation takes place in the middle of the night. More advanced criteria should be included in the irrigation module to allow the user to estimate optimal irrigation schedules.

The thesis has provided some examples of how the model can be applied to study the impact of different management approaches on irrigated agro-ecological systems in tropical regions, and how variables such as WUE, RUE and WP can be estimated to analyse these systems. This tool could thus be applied to answer many pressing questions on agricultural potential and water productivity under different hydroclimatic conditions, as well as the impact of management practices. For example, gains in water productivity from different activities, such as by changing from one crop type to another, adding fertiliser to a crop, or implementing a supplementary irrigation system, can be estimated. By coupling this one-dimensional model to a regional model, it would be possible to upscale the impact of changes from implementing management techniques in the fields for the whole catchment.

From what has been said above, it is clear that the model can be used as a tool by both regional water planners and extension officers. The huge obstacle for the application of models in planning lies in the lack of user friendliness and the access to computers. In terms of user friendliness, this could be improved by simplifying the number and character of many options and the layout of many models, in addition to producing simple instruction booklets and providing training. By linking the model to a database containing information about crops, soils, climate and management techniques, less information needs to be collected in the field. Thus, ideally, the user would only be required to choose between a number of crops, soils and management options, and to provide a location to link the site to a specific hydroclimate.

CONCLUSIONS

There is a potential for saline-water irrigation of crops in water scarce areas. Agricultural systems based on low-cost drip irrigation with saline water (6 dS m^{-1}) resulted in a successful harvest from two consecutive crops of tomato in semi-arid South Africa. An integrated ecosystems model for the study of crop yield and long-term sustainability in a drip irrigation system with saline water was developed. The usability of the model as an evaluative tool for specific management options was subsequently successfully tested on data from two field experiments on tomatoes. Special emphasis was placed on assessing the effect of salinity stress on plant growth, estimating soil evaporation from a distributed (wetted and dry) surface, and the interaction between climate on the one hand and photosynthesis and transpiration on the other. The applicability of the model was demonstrated by analysing the water balance in the drip-irrigation system for different management options. Furthermore, 30-year simulations were run for two sites in South Africa, to evaluate the impact of different management approaches on long-term sustainability and yield. These simulations highlighted the importance of rainfall to provide adequate leaching of salts from the root-zone. In addition, it was shown that irrigation water requirements to achieve a sustainable leaching fraction could be reduced by applying mulch, thus minimising soil evaporation even further. Decisions on the selection of the optimal irrigation water salinity, leaching fraction and soil coverage may differ between the farmer and ecohydrologist, due to different preferences. While the farmer aims at maximising yield, while minimising labour, time and water inputs, the ecohydrologist is likely to be more focused on balancing fresh water productivity against potential pollution of nearby water bodies. The modelling approach allowed WUE and RUE to be calculated, which proved to be useful indices of ecosystem behaviour. RUE is a general indicator of the stress level in the ecosystem, while WUE specifically measures the combined influence of a number of factors affecting the exchange of water and carbon dioxide through stomata. One of the greatest challenges in the future lies in successfully balancing water allocated for food production versus water allocated to nature. In this respect, the sustainable use of saline water for crop production has significant potential.

REFERENCES

Abel, G.H. and MacKenzie, A.J., 1964: *Salt tolerance of soybean varieties (* Glycine max *L. Merrill) during germination and later growth*. Crop Sci. 4: 157-160.

Al-Tahir, O.A. and Al-Abdulsalam, M.A., 1997: *Growth of faba bean (* Vicia faba *L.) as influenced by irrigation water salinity and time of salinization*. Agr. Water Manage. 34: 161-167.

Annandale, J.G., Benadé, N., Jovanovic, N.Z., Steyn, J.M. and Du Sautoy, N., 1999: *Facilitating irrigation scheduling by means of the soil water balance model*. WCR Report No 753/1/99. Water Research Commission, South Africa. 285 pp.

Ayers, R.S. and Westcot, D.W., 1985: *Water quality for agriculture*. FAO Irrigation and Drainage Paper, Food and Agriculture Organisation (FAO), United Nations, Rome, Italy. 29 rev.1.

Barron, J., 2004: *Dry spell mitigation to upgrade semi-arid rainfed agriculture: water harvesting and soil nutrient management for smallholder maize cultivation in Machakos, Kenya*. Doctoral thesis in Natural Resource Management, Department of Systems Ecology, Stockholm University, Sweden. 39 pp.

Belmans, C., Wesseling, J.G. and Feddes, R.A., 1983: *Simulation model of the water balance of a cropped soil: SWATRE*. J. Hydrol. 63: 271-286.

Beltrán, J.M., 1999: *Irrigation with saline water: benefits and environmental impact*. Agr. Water Manage. 40: 183-194.

Bernstein, L., 1964: *Salt tolerance of plants*. Agriculture Information Bullentin No. 283, U.S. Department of Agriculture, U.S. 23 pp.

Bresler, E., McNeal, B.L. and Carter, D.L., 1982: *Saline and sodic soils: principles-dynamics-modeling*. Advanced Series in Agricultural Sciences 10. Springer Verlag, Berlin, Germany. 236 pp.

Brugnoli, E. and Björkman, O., 1992: *Growth of cotton under continuous salinity stress: influence on allocation pattern, stomatal and non-stomatal components of photosynthesis and dissipation of excess light energy*. Planta. 187: 335-347.

Chigerwe, J., Manjengwa, N., van der Zaag, P., Zhakata, W. and Rockström, J., 2004: *Low head drip irrigation kits and treadle pumps for smallholder farmers in Zimbabwe: a technical evaluation based on laboratory tests*. Phys. Chem. Earth. 29: 1049-1059.

Chitsiko, R.J. and Mudima, K.T., 2002: *Adapting modern irrigation technologies for use by smallholder farmers - the Zimbabwean experience*. Paper presented at the seminar: "Smallholder Land and Water Management Systems - Sharing Lessons from Experiences in Africa and Asia", 1-5 July 2002, Bangkok, Thailand. 11 pp.

Dai, Y., Dickinson, R.E. and Wang, Y.-P., 2004: *A two-big-leaf model for canopy temperature, photosynthesis and stomatal conductance*. J. Climate. 17(12): 2281-2299.

Dasberg, S. and Or, D. 1999: *Drip irrigation*. Springer-Verlag. Berlin, Germany. 162 pp.

de Lange, M., Adendorff, J. and Crosby, C.T., 2000: *Developing sustainable small-scale farmer irrigation in poor rural communities: introduction to guidelines and checklists for trainers and development facilitators*. 6th International Micro-Irrigation Congress, "Micro-irrigation Technology for Developing Agriculture", Conference Papers. South Africa. 15 pp.

de Soyza, A.G., Franco, A.C., Virginia, R.A., Reynolds, J.F. and Whitford, W.G., 1996: *Effects of plant size on photosynthesis and water relations in the desert shrub* Prosopsis glandulosa *(Fabaceae)*. Am. J. Bot. 83(1): 99-105.

de Wit, C.T., 1958: *Transpiration and crop yields*. Verslagen van Landbouwkundige Onderzoekingen, No. 64.6, Wageningen, the Netherlands. 88 pp.

du Plessis, F.J. and van der Stoep, I., 2000: *Evaluation of the appropriateness and management requirements of micro-irrigation in small-scale farming*. 6th International Micro-Irrigation Congress, "Micro-irrigation Technology for Developing Agriculture", Conference Papers, South Africa. 11 pp.

Epstein, E., 1980: *Responses of plants to saline environments*. In: Rains, D.W., Valentine, R.C. and Hollaender, A. (Eds.), Generic engineering of osmoregulation: impact on plant productivity for food, chemicals and energy. Plenum Press, New York, U.S. 381 pp.

FAO, 1997: *Small-scale irrigation for arid zones. Principles and options*. FAO, Development Series 2. Food and Agriculture Organisation of the United Nations, FAO, Rome, Italy. 51 pp.

FAO, 2004: *A perspective on water control in southern Africa. Support to regional investment initiatives. Land and water discussion paper 1*. Subregional Office for Southern and East Africa and FAO Land and Water Development Division, FAO, Rome, Italy. 36 pp.

Falkenmark, M. and Rockström, J., 1993: *Curbing rural exodus from tropical drylands*. Ambio. 22(7): 427-437.

Falkenmark, M. and Rockström, J., 2004: *Balancing water for humans and nature - the new approach in ecohydrology*. Earthscan, London, UK. 247 pp.

Farquhar, G.D., von Caemmerer, S. and Berry, J.A., 1980. *A biochemical model of photosynthetic CO_2 assimilation in leaves of C3 species*. Planta. 149: 78-90.

Feddes, R.A., 1988: *Modelling and simulation in hydrologic systems related to agricultural development: state of the art*. Agr. Water Manage. 13: 235-248.

Feddes, R.A., Kowalik, P.J. and Zaradny, H., 1978: *Simulation of field water use and crop yield*. Centre for Agricultural Publishing and Documentation, Wageningen, the Netherlands. 189 pp.

Ferrer-Alegre, F. and Stöckle, C.O., 1999: *A model for assessing crop response to salinity*. Irrig. Sci. 19: 15-23.

Fox, P. and Rockström, J., 2003: *Supplemental irrigation for dry-spell mitigation of rainfed agriculture in the Sahel*. Agr. Water Manage. 1817: 1-22.

Fung, L.E., Wang, S.S., Altman, A. and Hütterman, A., 1998: *Effect of NaCl on growth, photosynthesis, ion and water relations of four poplar genotypes*. Forest Ecol. Manag. 107: 135-146.

Greenway, H. and Munns, R., 1980: *Mechanisms of salt tolerance in nonhalophytes*. Annual Review of Plant Physiology. 31: 149-190.

Greenway, H. and Munns, R., 1983: *Interactions between growth, uptake of Cl- and Na+, and water relations of plants in saline environments. II. Highly vacuolated cells*. Plant Cell Environ. 6: 575-589.

Harwood, R.R., 1990: *A history of sustainable agriculture*. In: C.A. Edwards, R. Lal, P. Madden, R. Miller and G. House (Eds.). Sustainable Agricultural Systems. Soil and Water Conservation Society, Ankeny, Iowa, U.S. 3-19.

Hussain, G., Al-Jaloud, A.A., Al-Shammary, S.A., Karimulla, S. and Al-Aswad, S.O., 1997: *Effect of saline irrigation on germination and growth parameters of barley (*Hordeum vulgare *L.) in a pot experiment*. Agr. Water Manage. 34: 125-135.

IFPRI, 2004: *2003-2004 Annual report*. International Food Policy Research Institute (IFPRI), Washington D.C., U.S. 74 pp.

Jacoby, B., 1994: *Mechanisms involved in salt tolerance by plants*. In: Pessarakli, M. (Ed.), Handbook of Plant and Crop Stress. Marcel Deker, Inc., New York, U.S. 97-123.

Jansson, P-E. and Halldin, S., 1979: *Model for the annual water and energy flow in a layered soil*. In: S. Halldin (Editor), Comparison of Forest and Energy Exchange Models, Society for Ecological Modelling, Copenhagen. 145-163.

Jansson, P-E. and Karlberg, L., 2004: *CoupModel - Coupled heat and mass transfer model for soil-plant-atmosphere systems*. Royal Institute of Technology, Dept. of Land and Water Resources Engineering, Stockholm, TRITA-LWR report. 3087: 427 pp.

Kabutha, C., Blank, H. and van Koppen, B. 2000: *Drip irrigation kits for small-holder farmers in Kenya: experience and a way forward*. 6th International Micro-Irrigation Congress, "Micro-irrigation Technology for Developing Agriculture", Conference Papers, South Africa. 7 pp.

Katerji, N., van Hoorn, J.W., Hamdy, A., Mastrorilli, M. and Mou Karzel, E., 1997: *Osmotic adjustment of sugar beets in response to soil salinity and its influence on stomatal conductance, growth and yield*. Agr. Water Manage. 34: 57-69.

Katerji, N., van Hoorn, J.W., Hamdy, A. and Mastrorilli, M., 1998: *Response of tomatoes, a crop of indeterminate growth, to soil salinity*. Agr. Water Manage. 38: 59-68.

Khroda, G., 1996: *Strain, social and environmental consequences and water management in the most stressed water systems in Africa*. In: E. Rached, E. Rathgeber and D.B. Brooks (Eds.), Water Management in Africa and the Middle East - Challenges and opportunities, IDRC, Canada. 295 pp.

Lagerwerff, J.V. and Eagle, H.E., 1961: *Osmotic and specific effects of excess salts on beans*. Plant Physiol. 36: 472-477.

Leonardi, C., Guichard, S. and Bertin, N., 2000: *High vapour pressure deficit influences growth, transpiration and quality of tomato fruits*. Scientia Horticulturae. 84: 285-296.

Letey, J., Dinar, A. and Knapp, K.C., 1985: *Crop-water production function model for saline irrigation waters*. Soil Sci. Soc. Am. J. 49: 1005-1009.

Li, J., Zhang, J. and Rao, M., 2004: *Wetting patterns and nitrogen distributions as affected by fertigation strategies from a surface point source*. Agric. Water Manage. 67: 89-104.

Li, Y.L., Stanghellini, C. and Challa, H., 2001: *Effect of electrical conductivity and transpiration on production of greenhouse tomato (* Lycopersicon esculentum *L.)*. Scientia Horticulturae. 89: 9-21.

Lindroth, A., 1985: *Canopy conductance of coniferous forests related to climate*. Water Resour. Res. 21(3): 297-304.

Lohammar, T., Larsson, S., Linder, S. and Falk, S.O., 1980: *FAST – simulation models of gaseous exchange in Scots pine*. In: T. Persson (Editor), Structure and Function of Northern Coniferous Forests – An Ecosystem Study, Ecol. Bull., Stockholm. 32: 505-523.

Läuchli, A. and Epstein, E., 1990: *Plant responses to saline and sodic conditions*. In: K.K. Tanji (Ed.), Agricultural Salinity Assessment and Management, ASCE Manuals and Reports on Engineering Practice No.71, ASCE, N.Y., U.S. 113-137.

Maas, E.V., 1986: *Salt tolerance of plants*. Applied Agricultural Research. 1(1): 12-26.

Maas, E.V. and Hoffman, G.J., 1977: *Crop salt tolerance - current assessment*. Journal of the Irrigation and Drainage Division. American Society of Civil Engineers (ASCE). 103: 114-134.

Maas, E.V., Hoffman, G.J., Chaba, G.D., Poss, J.A. and Shannon, M.C., 1983: *Salt sensitivity of corn at various growth stages*. Irrig. Sci. 4: 45-57.

Marler, T.E. and Mickelbart, M.V., 1998: *Drought, leaf gas exchange and chlorophyll fluorescence of field-grown papaya*. J. Am. Soc. Hortic. Sci. 123(4): 714-718.

Meiri, A., 1984: *Plant response to salinity: Experimental methodology and application to the field*. In: Shainberg, I. and Shalhevet, J. (Eds.), Soil Salinity under Irrigation: Processes and Management. Ecological Studies, Springer-Verlag, Berlin, Germany. 51: 284-297.

Monteith, J.L., 1965: *Evaporation and environment*. In: G.E. Fogg (Editor), The State and Movement of Water, in Living Organisms, 19th Symp. Soc. Exp. Biol., Cambridge: The Company of Biologists. 205-234.

Monteith, J.L., 1977: *Climate and the efficiency of crop production in Britain*. Philosophical Transactions of the Royal Society of London, Serie B. 281: 277-294.

Nimah, M.N. and Hanks, R.J., 1973: *Model for estimating soil water, plant, and atmospheric interrelations: I. Description and sensitivity*. Soil Sci. Soc. Am. J. 37: 522-527.

Pinstrup-Andersen, P., Pandya-Lorch, R. and Rosegrant, M.W., 1997: *The world food situation: recent developments, emerging issues, and long-term prospects*. Food Policy Report, The International Food Policy Research Institute (IFPRI), Washington D.C., U.S. 36 pp.

Postel, S., Polak, P., Gonzales, F. and Keller, J., 2001: *Drip irrigation for small farmers. A new initiative to alleviate hunger and poverty*. Water Int. 26(1): 3-13.

Reardon, T. and Vosti, S.A., 1995: *Links between rural poverty and the environment in developing countries: asset categories and investment poverty*. World Dev. 23(9): 1495-1506.

Rhoades, J.D., Kandiah, A. & Mashali, A.M., 1992: *The use of saline waters for crop production*. FAO Irrigation and Drainage paper. FAO, United Nations, Rome, Italy. 48 pp.

Rosegrant, M.W., Cai, X. and Cline, S.A., 2002: *World water and food to 2025: dealing with scarcity*. International Food Policy Research Institute (IFPRI), Washington D.C., U.S. 322 pp.

Scherr, S.J., 2000: *A downward spiral? Research evidence on the relationship between poverty and natural resource degradation*. Food Policy. 25(4): 479-498.

Schulze, E.-D., Beck, E. and Müller-Hohenstein, K., 2002: *Plant ecology*. Springer-Verlag, Berlin, Germany. 702 pp.

Sellers, P.J., Randall, D.A., Collatz, D.A., Berry, J.A., Field, C.B., Dazlich, D.A., Zhang, C., Collelo, G.D. and Bounoua, L., 1996: *A revised land surface parameterization (SiB2) for Atmospheric GCMs. Part I: Model formulation*. J. Climate. 9: 676-705.

Shalhevet J., 1994: *Using water of marginal quality for crop production: major issues*. Agr. Water Manage. 25: 233-269.

Shani, U. & Dudley, L.M., 2001: *Field studies of crop response to water and salt stress*. Soil Sci. Soc. Am. J., 65: 1522-1528.

Sijali, I.V., 2001: *Drip irrigation - options for smallholder farmers in eastern and southern Africa*. Technical Handbook No. 24, Regional Land Management Unit (RELMA), Nairobi, Kenya. 60 pp.

Smets, S.M.P., Kuper, M., van Dam, J.C. and Feddes, R.A., 1997: *Salinization and crop transpiration of irrigated fields in Pakistan's Punjab*. Agr. Water Manage. 35: 43-60.

Szabolcs, I., 1994: *Geostatistical modeling of salinity as a basis for irrigation management and crop selection - a case study in central Tunisia*. Environ. Geol. Water S. 20(2): 85-92.

Tanji, K.K., 1990: *Nature and extent of agricultural salinity*. In: K.K: Tanji (Ed.), Agricultural salinity assessment and management. ASCE Manual Reproductions of Engineering Practices. 71, New York.

Tesfamariam, E., 2004: *Modelling the soil water balance of canola (* Brassica napus *L. cv.* Hyola *60)*. M.Sc. Agric. Dissertation, University of Pretoria, South Africa.

UNEP, 1999: *GEO-2000, Global Environmental Outlook 2 (GEO-2)*. United Nations Environment Programme, UNEP, Nairobi, Kenya. 398 pp.

UNEP, 2002: *Global Environment Outlook 3 (GEO-3)*. United Nations Environment Programme (UNEP). Earthscan, London, UK. 416 pp.

van Dam, J.C., Huygen, J., Wesseling, J.G., Feddes, R.A., Kabat, P., van Walsum, P.E.V., Groenendijk, P. and van Diepen, C.A., 1997: *Theory of SWAP version 2.0. Simulation of water flow, solute transport and plant growth in the soil-water-atmosphere-plant environment*. Report 71, Department of Water Resources, Wageningen Agricultural University, Technical Document 45, DLO Winard Staring Centre, The Netherlands. 167 pp.

van Genuchten, M.Th., 1983: *Analyzing crop salt tolerance data: Model description and user´s manual*. Research Report No.120, United States Department of Agriculture, Agricultural Research Service, U.S. Salinity Laboratory, Riverside, California, U.S. 49 pp.

van Genuchten, M.Th. and Hoffman, G.J., 1984: *Analysis of crop salt tolerance data*. Ecological Studies: analysis and synthesis. 51: 258-271.

van Genuchten, M.Th. and Gupta, S.K., 1993: *A reassessment of the crop tolerance response function*. Journal of the Indian Society of Soil Science. 41(4): 730-737.

Vinten, A., Shalhevet, J., Meiri, A. and Peretz, J., 1986: *Water and leaching requirements of industrial tomatoes irrigated with brackish water*. Irrig. Sci. 7: 13-25.

Zeng, L., Shannon, M.C. and Lesch, S.M., 2001: *Timing of salinity stress affects rice growth and yield components*. Agr. Water Manage. 48: 191-206.