ECONOMIC MANAGEMENT OF WATER AND SALT STRESS FOR IRRIGATED AGRICULTURE: A PRECISION AGRICULTURE CASE STUDY

Report to the
WATER RESEARCH COMMISSION

by

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EXECUTIVE SUMMARY

BACKGROUND AND MOTIVATION

All over the world, pressure is mounting to use water more efficiently through the adoption of better irrigation technology, irrigation scheduling, site-specific management, and the cultivation of high-valued crops. A trade-off exists between improving irrigation scheduling practices, with the aim of improving water use efficiency, and reducing salt build-up in the soil. Uncontrolled build-up of salts in the soil may give rise to salinity levels that negatively affect crop growth and yield through osmotic pressure that reduces the availability of soil water, resulting in early plant-water stress and loss of yield.

Recently, the Water Research Commission (WRC) funded research on "Management guidelines for technology transfer to reduce salinisation of irrigated land with precision agriculture" (Van Rensburg *et al*., 2021a; 2021b; Barnard *et al*., 2021). The research provides methods for spatial assessment of soil water and salt status by using electromagnetic induction (EMI) techniques. The information gathered with the EMI techniques provides the necessary inputs to evaluate spatial management of soil water and salinity through using the transient state simulation model, Soil Water Management Programme (SWAMP). The project did not consider the financial implications of managing soil salinity, which is considered important in new technology adoption decisions.

Spatial economic management of salinity is complex, as it requires the irrigator to integrate information on irrigation water quality, irrigation technology, crop water requirements, salinity tolerance of crops and soil salinity levels, as well as economic parameters such as energy costs, other production costs and output prices. Previous research on the economics of salinity management over-simplified the representation of the soil-water-crop interactions under saline conditions, as they made use of steady state approaches in their economic models. Consequently, their modelling provides a misrepresentation of the impact of management decisions because the models do not take dynamic changes in soil water content and osmotic pressure into consideration. Site-specific spatial economic management of salinity requires an integrated modelling approach whereby an economic model is linked to a transient-state soil-water-crop model that can model the spatial variation within the soil-water-crop system.

PROBLEM STATEMENT AND OBJECTIVES

The unavailability of a modelling framework that accounts for the spatial, dynamic interactions between economics, management decisions and changes in the soil-water-crop systems hampers site-specific economic management of soil salinity.

The overall aim of the research is to develop and apply a bioeconomic model to economically manage site-specific water and salt stress in irrigated agriculture.

The project aim will be attained by achieving the following specific objectives:

- To develop and apply a bioeconomic model to economically manage site-specific water and salt stress in irrigated agriculture.
- To develop and integrate an economic model with a transient state salinity simulation model to evaluate the profitability of alternative salinity management guidelines for selected case studies.
- To optimise the integrated bioeconomic simulation model to determine optimal management strategies for selected case studies.
- To develop economic guidelines for managing site-specific water and salt stress.

APPROACH AND METHODS

This research is closely linked to the recently completed WRC-funded project on precision agriculture guidelines for managing salinisation carried out by Barnard *et al*. (2021). Data from the research conducted by Barnard *et al*. (2021) was used to characterise spatial production conditions in Vaalharts and Oranje-Riet as the case studies for this research.

The site-specific economic management of salinity requires a bioeconomic modelling framework that integrates economic decision-making with soil-water-crop simulation to determine the impact of alternative management actions on the soil-water-crops system. A literature review was conducted to familiarise the multi-disciplinary research team – consisting of agricultural economists and a soil/crop scientist – with the different components of bioeconomic salinity management. The fact that the members of the research team are from the same institution benefited the research as it allowed for frequent interactions.

Bioeconomic optimisation is complex and requires a thorough understanding of the workings of the different components (economics, soil-water-crop system, and optimisation) of the bioeconomic model to facilitate integration as well as interpretation of the results. The research team selected the SWAMP model to represent the soil-water-crop system. The economists were tasked with the integration of different components to develop the bioeconomic model. As part of their endeavours to understand SWAMP better, the calculation procedures of the model were reproduced in Excel spreadsheets. Implementing SWAMP in Excel spreadsheets enabled a seamless integration of SWAMP with the electricity cost calculation procedures developed by Venter *et al*. (2017) and readily available enterprise budget calculation procedures. The resulting integrated bioeconomic simulation model serves as a means to simulate the impact of predefined irrigation decisions on the status of the soil-water-crop system and the profitability thereof.

The impacts of spatial variability of soil properties and of salinity levels on the soil-water-crop system were accounted for by simulating the soil-water-crop system, using 36 SWAMP simulations. Each simulation represents the unique soil properties and salinity levels of the sections of a circular field under pivot irrigation. Optimising irrigation decisions with an evolutionary algorithm implies iteratively repeating the bioeconomic simulation model with different irrigation schedules, while evaluating the profitability of each iteration. A tight coupling between the algorithm and the simulation model is desirable to speed up the convergence of the solution to a near optimal solution.

The benefit of using spatial information to manage salinity is demonstrated by comparing a uniform irrigation strategy with a spatially optimised irrigation schedule in Vaalharts and Douglas. The predefined uniform strategy is simulated with the bioeconomic simulation model, while the spatially optimised irrigation schedule is optimised with the bioeconomic optimisation model.

SUMMARY OF RESULTS AND CONCLUSIONS

The results of applying a uniform irrigation strategy to the different soils for the two case studies will be discussed first. The uniform irrigation strategy applied 30 mm of irrigation water when the soil water content was depleted to a specified, management-allowed deficit (MAD). Results for Vaalharts show that applying the same MAD on the different soils results in similar gross irrigation amounts (686-690 mm) when irrigation water quality is good (21 mS/m). However, the irrigation applications for the lower irrigation water quality (200 mS/m) show larger variability (653-718 mm) between the different soils. Furthermore, it was necessary to decrease the MAD to achieve, on average, the same seasonal water applications as with the good irrigation water quality. Consequently, the matric potential for the same soil was larger when irrigating with low-quality irrigation water, while the osmotic potential was lower, resulting in lower crop yields and lower margin above specified costs (MAS). Changes in the MAS of each soil are influenced more by changes in crop yield, when compared with production cost changes. The same trends were observed for the Orange-Riet case study. Larger initial salinity levels in this area, however, resulted in overall lower crop yields and MAS. The conclusion is that the application of the same MAD percentage to the same soils with different irrigation water quality or to different soils may result in under irrigation or over irrigation.

Results from the site-specific management strategy in Vaalharts indicate that, on average, 642 mm of water is applied. The water application variability between segments is large (581-821 mm) due to large gross water applications in areas with higher salinity levels to induce leaching of salts. The extent of salt leaching is such that the osmotic potential of the soil water remains relatively low when compared with other segments with lower initial salinity levels. Consequently, the higher irrigation application costs and lower crop yields cause the MAS of segments with high initial salinity levels to be lower than those segments with relatively lower initial salinity levels, which shows that leaching is not a profitable strategy for achieving maximum yield potential. Applying the uniform irrigation strategy of the dominant soil (Soil3) to all the segments clearly shows that such a strategy is sub-optimal even when one acknowledges that Soil3 represents 94% of the total pivot area. Managing the matric and osmotic potential simultaneously is beneficial, as the site-specific management strategy shows that the total potential of the soil water is always lower than the uniform strategy, even though the site-specific strategy applies less water, on average. The financial benefit of using a site-specific irrigation strategy, as compared with the dominant soil strategy, was quantified to be R2 094/ha, on average. Mistakenly applying the uniform irrigation strategy to the total area diminishes the benefit of using a site-specific irrigation strategy. The maximum benefit for the Vaalharts case study was R3 851/ha, using Soil1 as reference. The conclusion is that irrigation strategies that utilise site-specific information to manage matric and osmotic potentials are more beneficial than managing matric potential alone is.

The silt plus clay (s+c) content of the Orange-Riet case study was generally higher when compared to Vaalharts, while the distribution was less homogenous. On average, the irrigation applications are 635 mm in Orange-Riet. The variability between segments is less dramatic (58-724 mm) when compared with the Vaalharts case study, mainly due to the differences in the way salinity was managed by the optimisation algorithm. Soils with higher s+c content require higher irrigation application rates to leach the same amount of salts from the soil profile, compared with soils with lower s+c contents. The increased costs of leaching cause the optimisation algorithm to reduce drainage to a maximum of 24 mm. Despite lower drainage levels and higher initial soil salinity levels in the Orange-Riet case study, the site-specific management strategy still manages to keep osmotic pressure below -300 kPa through the application of above-average irrigation amounts. Consequently, crop yields in segments with higher salinity levels are only marginally lower than in other segments. The crop yields between segments varied between 14.99 t/ha and 15.57 t/ha, with an average of 15.4 t/ha. Interestingly, the benefit of using a site-specific irrigation strategy was highest (R5 206/ha) when compared with the irrigation strategy of the dominant soil (Soil3). The lowest benefit of R4 514/ha occurred if Soil3 was chosen as the reference. The conclusion is that the drainage potential of the soil has an important bearing on the specific irrigation strategy to be applied to manage salinity. Lowering the matric potential of soils with low drainage potential will result in lower osmotic potentials, with resulting improvements in crop yield. Furthermore, it is more important to follow a strategy that will ensure high crop yields with high production income to increase profitability, compared with a cost minimising strategy that focuses on reducing input levels to increase profits.

ECONOMIC GUIDELINE FOR SALINITY MANAGEMENT

Developing economic guidelines for water and salinity management is difficult due to the interactive nature of economics with biophysical production decisions. However, economic theory provides us with some guidance on the economic management of water and salinity.

First, decision-makers have to maximise the MAS by maximising yield. Yields can be maximised or increased by increasing the factors of production to increase crop yields. Alternatively, MAS can also be maximised by decreasing or minimising the production costs. However, given the current product prices and input prices, the return on increased input use is high. Therefore, decision makers can produce at maximum yield and not be concerned with minimising production costs. The first guideline is, therefore, that the producer should produce for maximum yield.

Economic theory states that inputs are used efficiently when the marginal factor cost (MFC) is equal to the value of the marginal product (MVP). In the absence of production functions, it is possible to use the price of the input and the output ($\frac{P_{water}}{P_{maize}}$) to determine the increase in output necessary for a one-unit increase in input. Given the current cost to apply one more millimetre of irrigation water and the price of the crop yield, the increase in income (MVP) would outweigh the increased production cost (MFC). As a result, the producer would always use more irrigation water to irrigate for maximum yield.

Scarce resources, such as water, should be protected. When water is the limiting input, the decision-maker can reduce production by using smaller-reach irrigation pivots (thus reducing the hectares irrigated), or the decision-maker can produce the same area and use technology to implement deficit irrigation. When land is the limiting input, decision-makers should produce the total available area and intensify production to ensure maximum yield. Alternatively, decision-makers can produce high-value crops, assuming a market exists for the product.

The indirect measuring of water use also has a negative effect on the optimal use of water resources. Because water is allocated to farmers, based on the area in production, and an increase in the area produced (even if the aggregate water consumption does not increase) would result in increased water tariffs, the decision-maker has no incentive to use water optimally.

The decision to leach to manage salinity also requires that the decision-maker should make a trade-off between the cost of leaching and the gain in crop yield. Assuming that the MFC of leaching is lower than the MVP, it is beneficial for the decision-maker to leach. However, the decision-maker has to be sure that the soils are conducive to leaching. Alternatively, the study results have shown that ensuring that the soils remain wet reduces the need for leaching.

The economic management of water and salinity requires that decision-makers manage a complex system. Therefore, the decision-maker must consider how complementary inputs such as fertilisers are used and the advantages of alternative cropping practices, such as increased crop yield due to ripping deeper into the soil. Management of the complex system requires information, and the farmers are willing to pay for information that allows them to manage the production system.

RECOMMENDATIONS FOR FUTURE RESEARCH

- The site-specific variable rate irrigation strategy was developed by assuming access to complete information of the soil-water-crop status throughout the season. The impact of incomplete information on the benefit of site-specific irrigation management should be quantified by using risk analysis.

- The benefit of the site-specific variable rate irrigation strategy strongly hinges on the baseline uniform irrigation strategy used. Research is needed to incorporate actual farmer decision-making within soil-water-crop simulation models to provide a better indication of the maximum benefit of site-specific variable rate irrigation strategy.
- The technical and financial feasibility of adopting the site-specific variable rate irrigation strategy should be further investigated.
- Information is key to the implementation of the site-specific variable rate irrigation strategy. More research is needed to validate the soil-water-crop simulation models under real conditions faced by farmers.
- The research version of the bioeconomic model should be operationalised and made accessible to agricultural advisors.
- Parallel processing should be investigated to reduce solution time.
- Approaches to delineate management zones require further investigation, for example the use of multi-resolution image segmentation as a delineation approach.

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ANN	Artificial Neural Network
BD	Bulk density
CNRS	Centre Nationale de la Recherche Scientifique
CR	Crossover rate
CZ	Capillary zone
DE	Differential Evolution
DEA	Data envelopment analysis
DEM	Digital elevation maps
EA	Evolutionary algorithms
EC	Electrical Conductivity
EMI	Electromagnetic induction
EU	European Union
GA	Genetic Algorithm
GI	Gross income
GIS	Geographic Information System
GWK	Griekwaland-Wes Korporatief
LP	Linear programming
MAD	Management-allowed deficit
MAS	Margin above specified costs
MFC	Marginal factor cost
MGO	Modular Groundwater Optimizer
MINLP	Mixed-integer nonlinear optimisation problem
MP	Mathematical programming
MVP	Marginal value product
ORDI	Optimised regulated deficit irrigation
PA	Precision agriculture
PCA	Principal component analysis
PMP	Positive mathematical programming
RAW	Readily available water
s+c	Silt plus clay
SALMOD	Salinity and Leaching Model for Optimal Irrigation Development
SWAT	Soil and Water Assessment Tool
SWAMP	Soil Water Management Program
TAW	Total available water
US	United States
USDA-ARS	United States Department of Agriculture – Agricultural Research Service
WRC	Water Research Commission
WTU	Water table uptake

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

The pressure to produce more amounts of food with a limited amount of available water and land is mounting due to increasing population growth that increases food and water demand (Gu *et al.*, 2020). In this respect, irrigation plays a vital role in increasing the productivity of land. In water-scarce countries like South Africa, where the majority of all surface and groundwater is used for irrigation, the pressure is mounting to use water more efficiently through the adoption of better irrigation technology, irrigation scheduling, site-specific management, and the cultivation of high-valued crops. A trade-off exists between improving irrigation scheduling practices, with the aim of improving water use efficiency, and salt build-up in the soil. The uncontrolled build-up of salts in the soil may give rise salinity that affects crop growth and yield directly through osmotic pressure that reduces the availability of soil water, resulting in early plant-water stress and loss of yield.

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The spatial economic management of salinity is complex, as it requires that the irrigator should integrate information on irrigation water quality, irrigation technology, crop water requirements, salinity tolerance of crops, and soil salinity levels, as well as economic parameters such as energy costs, other production costs and output prices, to manage salinity economically. Some of these variables, such as water quality, crop choice, initial soil salinity levels and irrigation technology, might be known at the beginning of the season. However, decisions regarding the timing and quantity of irrigation to provide water for consumptive use, management of soil salinity, and minimising energy costs when using time-of-use electricity tariffs, necessitate dynamic adjustments throughout the season, which voids the application of steady state models.

Previous research on the economics of salinity management has used mathematical programming techniques that require simplified steady state approaches to model bioeconomic interactions within a constrained optimisation framework (e.g. Matthews *et al.*, 2010; Armour and Viljoen, 2008). The problem with steady state analyses is that when flow analysis of water and salt are considered mathematically, the soil-water content and salt concentration at a given point will remain constant with time in a steady state system (Letey *et al*., 2011). Consequently, the impact of management decisions on dynamic changes in soil-water content and osmotic pressure is assumed away. Transient state models that simulate dynamic changes in soil-water-crop systems are too complex to be represented in mathematical programming models. An integrated modelling approach, whereby an economic model is linked to a transient state soil-water-crop model, is necessary to enhance spatial soil water and salinity management economically.

1.2 PROBLEM STATEMENT

The unavailability of a modelling framework that accounts for the spatial dynamic interactions between economics, management decisions and changes in the soil-water-crop systems hampers the site-specific economic management of soil salinity.

The overall aim of this research is to develop and apply a bioeconomic model to economically manage site-specific water and salt stress in irrigated agriculture.

The project aim will be attained by achieving the following specific objectives:

- To develop and apply a bioeconomic model to economically manage site-specific water and salt stress in irrigated agriculture;
- To develop and integrate an economic model with a transient state salinity simulation model to evaluate the profitability of alternative salinity management guidelines for selected case studies;
- To optimise the integrated bioeconomic simulation model to determine optimal management strategies for selected case studies;
- To develop economic guidelines for managing site-specific water and salt stress.

1.3 ORGANISATION OF THE REPORT

Chapter 1 provides the motivation for the research as well as the problem statement and objectives of the research.

Chapter 2 provides an overview of the literature on salinity management. The chapter commences with a review of the salinity management guidelines developed by Van Rensburg *et al*. (2012) for South African conditions. Next, the spatial management of agricultural inputs through using precision agriculture is reviewed. The project strongly hinges on the ability to represent the soil-water crop interactions under saline conditions. Alternative methods/models to model these interactions are reviewed in the third section. Next, bioeconomic modelling that integrates economic models with soil-water-crop models is reviewed. The last part of the chapter is devoted to a description of the SWAMP simulation model.

The application of the bioeconomic model that is used to evaluate the site-specific salinity and water management of the two case studies is described in Chapter 3. The chapter commences with a description of the management zones, as related to the uniform irrigation strategy and the variable rate irrigation strategy. Next, the procedures to simulate the soil-water-crop system with SWAMP and the procedures of the economic model to calculate the MAS are discussed. The integration of SWAMP with the economic model, as well as the optimisation procedure, is discussed next. The last part of the chapter covers the setup of the bioeconomic models and procedure for analysing the two case studies.

The results of applying the integrated bioeconomic simulation model to evaluate the site-specific management of salinity and water are discussed in Chapter 4. The conclusions, guidelines for salinity management, and recommendations for further research are given in Chapter 5.

CHAPTER 2: LITERATURE REVIEW

The development of economic guidelines to manage water and salt stress requires a link to be established between management decisions and the economy, and estimated crop yield provides the link. As a result, a model that relates crop yield to crop water use and the changes to soil water content and salinity are needed. There are two ways to model crop yield, and the next section will discuss the approaches to simulating crop yield.

2.1 SALINE CROP YIELD SIMULATION

The literature identifies two ways by which to model crop yield. The first is a steady state approach, based on seasonal evapotranspiration. The second is the transient state approach, which allows for crop growth changes during the different growth stages due to evapotranspiration changes. The next sections will discuss the steady state crop yield and the transient state models in more detail.

2.1.1 STEADY STATE MODELS

Steady state models assume that the effect of salt build-up on yields can be represented using a constant factor (e.g. leaching fractions). The factor contracts or expands the yield function for the entire season, based on average evaporation over the season. Literature has proved that crop development is influenced by the salt stress that a crop experiences during the different growth stages (Domínguez *et al*., 2011; Lauchli and Grattan, 2007). By implication, a steady state crop response could generate incorrect guidelines for the economic management of water and salt stress. As a result, water uptake simulation models have moved to transient state models, which allow for temporal changes in the crop, changes in crop salt tolerance through the growing season, and groundwater salinity changes (Letey *et al*., 2011).

The next section will focus on the biophysical models that can model temporal changes in matric and osmotic stress.

2.1.2 TRANSIENT STATE CROP MODELS

Transient state mathematical models have played an important role in understanding the complexity and integrated nature of water and salt management due to irrigation, rainfall, and evapotranspiration. These models relate crop water use and crop yield to the continuous changes of soil salinity (osmotic potential) and soil water content (matric potential) that occur in the root zone. Therefore, the water flow and salt transport equations are the cornerstones of transient state models (Letey and Feng, 2007).

Several models have been developed to model salt and water flow and the response of field crops to matric and osmotic stress. Some transient state models will also allow for the chemistry of major dissolved ions in soil water to provide an approach to account for cation exchange, mineral dissolution and precipitation. The effects of salinity, sodicity and pH on hydraulic conductivity and hence water flow can also be simulated. The transient state models found in the literature include ENVIRO-GRO (Feng *et al*., 2003), SWAP (Van Dam *et al*., 2008), HYDRUS (Šimůnek *et al*., 2008), UNSATCHEM (Suarez and Šimůnek, 1997), SALTMED (Ragab *et al*., 2005), SWB (Annandale *et al*., 1999) and SWAMP (Barnard *et al*., 2015; Bennie *et al*., 1998).

Models like ENVIRO-GRO (Feng *et al*., 2003), SWAP (Van Dam *et al*., 2008), HYDRUS (Šimůnek *et al*., 2008), UNSATCHEM (Suarez and Šimůnek, 1997), and SALTMED (Ragab *et al*., 2005) use empirical functions to determine water uptake, based on a response to water potential. These models use the Richards equation to simulate water flow, convection-dispersion equations for salt transport, and various plant-water stress functions to relate crop response to matric and osmotic stress. Furthermore, all the models assume a linear relationship between relative crop transpiration and relative dry matter production.

A dimensionless water stress response function is used to relate matric and osmotic stress to crop water uptake. The reduction ($\alpha(h)$) due to changes in the pressure head (water stress) is computed with either a piecewise linear or a smooth S-shaped reduction function. The water uptake reduction due to critical osmotic heads ($\alpha(\pi)$) is normally estimated with the Maas and Hoffman (1977) threshold and slope parameters. Once the matric and osmotic stresses are estimated, an additive or a multiplicative approach can be used to determine a combined stress factor. Skaggs *et al*. (2006) argued that crop salt tolerance information serves only as a guideline since the crop's absolute tolerance will vary, based on climate, soil conditions, and agronomic practices. It is, therefore, a challenge to determine the salinity threshold and slope parameters for $\alpha(\pi)$.

Soil water flow models can be grouped into two, namely simple and complex, depending on the degree of complexity followed in modelling the soil profile. Complex transient state models (e.g. ENVIRO-GRO, SWAP, HYDRUS, UNSATCHEM, and SALTMED) consider the soil profile to be continuous, and simulate water flow while simultaneously considering crop water uptake functions by using the basic equations for hydraulic and hydrodynamic behaviour of water through a porous soil medium. These models can simulate downward water movement and the upward flow of water due to capillary rise from a shallow water table. They depend on numerical solutions to solve the Richards equation for soil water flow (Barnard *et al*., 2015; Van Rensburg *et al*., 2012) and require water retention ($a(h)$) and hydraulic conductivity functions ($k(h)$) for a specific soil. On the other hand, simple soil water models (e.g. SWAMP and SWB) have a fixed number of soil layers and a cascading (tipping bucket) approach to water movement or redistribution of rainfall and irrigation. These models require parameters such as the initial volumetric soil water content (ϑ_{start}) of each soil layer, the volumetric soil water content at field capacity (ϑ_{FC}, drain upper limit or upper limit of plant-available water), and permanent wilting point (ϑ_{WP}, lower limit of plant-available water) (Barnard *et al*., 2015).

Most crop growth models do not simulate plant growth, but rather simulate water uptake. Relative yield is then calculated as the ratio of the simulated seasonal water uptake to the seasonal potential water uptake (Oster *et al*., 2012). Plant characteristics and climatic factors are the only factors that determine the potential uptake, which refers to non-limiting water supply from the soil profile.

2.1.3 SIMPLIFIED MODELS USING TRANSIENT STATE EQUATIONS

The behaviour of crops when experiencing water and salt stress has been examined extensively in the literature (Letey *et al*., 1985; Majeed *et al*., 1994; Castrignanò *et al*., 1998; Allen *et al*., 1998; Ferrer-Alegre and Stockle, 1999; García *et al*., 2006; Pereira *et al*., 2007). Simulating the impact of salinity on crop yield is the first step in developing a bioeconomic model to manage salinity economically.

In the absence of salinity, Stewart *et al*. (1977) estimate transient state crop yield as a function of actual crop evapotranspiration (ET_a) and potential evapotranspiration (ET_m) in the different growth stages.

$$\frac{Y_a}{Y_m} = \prod_{j=1}^{n=4} \left(1 - k_{yj}\left(1 - \frac{ET_{aj}}{ET_{mj}}\right)\right) \quad 2.1$$

where Y_a and Y_m are the actual and potential crop yields, n is the number of growth stages, j is the growing stage under consideration, and k_y is the crop yield response factor. When ET_a is less than ET_m the plant becomes stressed, which results in a reduction of actual yield (Y_a).

The literature identifies three approaches to estimating actual evapotranspiration (ET_a) under water stress and salinity conditions. Changes in evapotranspiration due to water or salt stress will change the behaviour of crops. The next section will discuss the three approaches to estimating evapotranspiration changes due to matric and osmotic stress during the growth states of a crop.

2.1.3.1 The Allen et al. (1998) approach

In the first approach, Allen *et al*. (1998) argue that a crop's evapotranspiration capacity is related to the soil water content of the root zone. Therefore, as long as the crop can extract the required amount of water, the crop should not experience water stress. The ET_a for water stress conditions (ET_{aw}) can be estimated as follows:

If $TAW - Dr \geq (1-p)TAW = TAW - RAW$ then $ET_{aw} = ET_m$ 2.2

Otherwise, $ET_{aw} = \frac{TAW-Dr}{(1-p)TAW} ET_m$ 2.3

where TAW is the total available water in the root zone, RAW is the readily available water, Dr is the root zone depletion at any time (mm), and p is the fraction of TAW that a crop can extract without suffering water stress. Allen *et al*. (1998) also stated that the osmotic potential in the root zone would reduce crop yield due to reduced evapotranspiration capacity. Allen *et al*. (1998) therefore proposed the following equation to evaluate the combined effect of water and salinity stress on ET_a.

$$\frac{ET_{aws}}{ET_m} = K_{sc} = K_{ss}K_{sw} = \left[1 - \frac{b}{k_y 100}(EC_e - EC_{et})\right]\frac{TAW - Dr}{(1-p)TAW} \quad 2.4$$

where ET_{aw} is ET_a under water and saline stress conditions, K_{sc} is a dimensionless transpiration reduction factor that is determined by K_s and K_{sw}. K_{ss} is a dimensionless transpiration reduction factor that is dependent on the electrical conductivity of soil saturation extract[1], and K_{sw} is a dimensionless transpiration reduction factor dependent on available soil water[2]. EC_e is the actual electrical conductivity of the soil saturation extract calculated for the average root zone (dS/m), EC_{et} is the threshold EC_e level above which the crop would show yield reductions due to salt stress (dS/m), and b is a crop-specific parameter that shows the rate at which yield decreases due to a per unit increase in salinity.

2.1.3.2 The Pereira et al. (2007) approach

The second model reduces readily available water (RAW) since the combined effect of matric and osmotic potentials is argued to change the wilting point (Beltrão and Ben Asher, 1997). Pereira *et al*. (2007) use three equations to alter the water budget and thereby the crops' evapotranspiration. In the first equation, the depletion fraction, p, is modified to p_{cor} (mm) due to the saline conditions:

$$p_{cor} = p - \left[\frac{b}{100}(EC_e - EC_{et})\right]p \quad 2.5$$

A decreased p means that a smaller soil water depletion is required for the crop to transpire at a rate lower than potential evapotranspiration at a higher soil water content without salinity. Since the wilting

1 K_{ss} ranges between 0 and 1, where K_{ss}=1 if $EC_e \leq EC_{et}$.

2 K_{sw} ranges between 0 and 1, where K_{sw}=1 if $Dr \leq RAW$.

point is expected to change due to the osmotic effects, the value for the soil water content at the wilting point is recalculated to account for saline conditions:

$$\vartheta_{WPsalt} = \vartheta_{WP} + b(\frac{EC_e - EC_{et}}{100})(\vartheta_{FC} - \vartheta_{WP}) \qquad 2.6$$

where ϑ_{WPsalt} is the soil water content at wilting point under saline conditions (mm/mm), ϑ_{WP} is the soil water content at wilting point under non-saline conditions (mm/mm) and ϑ_{FC} is the soil water content at field capacity (mm/mm). The total available water (TAW) must then be corrected for salinity effects:

$$TAW_{salt} = (\vartheta_{FC} - \vartheta_{WPsalt})Zr \qquad 2.7$$

where TAW_{salt} is the adjusted TAW, and Zr is the root depth (mm). Based on the corrections due to salinity conditions, ET_a adjusted for water stress and saline conditions can then be given as:

$$\frac{ET_{aws}}{ET_m} = K_{sc} = K_{ss}K_{sw} = \left[1 - \frac{b}{k_y 100}(EC_e - EC_{et})\right]\frac{TAW_{salt} - Dr}{(1-p)TAW_{salt}} \qquad 2.8$$

2.1.3.3 The García et al. (2006) approach

The last model relates ET_m to the soluble salts content and the matric pressure head in the root zone as follows:

$$\frac{ET_{aws}}{ET_m} = \frac{1}{1 + (\frac{ah + \psi}{2\psi_{50}})^3} \qquad 2.9$$

where ψ is the salt concentration in the soil water (units of equivalent pressure head, cm), and ψ_{50} is the salt concentration that results in a 50% reduction in uptake by the crop (cm), as measured in pressure head equivalents (Doorenbos and Pruitt, 1977). $a = \frac{\psi_{50}}{h_{50}}$ where h_{50} is the analog of ψ_{50}, and h is the matric pressure head, which is a function of water content. Both ψ and h may be estimated through the equations proposed by Adiku *et al*. (2001) and Campbell (1974), respectively.

$$\psi = -400EC_{sw} = -400\frac{SC_r}{WC_r 640} \qquad 2.10$$

$$h = h_b\left(\frac{WC_r}{\vartheta_s Zr}\right)^{-d} \qquad 2.11$$

where EC_{sw} is the electrical conductivity of the soil water (dS/m), SC_r is the soluble salt content in the root zone (mg/m^3), WC_r is the equivalent water depth to the soil water content in the root zone (mm), h_b is the air entry pressure (cm), ϑ_s is the saturated water content, and d is Campbell's parameter (Campbell, 1974).

2.1.4 DISCUSSION

Steady state models contract or expand the yield function for the entire production season, based on average evaporation over the season. Crop development is influenced by the salt stress that a crop experiences during the different growth stages. Therefore, a steady state crop response could generate incorrect guidelines for the economic management of water and salt stress. An alternative to the steady state approach used in water uptake simulation models is presented by transient state models. Transient state models allow for temporal changes in the crop, crop salt tolerance changes through the growing season, and changes in groundwater salinity.

The literature identifies three approaches for estimating actual evapotranspiration (ET_a) under water stress and salinity conditions. Changes in evapotranspiration due to water or salt stress will change the behaviour of crops. Three models are identified in the literature. The Allen *et al*. (1998) model stresses crop growth by reducing total available water, while the Pereira *et al*. (2007) model stresses the crop by reducing readily available water. The final approach by García *et al*. (2006) changes the matric and osmotic pressure head to stress the crop.

Van Rensburg *et al*. (2012) used the transient state SWAMP model to determine salinity management guidelines for the Orange-Riet and Vaalharts irrigation schemes. The salinity management guidelines developed by Van Rensburg *et al*. (2012) will be discussed in the next section.

2.2 SALINITY MANAGEMENT GUIDELINES

Van Rensburg *et al*. (2012), in a study done at the Orange-Riet and Vaalharts Irrigation Schemes developed best management practices and guidelines to manage the salt load of irrigation farming at farm and scheme level in the region. The study included a literature review of possible aspects that must be considered in formulating best management practices, field data covering 2 years (i.e. four [4] growing seasons) and long-term simulations (with SWAMP) of different irrigation scheduling decisions for various soil-crop and water quality combinations found in the two irrigation schemes.

During the investigation of the data and the simulation results, a few facts or observations that affected the guidelines' development became apparent. Firstly, it was found that high rainfall periods leach considerable amounts of salts from the root zone, especially when the amount of cumulative rainfall exceeds the cumulative evapotranspiration by at least a factor of two (Van Rensburg *et al*., 2012).

Secondly, salt leaching due to rainfall events or over-irrigation is more effective on wet soils where a shallow groundwater table is present. Salts are prone to accumulate more rapidly in freely drained soils (without a groundwater table) or in soils where a stagnant shallow groundwater table is present, especially during a dry spell with limited irrigation-induced leaching. Thirdly, leached salts from the soils will typically end up in the groundwater below the root zone. These salts are removed through artificial drainage and/or lateral groundwater flow from higher to lower-lying areas. Artificial drainage water blends with surface overflow irrigation water before returning to the river. Water users then use the blended water downstream. Lastly, it was found that shallow groundwater tables comprise an underutilised source of water. Using the groundwater table to supplement crop water requirements (through capillary rise) can result in substantial irrigation water savings. However, capillary rise from shallow groundwater tables can cause rapid salt accumulation in the root zone. High rainfall events and/or irrigation-induced leaching can remove the accumulated salts.

While keeping these observations in mind, Van Rensburg *et al*. (2012) identified certain best management practices that could be implemented at the farm level to control root zone soil salinity and improve irrigation water use efficiency. These best management practices are:

1) Efficiency in irrigation water use can be improved by using more efficient irrigation systems such as a centre pivots.
2) Scientifically sound scheduling methods should replace intuition and experience-based irrigation scheduling plans. When developing the more sophisticated schedules, crop water requirements, rainfall, soil physical properties, the presence, depth and condition (stagnant or lateral flowing) of shallow groundwater tables, and the level of salinity in the root zone must be considered.
3) Shallow groundwater tables should be used to supplement crop water use, thereby reducing irrigation water requirements. Simulation results and previous studies (Ehlers *et al*., 2003) have shown that irrigation water requirement could be reduced by 50% through capillary rise from shallow groundwater tables. The reduction in irrigation water application results in a reduction in irrigation water, a reduction in pumping hours and, thereby, pumping costs, and a reduction in salts added through the irrigation water. Van Rensburg *et al*. (2012) stated that rain-induced leaching would keep salinity levels of soils low. Therefore, irrigation farmers will benefit greatly by deducting the groundwater table uptake from the irrigation requirement of crops, without experiencing any major salt balance disturbances. Care should be taken when this practice is employed at scheme level, as the groundwater table depth could be significantly increased.
4) Due to the accumulation of salts over extended periods, it is necessary to regularly monitor root zone salinity, especially when yield reduction is observed.
5) When making crop production decisions, producers should consider the salt tolerance of the crop. Only salt-sensitive crops (e.g. peas) were affected by salinity during low rainfall periods or when the irrigation water quality was poor.

The guidelines developed by Van Rensburg *et al*. (2012) to manage on-farm root zone salinity for different soil types, while using different irrigation water qualities, are summarised in Table 2.1 below. The on-farm practices are managing rainfall, managing shallow groundwater tables, use of leaching, monitoring of root zone salinity, re-use of drainage water, and crop choice. Van Rensburg *et al*. (2012) stated that there is not a single method that can be used for all conditions. The chosen method must be adapted to changing conditions (e.g. water restrictions and droughts) to continue to meet the irrigation requirements.

Rainfall plays an important role in maintaining sustainable salinity levels in the soil, since rainfall can leach salts from the root zone. As a result, it is important to consider rainfall when managing water and root zone salinity. There are three options to deal with rainfall. The first option accounts for rainfall by subtracting the selected rain storage capacity from the drained upper limit (field capacity of soil). The second option subtracts the rainfall of the previous irrigation cycle from the current cycles' irrigation requirement. If this approach is used correctly, the recorded irrigation water savings can be as large as the growing season's rainfall. The last option ignores rainfall, which will increase the potential of salt leaching. The provision of rainwater storage and the subtraction of rainwater from irrigation requirements are preferred on deep, freely drained soils, irrigated with good quality water in the presence of a shallow groundwater table. Salts can accumulate in the root zone when irrigation farmers produce on freely drained soils with irrigation water where the EC is higher than 75 mS/m.

Only when a shallow groundwater table is present should the water table uptake to supplement the crop's water requirement be subtracted from the irrigation requirement. The simulated or calculated water uptake from the capillary zone in the water table soils will result in an irrigation water saving.

The leaching of salts from the root zone ensures sustainable concentrations for crop production. Multiplying the irrigation requirement by a leaching fraction induces leaching. Leaching should be prompted when the EC of irrigation water is more than 75 mS/m to ensure that root zone salinity does not become a problem on freely drained soils. The same can be said for shallow groundwater table soils. However, on soils with higher clay content that are also more prone to low internal drainage, irrigation-induced leaching should be prompted when the EC increases above 25 mS/m.

Table 2.1: On-farm best management practices for controlling root zone salinity on different soil type-irrigation water quality combinations

Soil type-irrigation water combinations		**On-farm best management practices**						
		Managing rainfall						
Soil type	**Electrical conductivity irrigation water (mS/m)**	**Provision for rain storage**	**Subtraction of rainfall from IR***	**Subtracting of water table uptake from IR***	**Multiplying IR with leaching fraction**	**Monitor salinity of root zone**	**Reuse of drainage water**	**Avoid salt-sensitive crops**
Sandy to sandy loam freely drained soils without a water table	**< 25**	Yes	Yes	-	No	-	Yes	No
	25-75	Yes	Yes	-	No	Yes	No	No
	> 75	No	No	-	When necessary	Yes	No	Yes
Sandy to sandy loam soils with a shallow water table	**< 25**	Yes	Yes	Yes	No	-	Yes	No
	25-75	Yes	Yes	Yes	No	-	Yes	No
	> 75	No	Yes	Yes	When necessary	Yes	No	Yes
Sandy clay loam to clay loam soils	**< 25**	No	Yes	-	No	Yes	Yes	No
	25-75	No	Yes	-	When necessary	Yes	No	Yes
	> 75	No	No	-	When necessary	Yes	No	Yes

*IR = Irrigation requirement per cycle

Source: van Rensburg et al. (2012)

Root zone salinity levels should be monitored to ensure that crop losses due to salinisation are kept minimal. Frequent monitoring of root zone salinity is encouraged on shallow groundwater table soils when the EC of irrigation water > 75 mS/m. On freely drained soils, it is expected that the monitoring would become important when the EC is more than 25 mS/m and rainfall is limited. On soils with high clay content, monitoring root zone salinity is always important, even at an EC < 25 mS/m. High clay content soils tend to have lower internal drainage, resulting in lower deep percolation levels, and an accumulation of salts in the soil.

The presence of a shallow groundwater table affects the decision of a farmer to re-use drainage water. Whenever a shallow groundwater table is present, the producers would re-use drainage water, even when the EC of irrigation water is 75 mS/m. It is advised not to re-use drainage water only when the EC of irrigation water is > 75 mS/m. When no shallow groundwater table is present, the risk associated with re-using water is higher; therefore, farmers will only re-use water when the EC of irrigation water is relatively good (< 25 mS/m).

Salt-sensitive crops can be planted on relatively sandy soils that are freely drained or have a shallow groundwater table, as long as the EC of irrigation water is relatively low (< 75 mS/m). The use of irrigation water where the EC is more than 25 mS/m would require more salt-tolerant crops if the farmers produce on soils with higher clay content and no shallow groundwater table. Therefore, the choice of when to avoid salt-sensitive crops corresponds with the decision to initiate leaching by multiplying the irrigation requirement with the leaching fraction.

2.3 PRECISION AGRICULTURE

Precision agriculture enables farmers to control production processes by reacting on a smaller scale to changes in soil, water or salt indicators in the soil. The next section will discuss precision agriculture and how the delineation of management zones will help to achieve precision agriculture objectives.

2.3.1 PRECISION AGRICULTURE DEFINED

Zhang and Kovacs (2012) argued for a technique or technology that stabilises or increases agricultural production, while mediating the environmental impacts of the production activity. Precision agriculture (PA) is such a technology since the technology enables the farmer to control the production processes. Blackmore *et al*. (1994) defined PA as a comprehensive system designed to optimise agricultural production through soil and crop management that is tailored to unique field conditions, while maintaining environmental quality. Haghverdi *et al*. (2015) defined PA as a method or means to account for field variation and to incorporate that variability into management decisions. Therefore, the aim of PA is to manage in-field heterogeneity to ensure the best possible crop yield.

Literature (e.g. Córdoba *et al*., 2013; Cid-Garcia *et al*., 2013) argues that heterogeneity within a field is due to the temporal and spatial variation of many factors such as climate, topography and biological activity. Management decisions must, therefore, be time- and site-specific and not rigidly programmed. Time- and site-specific management decisions require the adoption of precision technologies and principles to manage the variation associated with agricultural production (Brown *et al*., 2012; Powers *et al*., 2003).

Across field or in-field yield variability has shown a strong correlation to spatial variability in crop water availability. Yield variability is attributable to water stress changes, nutrients, and soil properties, including soil electrical conductivity (ECe) (Thorp *et al*., 2008). Lund *et al*. (2010) argued that the soil water holding capacity is a major factor affecting yield. One way of ensuring that sufficient water is available for crop growth is irrigation. Precision irrigation can be used to avoid over irrigation and under irrigation, thereby optimising water input and crop response while maintaining environmental integrity (Adeyemi *et al*., 2017). Precision irrigation is achieved with efficient irrigation application systems or as the variable application of irrigation, based on maps or feedback from sensors (Raine *et al*., 2007). Smith *et al*. (2010) and Al-Karadsheh (2002) have argued that applying sufficient irrigation water is not the only requirement for precision irrigation, and decision-makers are required to apply the optimal amount of irrigation water at the right time.

The implication of implementing precision irrigation to meet spatial variable crop water needs within a field requires having accurate knowledge of within-field variability. The use of precision irrigation, therefore, requires the identification of homogenous management zones or units. A management zone is a homogenous unit or area with similar soil water retention characteristics (Hedley and Yule, 2009). Dillon (2002) stated that one of the most fundamental issues with the variable rate technology of PA is configuring the management zones.

2.3.2 DELINEATION OF THE MANAGEMENT ZONES

Haghverdi *et al*. (2015) stated that a management zone is a homogenous sub-region of an existing field. The delineation of the homogenous sub-regions is done with respect to soil-landscape attributes, including soil water retention ability (Hedley and Yule, 2009). Dillon (2002) stated that management zones are geographic units that are treated separately with respect to input application. Doerge (1999) argued that the most meaningful factors to include in a management zone strategy are those with the most direct effects on crop yield: soil moisture relationships, soil pH, soil pathogen infestation, and extremes in soil nutrient levels (see also Cambardella *et al*., 1994; Ortega and Flores, 1999; Cid-Garcia *et al*., 2013).

Zoning can be achieved based on a single soil-crop variable or on multiple attributes that determine crop yield (Khosla *et al*., 2010). Some of the attributes and items of information on which zones can be delineated include yield maps, topography, satellite photographs, canopy images and soil apparent electrical conductivity (ECa).

Yield maps are useful for indicating within-field production variation. However, year-to-year yield variations make the delineation of zones based solely on yield maps difficult to accomplish (Khosla *et al*., 2010). Doerge (1999) stated that crop yield patterns from yield maps might not be stable enough across seasons, making the identification of accurate management zones without using supplemental information difficult. Combining yield data with other information or average yield data can help to explain the spatial variation and to identify more trustable zones.

Literature (e.g. Haghverdi *et al*., 2015) indicates several methods for delineating management zones from different information layers. Clustering techniques group similar data points into distinct groups. Methods, such as K-means and fuzzy K-means, are used widely (Li *et al*., 2005; Jiang *et al*., 2011) to perform cluster procedures. However, the approach's major limitation is that the identified zones can be fragmented (Li *et al*., 2005), oval-shaped, and disjointed (Córdoba *et al*., 2013). An alternative is to use principal component analysis (PCA) with cluster analysis (Ortega and Flores, 1999) to delineate the management zones. The components are determined to ensure that the original correlated variables are transferred into independent variables. Moral *et al*. (2010) used regression-kriging to interpolate spatial data, PCA, and fuzzy cluster classification to delineate zones based on soil texture information and EC data. The most important components are then used for the delineation process.

Another method has been made possible by the increased availability and accuracy of Geographic Information System (GIS) images, such as digital elevation maps (DEM), and the use of computer algorithms to discriminate between terrain properties (Drăgut and Blaschke, 2006; Baatz and Schape, 2000). The delineation process typically combines a digital elevation map with approaches such as overlaying, cluster analysis and fuzzy sets to classify homogenous regions. The main concern with these classifying approaches is that the pixel-based approach does not consider topological relationships when classifying the regions (Drăgut and Blaschke, 2006). Therefore, DEM literature is moving from pixel-based to object-based classification approaches. An example of object-based image analysis is multi-resolution image segmentation that uses multiple input variables to identify homogenous regions or segments (van Niekerk, 2010). Multi-resolution image segmentation is an object-based approach for delineating, based on attributes that are captured in the data layers, to identify boundaries between dissimilar areas, rather than to delineate similar characteristics.

More recently, Cid-Garcia *et al*. (2013) used integer linear programming to construct rectangular-shaped zones. The Integer Linear Programming Management Zone delineation method uses a mathematical programming approach to delineate management zones based on soil property data. The advantage of the approach, as argued by Cid-Garcia *et al*. (2013), is that the model is easy to insert into any decision support system, and the method allows itself to be applied to a variety of precision irrigation technologies.

The delineation of economic management zones or grid sizes is a complex problem that can help producers to achieve the combined goals of profit maximisation and risk management (Dillon, 2002). The treatment of separate management zones requires a high degree of accuracy regarding spatial input use information, on a fine a scale as possible. However, Adeyemi *et al*. (2017) stated that it is important that management zones be large enough to be managed individually, while still reflecting soil variation across the field. There is also a trade-off between the cost implication for increased accuracy and the additional income generated due to increased accuracy.

2.3.3 DISCUSSION

PA systems optimise agricultural production through soil and crop management that is tailored to unique field conditions, while maintaining environmental quality. Within the PA framework, it is possible to make time- and site-specific decisions in response to factors such as soil properties, water stress and salt stress. Precision irrigation can be achieved through efficient irrigation application systems and/or the use of variable application of irrigation across the field in a timely manner. The identification of management zones is an important factor when implementing variable rate technology to ensure precision management of site-specific crop stress.

The literature on the delineation of management zones addresses two issues; the first comprises the variables on which delineation is done. The second is the method used to delineate management zones. Although the literature agrees that delineation is best conducted on crop yield, there are some concerns with using only crop yields to delineate management zones. The argument is that the crop yield is not a trustable indicator of zones due to crop yield patterns. Therefore, the crop yield must be combined with other crop-related variables. Several approaches have been identified to delineate zones. Delineation approaches include clustering techniques such as the K-means and principal component analysis with cluster analysis, the use of pixel or object-based classification based on GIS information, and integrated linear programming.

2.4 BIOECONOMIC OPTIMISATION MODELS

Linking economic models with biophysical models, such as soil and crop growth models, may be referred to as integrated modelling (Janssen and van Ittersum, 2007). Integrated models can be developed with the use of mathematical programming. The advantage of using mathematical programming (MP) in facilitating multi-functionality is that a direct link can be made between the biophysical model and the economy (Buysse *et al*., 2007). Hazell and Norton (1986) also argued that MP could address the multivariate and highly interlinked nature of agriculture. Evolutionary algorithms (EA) comprise another approach to linking the biophysical and economic models. EAs are natural optimisation tools that could be used to achieve near global or optimal solutions (Nicklow *et al*., 2010; Spall, 2003). The popularity of EA as a tool for dealing with irrigation problems is attributable partly to the increase in computational power available in recent years (Carrillo Cobo *et al*., 2014; Fernández Garcia *et al*., 2013).

The discussion on creating a link between the economy and the biophysical processes associated with crop production will focus first on using MP to create the necessary links, before moving on to EA.

2.4.1 CONSTRAINED OPTIMISATION

Wichelns (1999) examined the economic causes of waterlogging and salinisation at the farm level for irrigation projects. The dynamic model was used to identify policies that would encourage farmers to consider the effect of irrigation and leaching decisions on regional water tables. The farm-level model aimed to maximise the net present value of the net revenue over time, while ensuring that the quality of productive resources is maintained. The crop yield on which the estimation of income is based is a function of the quantity and quality (salt concentrations) of the irrigation and leaching water used, the salinity level in the root zone, and the depth of the shallow water table. Wichelns (1999) stated that the model could be viewed as an optimal control model, where water used for leaching and irrigation are the control variables. Soil salinity is a state variable that changes over time as the salt load moves in and out of the soil. The water table and the groundwater salinity are treated as exogenous variables, since the farmers have no incentive to consider the impacts of their decisions on these variables. Results showed that appropriate policies might decrease the rate of increase in waterlogging and salinity. Policies that can be implemented include volumetric water pricing, water markets, tradable water allotments, and farmer incentives to reduce deep percolation through their irrigation decisions.

Matthews *et al*. (2010) used a mathematical model to evaluate the effect of declining water quality on the economic efficiency of irrigation farming. The optimisation model determined the optimal gross margin for income from crop production minus the irrigation costs, where irrigation costs consist of the cost of water applied to meet the crop water requirement and the cost of leaching excess salts from the soil. It should be noted that the leaching of salts was applied to ensure that the optimal economic yield was achieved. Yield reductions due to osmotic pressure were determined, based on the Maas and Hoffman (1977) salinity response function, and were estimated within a data envelopment analysis (DEA) framework. The DEA allowed the researchers to use limited data points to determine, through interpolation, crop responses to various irrigation water salinity levels. The model also used the leaching functions developed by Barnard (2006) to determine the amount of water required to reduce the soil water quality to a standard that would optimise the gross margin. The results show that leaching is profitable, irrespective of water supply conditions.

Ortega Álvarez *et al*. (2004) developed MOPECO to determine the economic optimal irrigation water management strategy, while accounting for the complex factors that govern irrigation planning and management. The MOPECO model consists of three (3) modules to simulate water requirements, the effect of uniform water application, and the effect of alternative production practices, including changes in production practices. The model begins with estimating crop yield, based on the Stewart *et al*. (1977) production function, which relates crop yield to evapotranspiration. Crop yield reductions attributable to deficit irrigation were accounted for by a decrease in water quantity in the root zone. The second module relates crop production to gross margin to evaluate the effect of deficit irrigation as indicated by the irrigation depth.

The gross margins used to evaluate the irrigation strategies were estimated based on the income from crop production, the possible subsidies for the crop, and the production costs. The cost component consisted of the direct production costs (e.g. fertiliser, harvest insurance, cost to use machinery) and financial costs (e.g. the cost of money invested temporarily in each agricultural production system, assumed an interest rate of 5%). The water cost was determined based on its value as a productive factor. In the MOPECO model, water cost is often estimated based on the cost of irrigation water applied and the system's gross application depth, where irrigation water applied is a function of the crop water requirement and the application efficiency of irrigation systems (Keller and Bliesner, 1990; López-Mata *et al*., 2010).

The final module is complex to solve due to the nonlinearity between some of the variables and the restrictions that must be included. As a result, Ortega Álvarez *et al*. (2004) resorted to different methodologies based on multi-criteria optimisation (Romero *et al*., 1987; Berbel, 1988), benefits expected (MOTAD) (Tauer, 1983), risk and uncertainty (English, 1981), and other solutions based on dynamic programming, evolutionary computation, etc. (Hillier and Lieberman, 2001). The optimisation methodology is based on genetic algorithms (GA), a technique that is used increasingly to solve engineering problems (Kuo *et al*., 2000; Montesinos *et al*., 2001). The MOPECO model has since been used to evaluate the effect of irrigation uniformity (López-Mata *et al*., 2010), the use of saline water on yield (Domínguez *et al*., 2011), and the use of optimised regulated deficit irrigation (ORDI) on maize production (Domínguez *et al*., 2012a) and onion production (Domínguez *et al*., 2012b).

Armour and Viljoen (2002) evaluated the short-run profitability and financial feasibility of alternative salinity management options over a season. These researchers considered alternative crops, irrigation systems with different leaching capacities, and the installation of artificial drainage as alternative management options. The Salinity and Leaching Model for Optimal Irrigation Development (SALMOD), used to evaluate the management alternatives, comprises a simulation module and an optimisation module. The simulation module calculates the economic parameters for all the management option combinations that are included in the optimisation module. The biophysical soil salinity interrelationships are simplified through the steady state Maas and Hoffman (1977) crop yield relationship, and the necessary leaching fractions to achieve a specific target yield when water quality is deteriorating. The optimisation module uses linear programming (LP) to maximise the gross margin above specified costs (MAS) of the management alternatives, minus the amortised cost of investments. The researchers found that the benefits of more leaching, as water quality deteriorates, outweigh the leaching costs, until return flows become constraining. In follow-up research, Armour and Viljoen (2007) investigated the long-term effects of salt build-up on irrigation farming sustainability. They emphasise the point that a better understanding of the dynamic changes in salinity over time is required to assess the sustainability of irrigation farming. However, the dynamics encountered in the optimisation framework that they had developed in 2002 posed problems, and in 2007, Armour and Viljoen had to resort to economic simulation. The simulation model uses the same methodology that Armour and Viljoen (2002) had used to quantify the impact of soil salinity on crop yields.

More recently, positive mathematical programming (e.g. Cortignani and Severini, 2009; Baum *et al*., 2016) has gained popularity in farm-level economic analyses (Cortignani and Severini, 2009) and the investigation of the economic management of salts.

2.4.2 POSITIVE MATHEMATICAL PROGRAMMING MODELS

Positive mathematical programming (PMP) had been used in policy-orientated modelling, even before Howitt (1995) formalised it. Howitt (1995) argued that the PMP approach requires minimal data to calibrate to input and output quantities and the objective value, without requiring additional constraints. As a result, the model is more flexible in its responses. The PMP method uses information in constraints to calibrate the model, instead of the upper and lower bounds used in LP (Heckelei and Britz, 2005; Buysse *et al*., 2007). As suggested by Howitt (1995), the PMP model consists of an LP model, bound to observed activity levels through the calibration constraints. The dual or shadow values are then used to construct a nonlinear objective function, such that observed levels of production can be reproduced by the optimal solution (Heckelei and Britz, 2005).

The first phase of the PMP model fits a linear model:

$$\max Z = \ p'x - c'x \qquad 2.12$$

subject to

$$Ax \leq b \qquad 2.13$$

$$x \leq (x^o + \varepsilon) \qquad 2.14$$

where Z is the objective function value (typically profit), c is the variable cost associated with the production of x, and where x is an (nx1) vector of output produced, and p is the product prices. A is an (nxm) matrix of coefficients in resource constraints, while b indicates resource availability. x^o is the observed level of production, while ε is a small positive number. The calibration constraint ensures that the optimal solution of the LP model almost perfectly reproduces x^o. Dual values are determined for the available resource quantities (δ) and the calibration constraints (λ). ε ensures that all binding resource constraints remain binding and avoid a degenerate dual solution (Heckelei and Britz, 2005).

The second phase of the procedure uses λ to specify a nonlinear objective function, such that the marginal cost of x is equal to x^o. Given that the variable cost function is convex to the activity levels, the optimised solution would be a boundary point, which is a combination of the binding constraints and the first-order conditions (Howitt, 1995; Heckelei and Britz, 2005). The nonlinear function can be represented using a general quadratic cost function:

$$C = d'x_j + x_j'\frac{1}{2}Qx_j \quad 2.15$$

where C is the variable cost, d comprises the parameters associated with the linear term, and Q comprises the parameters associated with the quadratic term of C. Given that the marginal cost ($\frac{\partial C}{\partial x}$) is equal to $c + \delta,$ the non-LP problem can be given as:

$$\max Z = \ p'x - d'x + x'\frac{1}{2}Qx \quad 2.16$$

subject to

$$Ax \leq b \quad 2.17$$

$$x \geq 0 \quad 2.18$$

Over the years, PMP has received an extensive reviews, critiques and extensions (e.g. Heckelei and Britz, 2005; Buysse *et al*., 2007). The model has been used widely in the European Union (EU) in sectoral and regional analyses to analyse policy instruments. The model has also been successfully used to examine the adoption of deficit irrigation (Cortignani and Severini, 2009) and agricultural production under waterlogging or salt stress (e.g. Houk, 2003), while Howitt *et al*. (2010) used the methodology to investigate climate change in California's irrigated agriculture. Some of the applications of PMP within irrigation agriculture will be discussed below.

Cortignani and Severini (2009) argued that the Howitt (1995) model could exactly reproduce observed behaviour, but the model fails to consider activities that are not observed during the calibration period. Cortignani and Severini (2009) investigated farmers' adoption of deficit irrigation as an option for irrigation farmers to cope with changes within the agricultural environment in the EU, such as increases in water costs, reductions in water availability, and changes in the prices of the products obtained from irrigated crops. The researchers extended the Röhm and Dabbert (2003)[3] model to include deficit irrigation techniques not observed within the reference group. These techniques were identified with the use of crop growth models developed by the FAO. Cortignani and Severini (2009) argued that the inclusion of the crop growth models allowed for greater flexibility in the PMP model. Furthermore, the researcher was able to investigate the adoption of deficit irrigation techniques currently not adopted in the reference group. Results of the study showed that water cost does not motivate the adoption of deficit irrigation. Reduced water availability obliges farmers to reduce the area under production and their water use. Farmers can produce on the same area if they increase their water use efficiency by adopting deficit irrigation. The results also showed that, if product prices were to increase, deficit irrigation techniques could be used to produce larger areas with the available water. As a result, water was not the constraining variable.

Baum *et al*. (2016) investigated the impact of future water shortages on the Israeli economy, while accounting for different water source and salinity levels within a meta-analysis framework. A CGE model was used to represent the Israeli economy, including the water system. A land-use and water-use PMP[4] was used to model the substitutability between the various irrigation water sources, while taking osmotic stress and the limitations of irrigating with treated wastewater into account. A static crop-specific production function was used to model water application under saline conditions. The production functions were calibrated for salinity on crop yield through using the simulation model suggested by Shani *et al*. (2007). The PMP model contained 45 crops, 21 regions and 4 water types with salinity levels. The water qualities considered comprised saline freshwater (100 mS/m), secondary- and tertiary-treated wastewater (200 mS/m) and brackish water (400 mS/m). The effect of treated wastewater was limited to specific crops and irrigation systems, where the production function was further calibrated to reflect the impact of the wastewater use. The Long-Term National Master Plan for The Water Economy (Shani *et al*. 2007) was used to guide the water shortage scenarios that were investigated. The results indicated that a water shortage could lead to a significant decline in Israel’s GDP due to a significant reduction in agricultural output. Water quality constraints on irrigation water resulted in very low substitution between the different irrigation water types used in the study. The lower water substitution rates mean that water shortages would have a large impact on the economy.

Houk *et al*. (2006), in a study along the Lower Arkansas River of Colorado, investigated the losses in agricultural productivity attributable to irrigation-induced waterlogging and soil salinisation. Their paper's objective was achieved by linking a detailed hydrologic model (the model was calibrated with extensive field data) to an economic model. The economic model was used to evaluate productivity losses due to waterlogging and soil salinisation at the field level within an MP framework. The impact of soil salinity on agricultural crops was determined using the Maas and Hoffman (1977) salinity response function,

3 Howitt (1995) see different production technologies for the same crop (variants) as different activities. It is therefore expected that producers could more easily switch between variants than mixing crops (switch from one crop to another). Röhm and Dabbert (2003) propose a different modelling approach that more easily allows the producer to switch to a different crop compared to switch to a different variation of the same crop.

4 The PMP was referred to as the Vegetative Agricultural Land-Use Economic (VALUE) model.

with the Maas and Grattan (1999) threshold and slope parameters. An approach similar to that of Gates and Grismer (1989), where a linear relationship between crop yield and water table depth was estimated, was used to estimate crop losses due to waterlogging. Similar to the Maas and Hoffman (1977) response function, the waterlogging response relationship consisted of a water table depth threshold and response coefficient. Houk *et al*. (2006) used a multiplicative approach to determine the combined effect of waterlogging and salt stress. The combined impact factor was multiplied by the yield potential to determine crop yield changes due to waterlogging and salt stress. The results indicate that on-farm losses due to reduced agricultural production are significant. Average annual profitability could increase from USD173.73 to USD241.82 (an approximate 39% increase) per acre, when the effects of waterlogging and soil salinity are removed. Houk *et al*. (2006) also indicated that if conditions continue to degrade, the magnitude of losses might increase drastically.

2.4.3 MODELS USING EVOLUTIONARY APPROACHES

MP models are complex to use to study agricultural problems, and getting the optimal solution for such problems is often difficult and tedious, as such problems exhibit nonlinearity, high dimensionality, and multi-modality (Elsayed *et al*., 2014; Maier *et al*., 2014; Sarker and Ray, 2009; Spall, 2003). An alternative is to use heuristic search algorithms (e.g. EA) to identify near optimal solutions. Haq *et al*. (2008) describe heuristics as approximate algorithms or inexact procedures because the solution obtained through these methods may not be optimal.

EA (also known as evolutionary computations) comprises one of the techniques that have been used extensively to address the problem of competing demands for the scarce freshwater resources (Maier *et al*., 2014; Garg and Dashich, 2014; Schütze *et al*., 2012; Geerts and Raes, 2009). Maier *et al*. (2014), in a recent review of EA, stress that the main objective of optimisation should be to explore the best management irrigation strategies for investigating problems, rather than achieving an optimal solution to problems. Therefore, this subsection is devoted to a brief literature review related to the advancement of the knowledge in optimisation, EA and GA.

2.4.3.1 Overview of metaheuristics

EA can be formulated as an optimisation procedure with an objective function (fitness function) and may have one or several constraints that determine the feasible space to be searched (Sivanandam and Deepa, 2008). EAs are a group of stochastic search and optimisation methods that try to mimic natural selection and natural genetics (Nicklow *et al*., 2010; Sivanandam and Deepa, 2008). In natural selection, stronger individuals are likely to be the winners in an environment where several species compete for scarce natural resources (Rana *et al*., 2008). Therefore, in EAs, the strongest offspring in a generation have a higher chance to survive and reproduce (Lehmann and Finger, 2014; Anwar and Haq, 2013; Sivanandam and Deepa, 2008). In nature, it is the process of replacing parents with offspring with suitable attributes of chromosomes that can adapt dynamically to their environment and thereby survive their parents, who had less suitable attributes (Nicklow *et al*., 2010; Haq and Anwar, 2010; Spall, 2003). Spall (2003) identified the four types of EAs as evolutionary strategies, evolutionary programming, genetic programming, and GA.

2.4.3.2 Genetic algorithm

GAs comprise the most popular EA procedure (Louati *et al*., 2011; Nicklow *et al*., 2010; Sivanandam and Deepa, 2008; Spall, 2003). The GA technique has been applied in water resource related problems over the past two decades (Elsayed, *et al*., 2014). GAs can be described as adaptive heuristic search algorithms that are used to solve optimisation problems (Johns *et al*., 2014; Schütze *et al*., 2012; Haq *et al*., 2008; Michalewicz, 1996). GAs use a population of potential solutions in their search for the optimal or near optimal solution in the state space (Rana *et al*., 2008; Spall, 2003), using only a fraction of the number of possible potential solutions (Van Vuuren *et al*., 2005). In their search for the best solution, GAs consider multiple initial solutions simultaneously and improve these candidate solutions at each iteration to formulate a new set of candidate solutions until they arrive at a possible global optimum solution (Johns *et al*., 2014; Sarker and Ray, 2009; Ines and Droogers, 2002). In the last generation of solutions, GAs provide multiple solutions close to the optimal solutions, creating an opportunity for decision-makers to see several alternatives to their decision-making process (Louati *et al*., 2011).

GAs are considered appropriate for many real-world problems, as compared with conventional optimisation methods such as linear and integer programming (Louati *et al*., 2011; Karamouz *et al*., 2010; Haq *et al*., 2008). Although the applications of GAs are wide, the approach is more commonly applied for function optimisation (Spall, 2003). The successful use of GAs requires that parameters are tuned and configured to the problem being solved (Van Vuuren *et al*., 2005). According to Haq *et al*. (2008), the most important points, when evaluating the effectiveness of a GA to solve a problem, are 1) the solution quality, how close the solution comes to the optimum; 2) computational complexity, the time required to obtain the final solution; and 3) robustness, how well the algorithm performs over a range of problems.

2.4.3.3 Steps to perform an evolutionary algorithm

In the search for optimal or near optimal solutions, the design of the GAs is based on using simple operators, such as random selection, crossover, and mutation, on a population of solutions (Elsayed *et al*., 2014; Anwar and Haq, 2013; Louati *et al*., 2011; Karamouz *et al*., 2010; Van Vuuren *et al*., 2005). The GA improves the initial individual solutions by creating new individuals, based on improvements in older generations (Sivanandam and Deepa, 2008). Every new solution (chromosome) is evaluated after the iteration to ensure that the iteration will improve the solution (Michalewicz, 1996; Mitchell, 1996).

Evaluation of the improved solutions is done using a fitness function, where the fitness function[5] is used as a measure to differentiate among solutions (Spall, 2003). The solutions (chromosomes) that passed the fitness test are then used to generate the next generation of solutions (Johns *et al*., 2014; Karamouz *et al*., 2010). This process of improving the solution is repeated in several iterations, and gradually the population solution will evolve toward the optimal solution (Akhbari and Grigg, 2014; Rana *et al*., 2008).

The iterative process used to identify the near optimal solution consists of five (5) steps. The process followed during the GA's solution procedure is presented as a flow chart in Figure 2.1 below. The discussion of the flow chart and the steps to find the final solution begins with a discussion of the selection of the parents used in the GA.

The most important point to consider in generating an initial population is that the population must be as diverse as possible, regardless of the method of initialising them (Rajkumar and Thompson, 2002). Parent solutions are evaluated with the fitness function to identify the ideal solutions to generate the next population of solutions (Karamouz *et al*., 2010). The initial population solutions that can satisfy the fitness function are given a higher probability of selection (Maier *et al*., 2014; Van Vuuren *et al*., 2005) and will therefore act as the parent solution. Any solution that is unable to satisfy the maximum fitness criterion is discarded from the population. Literature (such as Sivanandam and Deepa, 2008; Nicklow *et al*., 2010; Karamouz *et al*., 2010) identifies several selection procedures; however, the roulette wheel, uniform random, and tournament selection are the most popular for water research problems (Van Vuuren *et al*., 2005). A discussion on the weaknesses and strengths of the different selection methods can be found in the work of Nicklow *et al*. (2010). The evolution of the parent population to generate the next generation of solutions involves two steps, crossover and mutation. First, the process of crossover will be discussed.

5 The fitness function is closely related to, but not necessarily identical to, the value of the objective function (Maier *et al*., 2014; Anwar and Haq, 2013; Sivanandam and Deepa, 2008).

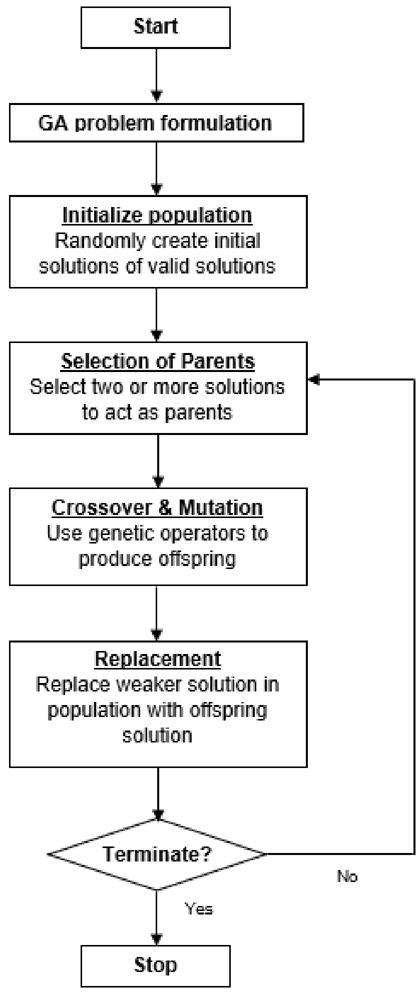


Figure 2.1: Flow chart of the basic methodology of genetic algorithms

(Source: Van Vuuren et al., 2005)

Van Vuuren *et al*. (2005) stated that the crossover process applied in GAs is the component that differentiates GAs from other EAs. Crossover aims to produce offspring that share some characteristics of the selected parent solutions (Elsayed *et al*., 2014; Anwar and Haq, 2013). Cross-mating of fitter individuals takes place according to specific criteria (Spall, 2003; Mitchell, 1996). The genes of parent solutions are mixed and recombined (crossed over) to produce new solutions in the new generation (Elsayed *et al*., 2014). This crossover process combines the parents' best traits to generate new offspring (Sivanandam and Deepa, 2008; Haupt and Haupt, 2004). Depending on the nature of the irrigation problem to be optimised, various crossover techniques are employed to guide the GAs to obtain a better solution (Van Vuuren *et al*., 2005; Spall, 2003). A number of crossover techniques are available, including single or multiple crossover, uniform random crossover, and arithmetic crossover (Spall, 2003). A detailed discussion of most of the available crossover techniques can be found in Van Vuuren *et al*. (2005) and Sivanandam and Deepa (2008). It is important to note that the literature on crossover currently does not provide a crossover method superior to others (Kerachian and Karamouz, 2005).

Some critically useful ‘genetic material’ can be lost during the crossover process (Kerachian and Karamouz, 2005). Various research papers, such as those by Nicklow *et al*. (2010) and Maier *et al*. (2014), suggest using a mutation operator to ensure that useful ‘genetic material’ is retained in the sample. Through mutation, some of the chromosomes in the solution population can mutate (change) randomly to mimic natural evolution. A recombination operator is employed to mix the desired ‘genetic material’ between the parents to produce one or more offspring. Mutation of the chromosomes allows the new offspring's chromosomes to be different from that of the parents’ chromosomes (Haupt and Haupt, 2004). If the parents are not allowed to mate, the parents are placed into the next generation, unchanged. According to Haupt and Haupt (2004) and Van Vuuren *et al*. (2005), the mutation could be performed on a bit-by-bit basis for binary encoding or a gene-by-gene basis for non-binary encoding. Each bit or gene is altered with a small probability, also termed as the mutation rate. The probability or the mutation rate indicates the probability of a given gene (Haq and Anwar, 2010; Cai *et al*., 2001). Since mutation is a diversity operator, the GA could result in a slow convergence time of the GA, or the GA could be trapped in a 'local optima' (Elsayed *et al*., 2014; Karamouz *et al*., 2010; Sivanandam and Deepa, 2008; Spall, 2003). Once the next generation of offspring has been generated, the offspring have to replace some of the parent solutions.

Deciding on the appropriate strategy for replacing chromosomes in the population with newly generated offspring chromosome is crucial (Van Vuuren *et al*., 2005). It is not always advisable to replace only the weakest member of the chromosomes, as this might lead to quick convergence (Spall, 2003). Van Vuuren *et al*. (2005) list some of the replacement strategies as 1) weakest replacement strategy, in which the member in the population with the lowest fitness value is replaced; 2) first weaker strategy, in which the first member found in the population with a fitness lower than that of the offspring is replaced; and 3) random replacement strategy, where a random member of the population is replaced.

2.4.3.4 Termination criteria

Once an appropriate selection, crossover and mutation operators, and a replacement strategy for a population member are designed, the algorithms run iterations to improve the chromosomes until an appropriate termination criterion is attained (Anwar and Haq, 2013; Haq and Anwar, 2010; Van Vuuren *et al*., 2005; Spall, 2003). Although several termination criteria procedures are available in the literature, Maier *et al*. (2014) point out that there is still a challenge to exactly determine what termination or convergence criteria are most appropriate for solving real-world irrigation problems. Most researchers stop the algorithm once a fixed number of iterations are reached, although it is not that easy to know how many iterations would be sufficient to solve a specific problem (Anwar and Haq, 2013; Van Vuuren *et al*., 2005). Another approach is to evaluate subsequent improvements in the fitness value of the individuals that converge. The fitness value should improve by a predefined percentage, or the fitness value should achieve a predefined value (Anwar and Haq, 2013).

The main use of termination criteria is to avoid early convergence in the algorithm. Nicklow *et al*. (2010) and Van Vuuren *et al*. (2005) stated that the right termination criteria could only be identified through experimentation. Spall (2003) has furthermore emphasised that the issue of convergence is critical to the selection of the right termination criteria. Therefore, GAs need to be formulated carefully and tested thoroughly (Nicklow *et al*., 2010; Haq *et al*., 2008).

2.4.3.5 Parameters

The selection of values for the parameters greatly determines the quality of the GA's solutions (Maier *et al*., 2014; Johns *et al*., 2014). These parameters include the size of the initial population, probability of crossover, probability of mutation, number of generations, and tournament size (Johns *et al*., 2014; Akhbari and Grigg, 2014; Nicklow *et al*., 2010; Goldberg, 1989). Most researchers use the parameter values suggested in Goldberg (1989) and De Jong (1975).

2.4.3.6 Benefits and limitations of GAs

The major advantages of GAs are their broad applicability, flexibility, and ability to find solutions with relatively modest computational requirements (Rana *et al*., 2008). Practical irrigation problems do not exhibit good (appropriate) mathematical properties as required by many traditional optimisation methodologies. GAs can solve highly nonlinear optimisation problems that are non-convex, discontinuous and multi-modal (Sarker and Ray, 2009; Rana *et al*., 2008). Therefore, GAs provide a very good alternative for solving irrigation problems (Fernández Garcia *et al*., 2013; Nicklow *et al*., 2010; Sarker and Ray, 2009). Provided that the GA is appropriately applied, the approach does not become trapped in a “local solution” as easily as traditional optimisation techniques (Nicklow *et al*., 2010; Spall, 2003).

There are some limitations to the application of GAs. These limitations include, but are not limited to: 1) GAs do not guarantee a global solution, although they do provide better solutions, 2) the use of a penalty function to include constraints could affect the efficiency with which the GA explores and exploits the search space (Van Vuuren *et al*., 2005). Another limitation is that selecting inappropriate values for the various parameters would increase the solution time (Van Vuuren *et al*., 2005). However, with the improvement of computer technology, this might not be a problem in the near future (Maier *et al*., 2014; Van Vuuren *et al*., 2005). A detailed discussion on the limitation of GAs can be found in Sivanandam and Deepa (2008).

2.4.3.7 Application of evolutionary and genetic algorithms in water research

Many water research problems exhibit high nonlinearity, high dimensionality, and non-convexity (Maier *et al*., 2014; Akhbari and Grigg, 2014). However, these problems can be reformulated as single or multi-objective optimisation problems (Sarker and Ray, 2009). Traditional optimisation approaches can solve such problems, but there is a high probability that these procedures could become trapped around local optima, making these approaches less desirable (Haupt and Haupt, 2004; Michalewicz, 1996). EA methods provide a good alternative, since the models can obtain an optimal or near optimal solution (Spall, 2003; Mitchell, 1996). As such, the application of EA in both single and multiple-objective water management research has increased (Elsayed *et al*., 2014).

During recent decades, the use of EA to solve complex real-world water-related problems has increased internationally (Maier *et al*., 2014; Nicklow *et al*., 2010). Some successful applications of EA include optimising management decisions in potato production in the context of different irrigation policy scenarios (Lehmann and Finger, 2014), irrigation scheduling problems (Schütze *et al*., 2012; Haq and Anwar, 2010; Anwar and Haq, 2013), salinity-related problems (Rana *et al*., 2008; Rajkumar and Thompson, 2002), minimising water and energy consumptions (Fernández Garcia *et al*., 2013; Sadati *et al*. 2014; Kumar *et al*., 2006), crop-planning problems (Sarker and Ray, 2009; Faramani *et al*., 2007), issues of irrigation as related to climate change (Carrillo Cobo *et al*., 2014; Schütze and Schmitz, 2010), water allocating policies (Kumar *et al*., 2006; Sadati *et al*., 2014), and water distribution network design (Johns *et al*., 2014).

Rajkumar and Thompson (2002) used GAs to model the complex nonlinear salinity intrusion problem in the Sacramento-San Joaquin River Delta system. The binary-coded GAs that were used to optimise an Artificial Neural Network (ANN) dealt with environmental problems in a river ecosystem. However, the model fails to address the long-term nature of salinity impact. Moreover, the study focused on salinity management in the watershed area, rather than on the impact of salinity on farmland and crops. Recently, within a watershed scale model, Akhbari and Grigg (2014) modelled the impact of irrigated farms' competition for scarce water by using multi-objective GAs. Water allocations available to the irrigation farms were reduced to ensure that water allocations were committed to environmental uses. The river flow simulations and the simulation of salinity were completed through using the Soil and Water Assessment Tool (SWAT). Rana *et al*. (2008) endeavoured to manage salinity problems by minimising the capillary up-flow rates from the water tables in the Murray Irrigation Area of Australia. The GA model that was developed aimed to optimise the pumping of the surface drainage, based on the principles of the spatio-temporal variation in groundwater dynamics. The Modular Groundwater Optimizer (MGO), a simulation-optimisation algorithm of MODFLOW and MT3D, was used to simulate the movement of water and salts through the soil. The GA was used to manage the groundwater level and groundwater salinity cost-effectively. Although the model did well in managing the groundwater table, the model does not account for the complex interaction between soil, plant, atmosphere, and crop growth.

Literature regarding the application of GAs for long-term planning in irrigation is limited. Available applications focus mostly on irrigation basin management. Cai *et al*. (2003; 2001) developed a hybrid GA and LP (GA-LP) model that ensures sustainable water management in irrigation-dominated basins.

The developed model can identify the optimal water management plan that is able to satisfy the water demand that arises from different sectors and field crop production. Kerachian and Karamouz (2007) demonstrated the use of a pure GA within the scope of water quality management in reservoir-river systems. The developed evaluation model, known as Stochastic Varying Chromosome Length Genetic Algorithm with water Quality constraints, was demonstrated by optimising long-term reservoir operation and waste load allocation by minimising the salinity of the water supplied to downstream rivers and the salt build-up in the reservoir. Karamouz *et al*. (2010) used a multi-period GA to investigate crop patterns on agricultural land, based on surface and groundwater availability. Even though the model deals with conjunctive water use management, the model attempts to use production functions to estimate the production of agricultural crops and the impact of deficit irrigation. The production function in the model uses the popular Doorenbos and Kassam (1979) production function model. However, similar to Ghahraman and Sepaskhah (2004), the paper used allocated water and crop water demand instead of actual and potential evapotranspiration. The above-mentioned GA applications demonstrate the importance of long-term planning in irrigation. However, most applications focus on basin or catchment management and do not address on-farm irrigation management.

Because of the increased pressure on the agricultural sector to increase water use efficiency, research on irrigation scheduling has intensified to save water (Schütze *et al*., 2012). Schütze *et al*. (2012) proposed an efficient and applicable GA model to investigate on-farm irrigation scheduling. The model is an open-loop optimisation and is defined by Schütze *et al*. (2012), citing Shani *et al*. (2004), as an optimisation tool that is based on forecasts generated by simulation or analytic functions of the water balance and crop production of an irrigation system for a whole growing period, in advance. The model is applied to address intra-seasonal irrigation scheduling under limited seasonal water supply. They modelled irrigation scheduling where they formulated the search space using only actual irrigation events (i.e. dates and amounts of water applied) in the form of a mixed-integer nonlinear optimisation problem (MINLP), which is basically an a priori unknown number of decision variables. The simulation-optimisation model (Schütze *et al*., 2012) is a tailored evolutionary optimisation tool that contributes to deficit irrigation studies on irrigated farms. Using the knowledge of varying crop yield response at different stages of the growth period is critical for deciding when and how much water to apply during the field crop's growing season (Ghahraman and Sepaskhah, 2004). The model was formulated with an objective function to maximise the crop yield and a number of constraints that relate to limited water resources, timing of irrigations, and irrigation depths.

The literature on the application of evolutionary algorithms and GA in a South African context is very limited. Van Vuuren *et al*. (2005) stated that EAs or GAs could be applied successfully to investigate water use in South Africa. Currently, the application of EAs within South Africa includes optimising water distribution systems (Van Dijk *et al*., 2008; Ndiritu, 2005), reservoir system optimisation to maximise yield (Ndiritu, 2003), and prediction of streamflow (Oyebode *et al*., 2014). Haile *et al*. (2014) used a GA model (Evolver) to optimise an irrigation scheduling problem, with the main aim to attain an optimal irrigation schedule that ensures the water and salt stress are as small as possible. SWAMP was used to simulate crop yield due to water stress, salinity stress, and the contribution of water uptake from a constant water table in the soil profile. The Haile *et al*. (2014) study focused more on the intra-seasonal aspect of irrigation scheduling, and did not consider salinity's long-term nature.

2.4.4 DISCUSSION

The main focus of MP is the attainment of optimal solutions. Solving problems requires the mathematical representation of the problem within a constrained optimisation framework. Optimality conditions are applied to determine the optimal level of decision variables. However, a detailed representation of complex irrigation scheduling problems results in nonlinearities and discontinuous functions (Venter, 2015), which complicate the application of optimality conditions to achieve optimal global solutions. Consequently, conventional methods cannot guarantee global or near global solutions, since such problems are often difficult and tedious to solve, as they exhibit nonlinearity, high dimensionality, and multimodality (Elsayed *et al*., 2014; Kerachian and Karamouz, 2007; Maier *et al*., 2014; Sivanandam and Deepa, 2008). Hence, computational intelligence techniques, such as EAs, GAs and simulated annealing (Faramani *et al*., 2007; Haupt and Haupt, 2004; Kerachian and Karamouz, 2007; Maier *et al*., 2014; Schütze *et al*., 2012), are suggested for solving very complex irrigation optimisation problems.

EA comprises powerful stochastic search algorithms with several practical applications for problems in irrigation management. When more and more variables are added to an optimisation problem, the problem becomes more complex and starts to exhibit nonlinearity, high dimensionality, and multimodality. As such, EAs or GAs could be applied to complex nonlinear irrigation problems to find optimal/near optimal solutions where the conventional optimisation approach fails. The advantage of EAs/GAs arises from the fact that they do not require the derivative principle to develop a solution; i.e. they are less dependent on mathematical criteria. EAs and GAs inherently mimic natural evolutions to optimise simple or complex problems. These techniques use operators of biological evolutions, such as crossover, selection, and mutations, to optimise solutions. EAs and GAs use a fitness function as solve evaluation criteria to improve solutions towards achieving the optimal or near optimal solution. The right choice of these operators and parameters do determine the final solutions.

2.5 DESCRIPTION OF THE SWAMP MODEL

In cases where a farmer uses low-quality water for irrigation, SWAMP provides a better balance between simplicity, accuracy, and robustness to simulate crop yield and soil salinity than most complex transient state models do. Barnard *et al.* (2015), citing Smith and Smith (2009), classify SWAMP, based on its inputs, output and scope, as a quantitative and deterministic model. In SWAMP, daily changes in water content of a multi-layer (ℓ) soil and seasonal influence on crop yield are determined from daily simulations of evaporation, root water uptake, water table uptake (WTU) through the capillary rise and percolation, and daily measurements of rainfall and irrigation. The model can be applied to cropping systems with a fallow period, freely drained soils, and a water table within or just below the potential root zone. This section will present the initial and boundary conditions, algorithms and parameters required by SWAMP.

2.5.1 CROP WATER USE

2.5.1.1 Infiltration

It is assumed that the rainfall and irrigation rate will not exceed the infiltration capacity of the soil. Hence, the model does not model infiltration, i.e. rainfall and irrigation water are infiltrated in a single event on a daily basis into the first soil layer.

2.5.1.2 Water budget (redistribution)

The net effect of convection and dispersion is assumed to simulate water flow in SWAMP. The cascading principle forms the basis of calculating the redistribution of water from the top of the soil profile, downwards. It is assumed that water will fill each soil layer only to the drained upper limit (DUL , mm) of the specific layer. Any excess water will drain to the layer below, provided it exceeds the deficit of the next specific layer to fill it to the DUL level. Using the DUL of each soil layer, the redistribution of water starts by calculating the effective rainfall and irrigation (EF, mm) that infiltrates the first layer of the soil on day i by using Equation 2.19, while run-off and run-on are assumed to be negligible.

$$EF_{RF(i)+IR(i)} = RF_{(i)} + IR_{(i)} \tag{2.19}$$

where RF and IR refer to rainfall (mm) and irrigation (mm) on a specific day, respectively.

In each layer, the water deficit (DF , mm) is computed from the difference in DUL and the simulated volumetric soil water content (θ) of each soil layer on a daily basis, according to Equation 2.20. It is assumed that, when there is a rainfall or irrigation event, the EF flows into (INF , mm) the first soil layer (Equation 2.21).

$$DF_{(\ell)(i)} = (\theta DUL_{(\ell)} - \theta_{(\ell)(i)})(Z_{(\ell)}) \tag{2.20}$$

$$INF_{(\ell=1)(i)} = EF_{RF(i)+IR(i)} \tag{2.21}$$

where $Z_{(\ell)}$ is the thickness (mm) of each soil layer.

Once the first layer is filled to its DUL, excess water flows from it to the next layer. The flow process will continue until a soil layer is reached, where the INF is less than the DF, as described in Equation 2.22.

$$INF_{(\ell)(i)} = INF_{(\ell-1)(i)} - DF_{(\ell-1)(i)} \qquad 2.22$$

The overall amount of applied water (AP, mm) retained in a specific soil layer is assumed to be equal to the DF when the INF into this particular layer is larger than the DF, as stated in Equation 2.23. But, if the INF is lower than DF then the AP is set equal to the INF in the layer under consideration (Equation 2.24). The calculation of the outflow (OTF, mm) from any specific layer is done according to Equation 2.25.

$$AP_{(\ell)(i)} = DF_{(\ell)(i)} \quad \text{when} \quad INF_{(\ell)(i)} > DF_{(\ell)(i)} \qquad 2.23$$

$$AP_{(\ell)(i)} = INF_{(\ell)(i)} - OTF_{(\ell)(i)} \quad \text{when} \quad INF_{(\ell)(i)} < DF_{(\ell)(i)} \qquad 2.24$$

$$INF_{(\ell+1)(i)} = OTF_{(\ell)(i)} = INF_{(\ell)(i)} - DF_{(\ell)(i)} \qquad 2.25$$

In summary, the fundamental Equations 2.19 to 2.25 illustrate the cascading principle used to calculate the daily water budget in each soil layer (Barnard *et al.*, 2015; Van Rensburg *et al.*, 2012).

2.5.1.3 Evaporation

The Ritchie Equation (as described in Equation 2.26) is used to estimate cumulative evaporation from a bare soil surface (E_{Bare}, mm) during irrigation or rainfall events by using an empirical coefficient (ϖ) and the number of days between rainfall or irrigation events (t). The evaporation from covered soil surfaces (E_{crop}, mm) is calculated with Equation 2.27 by reducing E_{Bare} by a factor equal to 1 minus the fractional shading of the soil (FB).

$$E_{Bare} = \varpi(t)^{0.5} \quad \text{where} \quad E_{Bare} = E_{Bare} - E_{Bare(i-1)} \qquad 2.26$$

$$E_{Crop} = E_{Bare}(1 - FB_{(i)}) \quad \text{where} \quad E_{Crop(i)} = E_{crop} - E_{crop(i-1)} \qquad 2.27$$

2.5.1.4 Potential transpiration or transpiration requirements

SWAMP uses Equation 2.28 to determine the potential seasonal transpiration (T_P), which is dependent only on climatic conditions and crop characteristics. The parameters required to calculate T_P are the mean atmospheric evaporative demand over the growing season (ET_o), a crop-specific parameter (ς), and a maximum biomass production parameter (Q_m , kg/ha).

$$T_P = ET_o \left(\frac{Q_m}{\varsigma} \right) \qquad 2.28$$

The T_P is used to compute the seasonal transpiration requirement (T_R) for a specific input target seed yield (Equation 2.29), where a total biomass production term (Q_a , kg/ha) is used for that particular target yield (Stewart *et al.*, 1977).

$$T_R = T_P - \left[T_P \left(1 - \frac{Q_a}{Q_m} \right) \right] \qquad 2.29$$

Daily estimations of transpiration requirements are obtained from the seasonal transpiration (T_R) with Equation 2.30 below. The seasonal transpiration uses a generated growth curve equation for computing the relative daily T_R ($T_{R\,Rel}$). The parameter needs inputs on days after planting (DAP). Parameters A' , B' , C' , and D' represent the number of days until the end of the establishment, vegetative growth, reproductive development and physiological maturity, respectively. Parameters a' and d' represent the relative crop water requirement at the end of phases A' and D', respectively, while ρ is the area under the relative daily T_R-line (Figure 2.2 below).

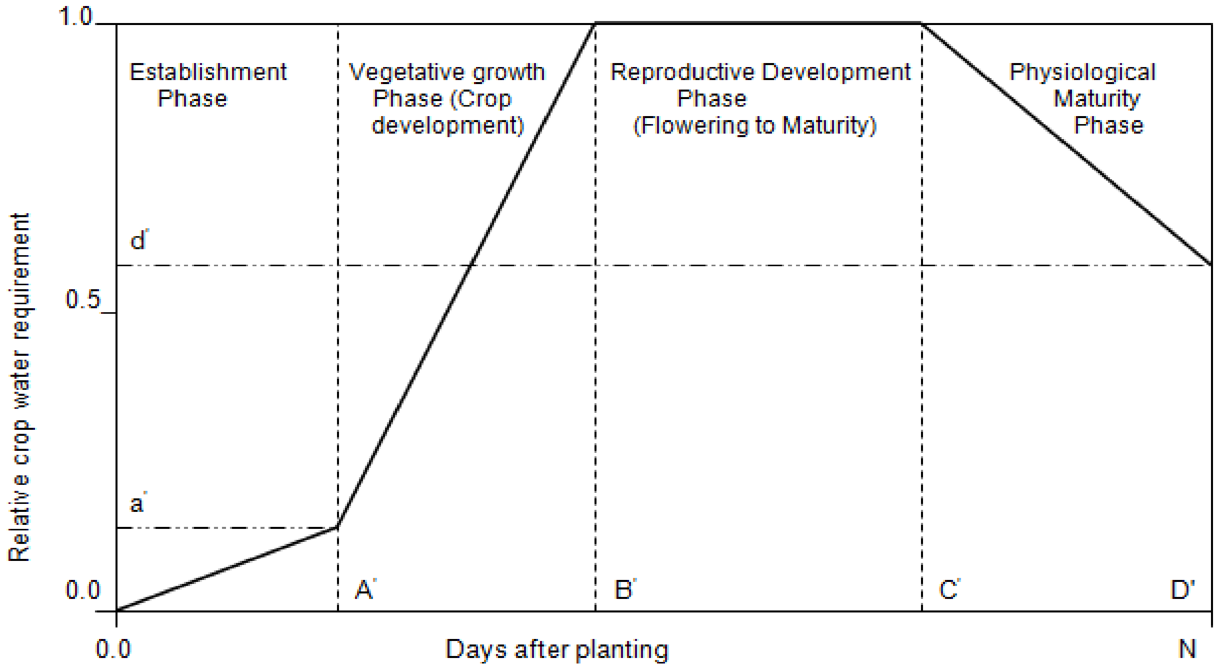


Figure 2.2: A hypothetical graph for estimating daily relative crop water requirements in a given growing season

(Source: Bennie et al., 1998)

$$T_{R(i)} = T_{R\,Rel(i)} \left(\frac{T_R}{\rho} \right) \quad 2.30$$

$$T_{R\,Rel(i)} = \left(\frac{a'}{A'} \right)(DAP) \text{ when } DAP \leq A' \quad 2.31$$

$$T_{R\,Rel(i)} = a' + \left(\frac{1-a'}{B'-A'} \right)(DAP - A') \text{ when } A' < DAP \leq B' \quad 2.32$$

$$T_{R\,Rel(i)} = 1 \text{ when } B' < DAP \leq C' \quad 2.33$$

$$T_{R\,Rel(i)} = 1 - \left[\left(\frac{1-d'}{D'-C'} \right)(DAP - C') \right] \text{ when } C' < DAP \leq D' \quad 2.34$$

2.5.1.5 Root density

Multiplying the default root growth rate parameter for the crop under consideration by the days after planting until the onset of the reproductive-growth stage is used to calculate the increase in rooting depth and total length per unit surface area ($rl_{(i)}$, mm/mm^2) during the growing season of the crop. Then, the rooting density (Lv, mm roots/mm^3 soil), which is the distribution of roots among the soil layers, is calculated with Equation 2.35, where $f_{(i)}$ represents the daily root-distribution coefficient (Barnard *et al.*, 2015; Van Rensburg *et al.*, 2012).

$$Lv_{(\ell)(i)} = \frac{rl_{(i)}\left[\left(1 - Exp\left(-f_{(i)(\ell)} Z_{(\ell)}\right)\right) - \left(1 - Exp\left(-f_{(i)(\ell-1)} Z_{(\ell-1)}\right)\right)\right]}{Z_{\ell}} \qquad 2.35$$

2.5.1.6 Actual transpiration

Demand and supply components characterise the water flow system of water uptake by plant roots in SWAMP. Daily estimated evaporation (E) and potential transpiration requirement (T_R) constitute the demand aspect, while the supply component is simulated as in Equation 2.36 and is determined by conditions in the soil-root system (Barnard *et al.*, 2015; Van Rensburg *et al.*, 2012).

$$PWSR_{(i)} = \sum_{\ell=1}^{n} LWSR_{(\ell)(i)} \qquad 2.36$$

where $PWSR_{(i)}$ refers to the daily profile water-supply rate and $LWSR_{(\ell)(i)}$ represents the layer water-supply rate on a specific day. The unit of measurement is in mm/day for both parameters.

Equation 2.37 is used to determine $LWSR_{(\ell)(i)}$, where F_{sr} is the soil-root conductance coefficient (mm^2 / d/ kPa), Lv the root density (mm roots /mm^3 soil), ψ_m the matric potential (-kPa), ψ_P the critical leaf-water potential where plant-water stress sets (-kPa), θ the simulated daily volumetric soil-water content (mm/mm), and θ_o the volumetric soil water content (mm/mm) where ψ_m = ψ_P, which is determined with Equation 2.38 (Barnard *et al.*, 2015; Van Rensburg *et al.*, 2012). Accordingly, the formula for calculating $LWSR_{(\ell)(i)}$ is:

$$LWSR_{(\ell)(i)} = F_{sr}\, ln\left(\frac{\theta_{(\ell)(i)}}{\theta_{o(\ell)(i)}}\right)\left(\pi Lv_{(\ell)(i)}\right)^{0.5}\left|\psi_{m(\ell)(i)} - \psi_p\right| Z_{(\ell)} \qquad 2.37$$

Daily simulated θ in combination with the calculated volumetric soil water content of the specific soil layer at 1 500 kPa (θ_{1500}), the volumetric soil water content of the specific layer at 10kPa (θ_{10}), and υ (calculated using Equation 2.39) are used to determine daily matric potential (ψ_m) with Equation 2.38.

$$\psi_m = 1500\left(\frac{\theta_{1500(\ell)}}{\theta_{(\ell)(i)}}\right)^{\upsilon(\ell)} \quad 2.38$$

$$\upsilon_{(\ell)} = \frac{-5.0056}{\ln\frac{\theta_{1500(\ell)}}{\theta_{10(\ell)}}} \quad 2.39$$

The $PWSR$ and T_R may be used in simulating the actual transpiration (T_A, mm/day). When $PWSR$ for a specific day is greater than T_R for that day, actual transpiration will be equal to the transpiration requirement (T_R). The daily transpiration rate is distributed among the soil layers by multiplying the relative water-supply rate from each layer, as shown in Equation 2.40.

$$T_{A(\ell)(i)} = \left(T_{R(i)}\right)\left(\frac{LWSR_{(\ell)(i)}}{PWSR_{(i)}}\right) \quad 2.40$$

However, if the $PWSR$ of a specific day is equal to or less than T_R for that day, the actual daily transpiration will be equal to $PWSR$. Equation 2.40 determines the water uptake from a specific rooted soil layer. The calculated T_A can be used to simulate yield, replacing seasonal transpiration T_R, by rearranging Equation 2.29 to obtain the actual biomass estimation, which gives the expected yield when it is multiplied by the HI of the specific crop (Barnard *et al.*, 2015; Van Rensburg *et al.*, 2012).

2.5.1.7 Water table uptake

One of the SWAMP model capabilities is calculating water table uptake (WTU, mm) from shallow water tables located within or below the potential root zone. The details of the process are explained in Ehlers *et al.* (2003). The process is simulated by relating the maximum upward flux (capillary fringe) from a water table to a specific height above the water table. Equation 2.41 relates the maximum upward flux (q_m, mm/day) from each layer within the capillary zone (CZ), where τ is an empirical parameter relating the decline in hydraulic conductivity above the water table, Z_f the height between the middle of the layer and the water table surface, and φ_s the saturated hydraulic conductivity (mm/day). If the T_A of a specific layer is less than q_m for that layer, the sum of daily uptake ($T_{A(i)}$) from each layer within the capillary fringe is considered as WTU. However, if $q_m < T_A$ for the specific layer, then the WTU is equal to q_m. SWAMP is capable of water uptake simulation in both constant and falling water tables (Barnard *et al.*, 2015; Van Rensburg *et al.*, 2012).

$$q_{m(\ell=CZ)} = (\varphi_s)(Exp^{\tau})(Z_f) \qquad 2.41$$

2.5.2 WATER SUPPLY UNDER OSMOTIC STRESS

Barnard *et al.* (2015) explored the SWAMP model to simulate water supply under osmotic stress and the impact on crop yield by adding additional inputs and parameters and defining adaptations to SWAMP's algorithms. The added inputs include the EC of a saturation extract of each layer at the beginning of the season ($EC_{e(\ell)}$), mean EC of the water table (EC_{WT}), mean EC of the irrigation water (EC_{IR}), and mean EC rainfall (EC_{RF}) required for the season. The fundamental principle followed by Barnard *et al.* (2015) is to quantify daily changes in the salt content (kg/ha) of a soil layer from simulations of water and salt added to, and lost from, the specific layer. The parameters added are c_1', c_2', and c_3'. Parameter c_1', which converts EC to salt content (kg salt /ha /mm), is multiplied by the relevant volume of water (mm) with the corresponding EC to calculate the amount of salt added to or lost from a specific layer. Parameters c_2' and c_3' were defined to convert EC to total dissolved salts (mg/L) and to convert total dissolved salts to osmotic potential (ψ_o). It is important to note that the extended model of Barnard *et al.* (2015) does not simulate salt added due to fertilisers and assumes the salt removed by field crops to be negligible.

SWAMP follows the cascading principle to salt flow in soil layers. Main salt addition to first soil layers comes from irrigation and rain, while salt addition to the layer beneath will be equal to salt removed from the layer above, until percolation to the layer beneath is 0 (Barnard *et al.,* 2015). In brief, the main adaptations followed by Barnard *et al.* (2015) and Van Rensburg *et al.* (2012) include the need to compute the osmotic potential (ψ_o, -kPa) and the modification required to compute $LWSR_{(\ell)(i)}$. Accordingly, consideration of matric and osmotic potential is needed to compute total potential in saline soils. Hence, Barnard *et al.* (2015) and Van Rensburg *et al.* (2012) replace the matric potential (ψ_m) in Equation 2.38 with the total soil potential (ψ_t, -kPa). Also, in the same Equation 2.38, θ_o was replaced by θ_t. The total soil potential is obtained by adding matric and osmotic potentials. The ψ_o is computed as (Equation 2.42):

$$\psi_{o(\ell)(i)} = \left[\frac{EC_{e(\ell)(i)}(c_2')(c_3')}{\theta_{(\ell)(i)}}\right]\theta_{s(\ell)} \qquad 2.42$$

where $EC_{e(\ell)(i)}$ is the simulated EC of daily saturated soil extract in a specific layer; and θ_s is the saturated soil-water content of a specific layer.

Using these adaptations, changes were made to Equation 2.37 to obtain an equation to compute $LWSR_{(\ell)(i)}$, which includes the impact of increasing salinity and decreasing osmotic potential on the supply of a rooted soil layer. The formula to calculate $LWSR_{(\ell)(i)}$ is set out in Equation 2.43:

$$LWSR_{(\ell)(i)} = F_{sr}\ ln\left(\frac{\theta_{(\ell)(i)}}{\theta_{t(\ell)(i)}}\right)\left(\pi Lv_{(\ell)(i)}\right)^{0.5}\left|\psi_{t(\ell)(i)} - \psi_P\right| Z_{(\ell)} \qquad 2.43$$

where θ_t represents the volumetric lower limit of plant-available water under matric and osmotic stress. If a saline soil is considered, θ_t is the volumetric soil water content where $\psi_m + \psi_o = \psi_P$.

2.5.3 CROP YIELD ESTIMATION

The SWAMP model currently estimates crop yield (Ya) based on the potential transpiration (Tp), actual transpiration (Ta), and the potential crop yield (Ym). The equation to estimate crop yield is as follows (Barnard *et al*., 2015):

$$Ya = Ym - Ym\left(1 - \left(\frac{Ta}{Tp}\right)\right) \qquad 2.44$$

The crop yield equation requires seasonal ET and therefore does not account for water or osmotic stress during the various growth stages. Literature (e.g. Domínguez *et al*., 2011; Lauchli and Grattan, 2007) indicates that the water or osmotic stress experienced during the different growth phases will affect crop development differently. Therefore, it can be stated that although SWAMP is a transient state model, the manner in which the effect is transferred into the crop yield equation results in the estimation of a steady state crop yield. Part of the development of the bioeconomic simulation model includes considering the effect of water and salt stress encountered during the different growth or development phases.

The Stewart *et al*. (1977) yield equation takes the effects of water and salt stress experienced during the different growth phases into account when calculating crop yield. Therefore, the adopted yield equation is shown by the following equation (Stewart *et al*., 1977):

$$Ya = Ym\prod_{g=1}^{4}(1 - Ky\left(1 - \left(\frac{ET_a}{ET_m}\right)_k\right)) \qquad 2.45$$

where crop yield is a function of ETa and ETm in the different growth stages. Whenever $ETa < ETM$, the plant would suffer stress, either matric and osmotic, and crop yield, Ya, would drop below the yield potential, Ym. Ky is the crop yield response factor for the different growth phases. Due to the response factor, Ky, that stress experienced within the growth phases is translated into different crop responses. The Ky response factors for the crops under consideration will be obtained from the literature (Doorenbos and Kassam, 1979).

2.6 IMPLICATIONS FOR THE RESEARCH

The development of economic guidelines to manage water and salt stress requires a link between management decisions and the economy. Crop yields provide a link between management decisions and the economic or financial implications of producers' decisions. As a result, a model that relates crop yield to crop water use and the changes to soil water content and salinity is needed. Two approaches to modelling crop yields exist, and the first is a steady state model that contracts or expands yield function for the entire production season, based on average evaporation. However, crop development is influenced by the water and salt stress that the crop experiences during the different growth phases. The second approach utilises transient state models that accommodate temporal changes in the crop growth during the different growth phases that are due to changes in evapotranspiration. In order to account for temporal changes in crop development, it is therefore necessary that the study use a transient state approach to model the effects of temporal water and salt stress.

Van Rensburg *et al*. (2012) used the transient state SWAMP model to determine salinity management guidelines for the Orange-Riet and Vaalharts irrigation schemes. Van Rensburg *et al*. (2012) identified certain best management practices that could be implemented at the farm level to control root zone soil salinity and improve irrigation water use efficiency. The best management practices devised include the use of efficient irrigation systems to increase irrigation water use efficiency. The use of sophisticated irrigation schedules must be developed by taking into consideration crop water requirements, rainfall, soil physical properties, the presence, depth and condition (stagnant or lateral flowing) of shallow groundwater tables, and the level of salinity in the root zone. Shallow groundwater tables are used to supplement crop water use, in combination with rain-induced leaching. The study also indicated that producers should monitor root zone salinity and that producers should consider the salt tolerance of the crops being produced. The evaluation of the economic management of water and salt stress should consider the best management practices identified by Van Rensburg *et al*. (2012). Issues such as irrigation systems, optimal irrigation schedules, crop choices and the use of shallow ground water tables can be easily investigated, given the use of a crop growth simulation model such as SWAMP.

PA is a method or means to account for temporal and field variation and to incorporate that variability into management decisions to ensure the best possible crop yield. Time- and site-specific management decisions require the adoption of precision technologies and principles to manage the variations associated with agricultural production. The literature on management zone delineation raises two issues: the variable(s) on which management zones are to be delineated, and the approach to be used to delineate management zones. Several variables have been identified on which to base the delineation of management zones, including variables such as soil-landscape attributes, topography, satellite images, soil apparent electrical conductivity, crop yield and crop yield related variables (soil moisture, soil pH or soil nutrient levels). Zoning can be based on a single soil-crop variable or on multiple variables. Although many studies do use crop yields to delineate zones, some researchers are concerned that crop yield is not stable across seasons and can, therefore, not be used to delineate management zones. The literature also identifies several approaches for delineating management zones, including techniques such as clustering, K-means, fuzzy K-means, pixel or object-based classification based on GIS information, and integrated linear programming. The delineation of economic management zones is a complex problem. The delineation of management zones requires a high degree of accuracy on spatial information, but it is also important that management zones should be large enough to be managed individually, while still reflecting soil variation across the field. The delineation of the management zones is important for ensuring the successful management of water and salt stress; however, the process of delineation is complex. Furthermore, as producers would probably not be able to apply difficult delineation procedures to identify management zones, the study will follow a simple delineation procedure, based on soil type and the applicable irrigation system.

Linking economic models with biophysical models, such as soil and crop growth models, requires an integrated modelling system to be used. Integrated models can be developed with the use of MP or EA. Although MP, including PMP, has been successfully used to evaluate agricultural production decisions, including irrigation and salinity management, the agricultural management problems can be complex. Due to the complexity of the problem, it is often difficult and tedious to obtain an optimal solution for such problems owing to nonlinearity, high dimensionality, and multimodality that often arises. Nevertheless, EA approaches, which are based on heurist search algorithms, can identify near-optimal solutions to complex problems. EA mimics natural evolution to optimise problems through the use of operators of biological evolution, such as crossover, mutation and selection. Due to the complexity of water and salt management decision and nonlinearities in the modelling system, EA will be used to determine the optimal solution.

Several transient state models exist that model salt and water flow and the response of field crops to matric and osmotic stress. Of these, SWAMP, which is a locally developed transient state crop growth model, provides a good balance between simplicity, accuracy, and robustness in simulating crop yield and soil salinity. SWAMP is a deterministic model that simulates crop growth, based on daily simulations of evaporation, root water uptake, water table uptake (WTU) through capillary rise and percolation, and daily measurements of rainfall and irrigation. However, the SWAMP model still estimates crop yield based on seasonal evapotranspiration and transpiration. Since the crop yield can be affected by differing water and osmotic stresses experienced during the different growth phases, it is necessary to replace the current seasonally based crop yield equation with the Stewart *et al*. Equation (1977). This equation considers the effect of water and salt stress experienced during the different growth phases when calculating yield.

CHAPTER 3: BIOECONOMIC MODEL DEVELOPMENT AND APPLICATION

Chapter 3 provides a description of the study region, discusses how the crop growth and the economic models were integrated, the data required to run the integrated bioeconomic model, and the development of the case studies used in the study.

3.1 DESCRIPTION OF THE STUDY AREA

The project uses the SWAMP model (Bennie *et al*., 1998; Barnard *et al*., 2015) to simulate the effect of matric and osmotic stress on crop growth. Variables in the SWAMP model that will affect crop development are weather information (ETo and rainfall), soil information (silt-and-clay percentage and depth of the soil, which is used to determine field capacity of a specific soil), water budget information (volumetric soil water content and irrigation water applied), salinity information (ECe start and the EC of the irrigation water applied), and crop information. Therefore, the development of the case studies requires information on the weather, soils, salinity and crops for the study region, which comprises the Orange-Riet and Vaalharts Irrigation Schemes located in the lower Vaal River basin, South Africa (Figure 3.1 below).

According to Van Rensburg *et al*. (2012), the Orange-Riet system receives its water from the Vanderkloof Dam (situated on the Orange River), from where it is conveyed and distributed along the Orange-Riet canal section (±120 km) to Jacobsdal. Tail-end and drainage water from the Settlement section of the scheme at Jacobsdal is transferred into the Riet River, which is conveyed downstream in an easterly direction to the Lower Riet River Section and the Vaal River. The Vaalharts Weir on the Vaal River, just upstream of Warrenton, diverts water into the Vaalharts main canal, which supplies the Vaalharts Irrigation Scheme located at Jan Kempdorp and Hartswater (±1176 km of concrete-lined canals). In addition, 314 km of concrete-lined drainage canals have been built to convey both stormwater and subsurface drainage water out of the irrigation scheme via the Harts River, in a south-westerly direction towards Spitskop Dam.

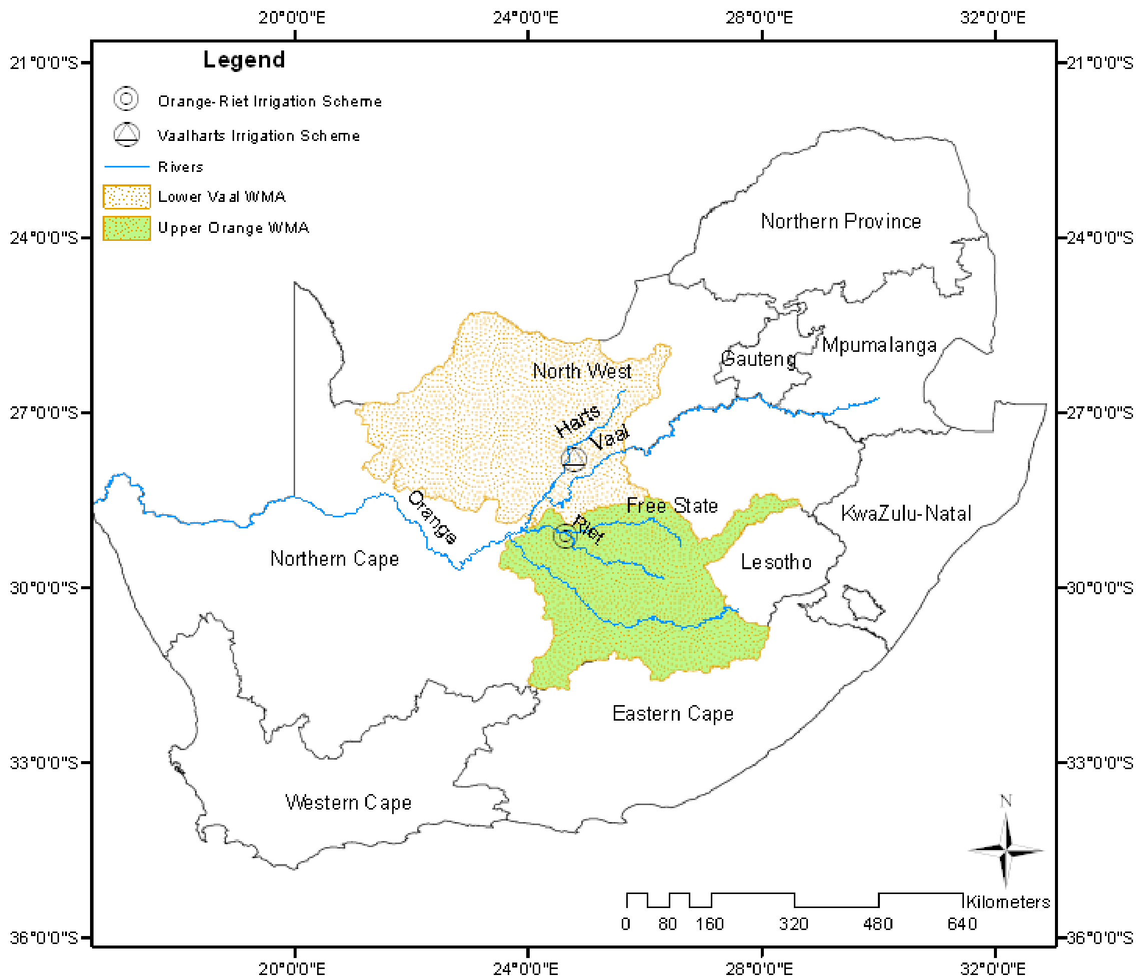


Figure 3.1: Locations of the Orange-Riet and Vaalharts Irrigation Schemes

Notes: These schemes are situated within the Upper Orange and Lower Vaal Water Management Areas, South Africa.
(Source: Van Rensburg et al., 2012)

To obtain a general overview (climate, soils, irrigation water quality, crops, agronomic management practices, etc.) of the study region, data gathered by the project of Van Rensburg *et al.* (2012), funded by the Water Research Commission, was evaluated. A synthesis of the data can be obtained in Barnard *et al.* (2021), which is briefly summarised below. The data details were obtained from weekly and seasonal measurements taken over a period of two years (July 2007 to July 2009) from a total of 28 measuring sites (at a point scale, 16 m^2 per site), located on 19 irrigated fields within Orange-Riet and Vaalharts.

Both Irrigation Schemes are located in a semi-arid zone, with long-term mean rainfalls of 397 and 427 mm per year for Orange-Riet and Vaalharts, respectively (Table 3.1 below). The aridity indexes for Orange-Riet and Vaalharts are 0.23 and 0.26, respectively. Rainfall mainly occurs in the form of thundershowers during the summer months (October to April) at both schemes. The warmest months at both schemes are November, December and January, with a long-term mean monthly maximum temperature of around 30°C. The coldest months are June and July, with a long-term mean minimum temperature around 0°C.

Table 3.1: Long-term mean weather data for the Orange-Riet (or) and Vaalharts (v) irrigation schemes

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

Notes: maximum temperature = Max T; minimum temperature = Min T; reference evaporative demand = ETo.

(Source: Van Rensburg et al., 2012)

Soils in the region are dominated (75% of soils, as shown in Table 3.2 below) by relatively homogenous, deep aeolion sandy to loamy sand soil. In general, the bulk densities over the root zones for the sandy to loamy sand and clayey soils were 1.65 and 1.62 g/cm^3, respectively. The pH (H_2O) at all the sites, except one, were above seven (7), while the CEC of the sandy to sandy loam soils were around 5 cmolc/kg, and the clayey soils more than 10 cmolc/kg (data not shown).

Fields irrigated with Orange River water had a mean ECi of 21 mS/m, with a limited variation (coefficient of variation = 12%), while fields irrigated with Vaal River water had a mean ECi of 65 mS/m (coefficient of variation = 8%). Some fields received blended water, from the Orange and/or Lower Riet, and/or the Modder, and/or artificial drainage, or Vaal and/or artificial drainage. The highest ECi of this blended water was more than 200 mS/m. None of the irrigation water was sodic as the sodium adsorption ratio was below 5, which was also true for the soil above the shallow groundwater table. Fields, where the mean ECe above the shallow groundwater table at the start of the measuring period was more than 200 mS/m, were limited in number. In general, the ECe was close to or below 100 mS/m at the start of the measuring period. Barnard *et al*. (2021) showed that during the four growing seasons (2-years), the highest increase in soil salinity was about 180%, which was associated with a maximum mean ECe of 152 mS/m because the mean ECe at the start was only 54 mS/m. The highest soil salinity that was recorded amounted to a mean ECe of about 380 mS/m.

Primarily, the winter crops grown during the study period were wheat and barley, while maize and groundnuts were planted in the summer (Barnard *et al*., 2021). Crop rotation systems employed by farmers consisted mainly of double and fallow cropping. With double cropping, a wheat-maize rotation was planted alternately for two years, or only for one year, whereafter either wheat or maize was replaced by barley or groundnuts, respectively, in the second year. At some fields, lucerne was also part of the rotation system. Fallow crop rotation systems consisted mainly of producing three crops, combined with one fallow period, over two years.

Table 3.2: Mean clay, silt and bulk density (BD) over a depth of 1.8 m

Field	MS	Texture	Clay (%)	Silt (%)	BD (g/cm^3)	ψ_m = -6 kPa (-60 cm)		ψ_m = -30 kPa (-300 cm)	
						θ_v (%)	K (mm/day)	θ_v (%)	K (mm/day)
1	or18, or20	Clay	45 (4)	23 (5)	1.59 (0.06)	35.97	0.7	28.91	0.019
2	or1, or2	Sandy clay loam	34 (4)	20 (4)	1.53 (0.06)	35.38	1.3	26.85	0.033
3	v10	Sandy clay loam	31 (1)	9 (2)	1.68 (0.02)	31.46	0.4	25.53	0.011
4	v1, v2	Sandy loam	17 (3)	9 (4)	1.67 (0.03)	26.53	1.6	17.81	0.021
5	or14, or15	Loamy sand	10 (2)	5 (2)	1.62 (0.03)	20.57	9.3	9.42	0.017
6	or12, or13	Loamy sand	10 (2)	4 (1)	1.65 (0.05)	19.99	9.7	9.13	0.016
7	v5	Loamy sand	9 (1)	7 (1)	-	21.83	10.2	10.12	0.023
8	or6, or7	Loamy sand	9 (1)	4 (1)	-	20.49	19.1	8.62	0.016
9	v4	Loamy sand	8 (2)	6 (2)	-	20.25	13.5	8.67	0.015
10	or9, or11	Loamy sand	8 (2)	3 (1)	-	19.76	24.4	8.03	0.013
11	or4, or5	Loamy sand	8 (2)	4 (1)	1.63 (0.03)	17.81	12.4	7.43	0.007
12	v11, v12	Loamy sand	8 (2)	4 (1)	1.64 (0.02)	17.73	12.0	7.43	0.007
13	v3	Loamy sand	8 (1)	6 (1)	-	19.76	13.5	8.33	0.013
14	v9	Loamy sand	8 (3)	5 (1)	-	19.91	16.4	8.33	0.014
15	v8	Loamy sand	7 (1)	5 (1)	-	19.01	17.1	7.74	0.011
16	v6	Loamy sand	7 (1)	5 (2)	-	18.55	17.2	7.48	0.008
17	v7	Sand	6 (2)	4 (2)	1.77 (0.01)	14.97	6.9	6.57	0.004
18	or17	Sand	6 (1)	4 (1)	-	16.28	20.3	6.47	0.002
19	or19	Sand	6 (1)	3 (1)	1.61 (0.02)	15.29	17.3	6.15	0.002

Notes: measured at the various sites located in the irrigated fields; the volumetric soil water content and the hydraulic conductivity at a matric potential of -6 and -30 kPa.

(Source: Barnard et al., 2021)

3.2 ECONOMIC MODEL

The economic model is used to determine what the economic implications of water and salt management decisions are. As a result, the economic model is used as the fitness function in the genetic algorithm. The production cost information was obtained using the "Griekwaland-Wes Korporatief" input costs guide for November 2019 (GWK, 2019).

3.2.1 GROSS INCOME

The gross income (GI) is a function of yield produced and the area planted. The production income is calculated as follows:

$$GI = Y \cdot P_y \cdot A \quad 3.1$$

where Y is the yield produced (ton/ha), P_y is the crop price (R/ton), and A indicates the size of the cropping area produced (ha). The crop yield is calculated using Equation 2.45, based on the water and salt stress that the crop has experienced during crop growth. The crop price was assumed to be R2 200/ton, while the size of the cropping area is dependent on the size of the area under production, but limited to the size of the relevant irrigation pivot.

3.2.2 AREA-DEPENDENT COSTS

The area-dependent costs are the costs that change, based on the area planted, and are calculated as follows:

$$ADC = A \cdot va \quad 3.2$$

where A is the size of the area planted (ha) and va comprises the area-dependent costs (R/ha). The area-dependent costs consist of the costs associated with planting the crop and are the costs associated with planting. The area-dependent cost was assumed to be R9 864.31/ha.

3.2.3 IRRIGATION-DEPENDANT COST

The irrigation-dependent costs are a function of the electricity cost to apply irrigation water (EIC), labour (LC), repair and maintenance costs (RC), and the water charges (WC).

$$IDC = EIC + LC + RC + WC \quad 3.3$$

The electricity cost is calculated based on the pumping hours, electricity tariffs, and the irrigation system. Both labour (LC) and repair and maintenance (RC) costs are driven by pumping hours (Meiring, 1989). The water cost (WC) is a function of the total amount of irrigation water applied and the water tariff. The water tariff is calculated according to a volumetric charge for irrigation water applied. The irrigation cost component, which consists of the labour, repair and maintenance costs, is R17.7/hour.

The electricity costs were calculated based on the assumptions made about the irrigation system, which include the design of the system (to be discussed later), irrigation water amount, and the electricity tariff structure. It was assumed that the producer uses the Ruraflex tariff structure. Ruraflex was designed to create the incentive to use electricity during low-demand seasons and off-peak hours. Ruraflex is available to all three-phase rural clients, with an installed capacity of up to 5 megavolt-ampere (MVA), on rural networks in rural areas as determined by Eskom. Electricity costs relate to Eskom tariffs and charges, as stipulated in the Eskom tariff booklet for the period 2019 to 2020 (Eskom, 2019/20). The variable and fixed electricity tariffs are set out in Table 3.3 below.

The Ruraflex fixed costs, as shown in Table 3.3, consist of a network access charge, service charge, administration charge, and reactive energy charge. The active energy and network access charges (fixed charges) are based on the 300 km to 600 km range transmission zone and a voltage smaller than 500 V. Reliability and network demand charges are also based on a voltage smaller than 500 V. The variable costs for Ruraflex depend on time-of-use. Time-of-use is divided into three time slots, namely off-peak, standard, and peak timeslots. Off-peak time covers the time of the day when the electricity demand is the lowest and comprises 82 hours/week. On the other hand, peak time covers the time of the day when electricity demand is the highest and comprises 25 hours/week. Variable costs consist of the active energy charge, reliability energy charge, and network demand charge.

Table 3.3: Variable and fixed electricity tariffs for the Ruraflex electricity tariff structure

Variable Electricity Costs Tariffs			
Active Energy Charge (c/kWh)	High (June-August)	Off-Peak	56.38
		Standard	104.61
		Peak	345.32
	Low (September-April)	Off-Peak	49.18
		Standard	77.51
		Peak	112.65
Reliability service Charge (c/kWh)			0.44
Network Demand Charge (c/kWh)			28.39
Reactive Energy Charge (c/kVArh)	High (June-August)		9.59
	Low (September-April)		0
Fixed Electricity Costs Tariffs			
Network Access Charge (R/KVA/month)			18.35
Service Charge (R/Account/day)			66.90
Administration Charge (R/POD/day)			31.02

A detailed discussion on the estimation of the irrigation dependent costs, including the electricity component, can be found in Venter and Grové (2016).

3.2.4 YIELD-DEPENDANT COSTS

The yield-dependent cost calculation is based on the cost reduction method (Grové and Oosthuizen, 2002). The yield-dependent cost is calculated using Equation 3.4.

$$YDC = vym - (y_m - Y)vy \qquad 3.4$$

The first part of the equation (vym) is the yield-dependent cost associated with maximum crop yield. The second component of the equation ($(y_m - Y)vy$) scales the yield-dependent costs downwards, based on the difference between the maximum and actual crop yields. Where y_m is the maximum yield potential (ton/ha), vy is the scaling factor used to reduce yield-dependent costs. The yield-dependent costs are given in Table 3.4 below.

Table 3.4: Parameters used to estimate the yield-dependent costs

Maximum Yield cost	R/ton	13 506.66
Target yield cost	R/ton	12 730.93
Scaling factor	R/ton	387.87
Maximum yield	ton/ha	17
Target yield	ton/h	15

3.2.5 GROSS MARGIN CALCULATION

The objective function of the economic model is to maximise the gross margin (MAS) above the specified costs. The MAS calculation is shown in Equation 3.5.

$$MAS = PI - AD - ICD - YDC \qquad 3.5$$

where the first component in the MAS equation indicates the calculation of the production income, and the remaining components are the costs associated with the production of the crop. The MAS calculation allows for some costs to vary with changes in area irrigated and others with crop yield changes.

3.3 MODEL INTEGRATION AND OPTIMISATION PROCEDURE

3.3.1 BIOECONOMIC SIMULATION MODEL

The bioeconomic simulation model consists of the SWAMP simulation model and the economic model that is used to simulate the MAS for a given irrigation strategy for the pivot in question. A flow chart of the bioeconomic simulation procedure is shown in Figure 3.2 below.

The simulation model, as shown in Figure 3.2, begins with the irrigation strategy, which provides the SWAMP model with information on the irrigation amounts and the days on which the irrigation amount is applied. The irrigation amounts are incorporated into the SWAMP crop growth model, which simulates the crop growth by using the assumed irrigation strategy, together with soil, crop and weather information. The crop growth model simulates the water stress in the water budget, in conjunction with salt stress in the salt budget. The crop yield for every irrigation strategy is used as an input in the economic model, along with the irrigation strategy information.

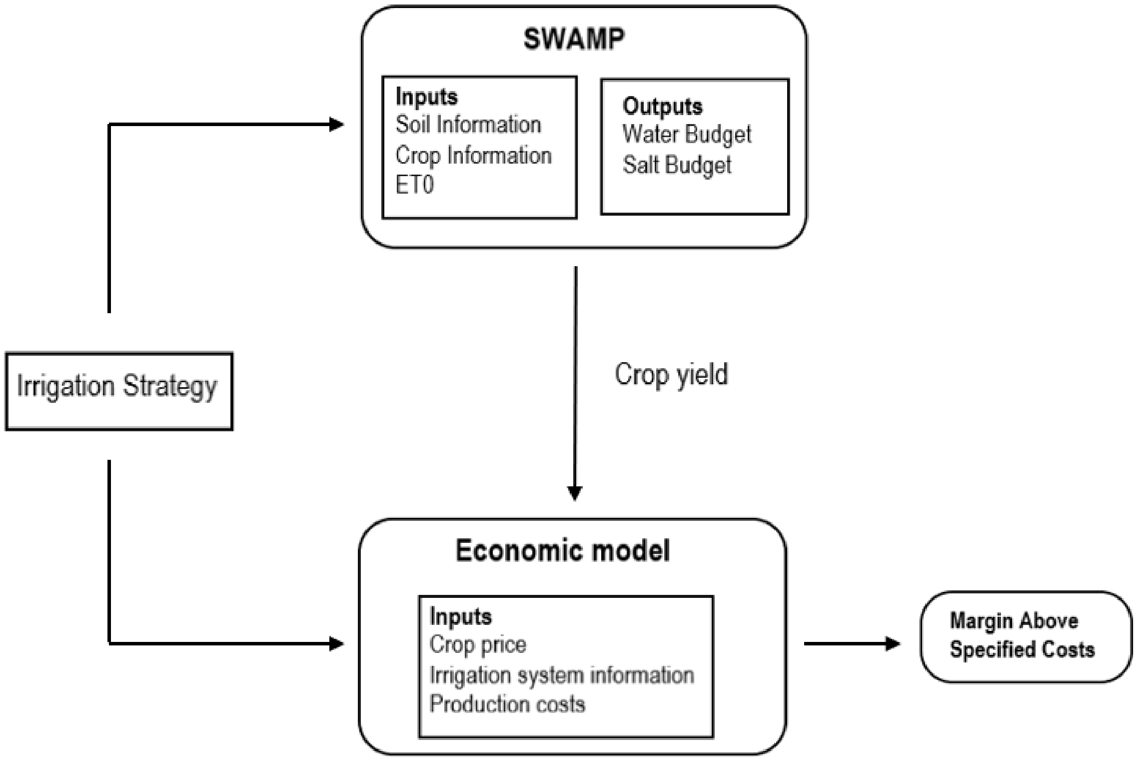


Figure 3.2: Flow chart of the bioeconomic model simulation procedure

The economic model requires information about the irrigation system used, in conjunction with the irrigation water strategy, to simulate the irrigation cost component of the MAS calculation. Other inputs that are necessary to calculate MAS consist of crop price information and other production costs, comprising area-dependent costs and yield-dependent costs. The economic model's output (MAS) is used as the fitness function in the optimisation model.

Next, the optimisation procedure, which extends on the simulation model, will be discussed.

3.3.2 BIOECONOMIC OPTIMISATION PROCEDURE

The SWAMP model is highly complex, which renders the application of standard MP algorithms, in order to optimise salt and water management, infeasible. Consequently, the research utilises a stochastic optimisation algorithm to optimise the bioeconomic model. More specifically, Differential Evolution (DE) is used. Biological evolution inspired the development of DE, which consists of an initialisation step, and an iterative step where mutation, crossover and selection are repeated over subsequent generations until the stopping criteria are met. Figure 3.3 below provides a flow chart of the different steps and operations necessary to optimise irrigation and salt management through using DE. What follows is a chronological description of the steps and operations.

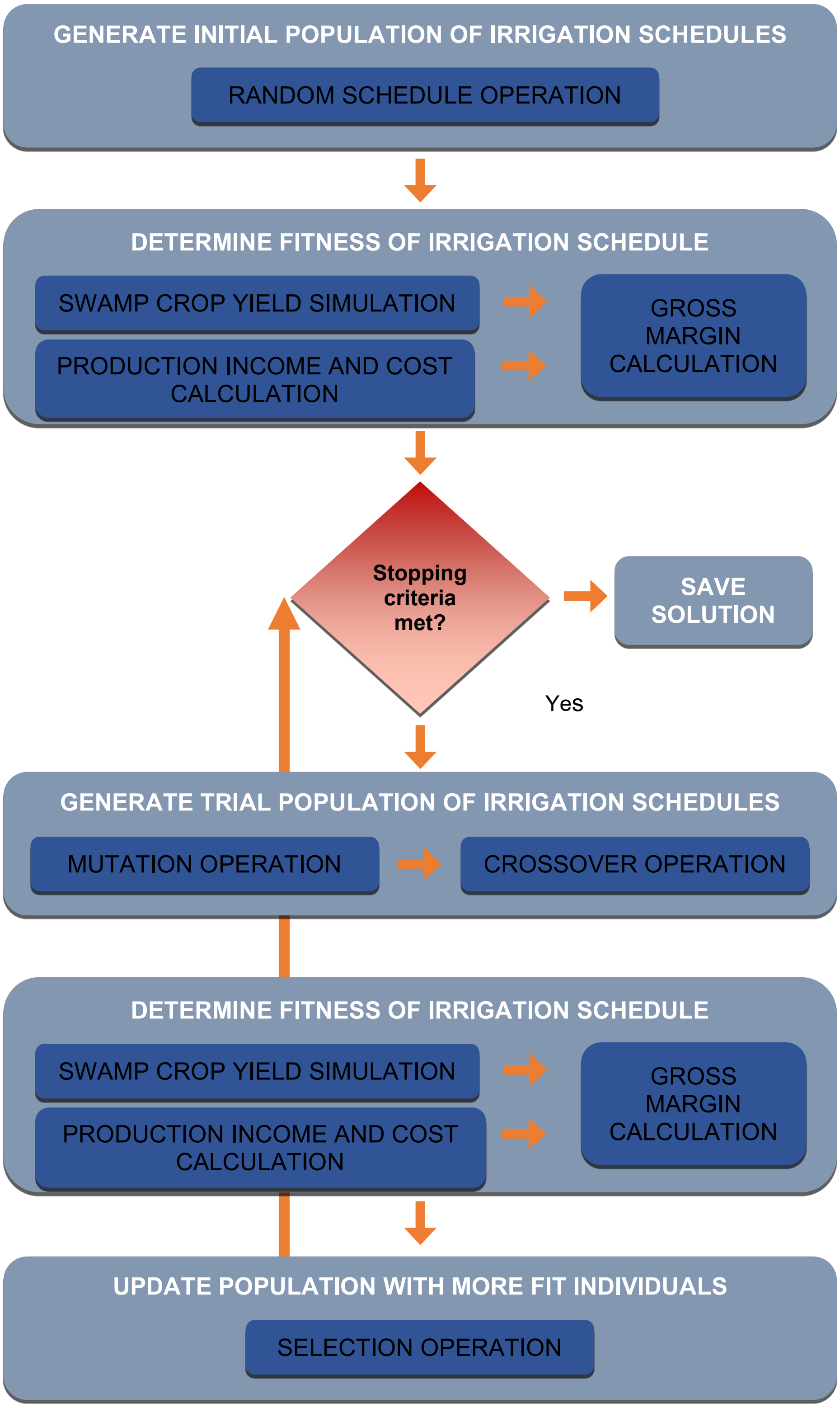


Figure 3.3: Flow chart of bioeconomic model optimisation procedure

3.3.2.1 Initialisation of candidate solutions

The first step is to initialise a population of NP vectors of irrigation schedules (individuals) that consist of D irrigation decisions. Each schedule represents a candidate solution to the optimisation problem. Let's symbolise each individual in a generation by $X_i^g = [x_{i,1}^g, x_{i,2}^g \cdots x_{i,D}^g]$, for i = 1, 2, … NP irrigation schedules, where g = 0, 1, … G is the current generation, with G representing the maximum number of generations and D representing the maximum number of irrigation decisions that an irrigator needs to make. Large heterogeneity in the initial population (g=0) is key to ensuring that as much as possible of the search space is covered. Most often, a uniform distribution is used to generate the initial search space.

An irrigation decision (d) is defined by the timing of the irrigation event and the amount of irrigation that is applied, where all the irrigation decisions within a growing season define an irrigation schedule (i). The assumption is that an irrigator allocates the necessary pumping hours over two consecutive days to make maximum use of the available off-peak hours when the electricity tariff is lowest. Consequently, D=66 for a maize growing season length of 133 days. For each d, the irrigator must decide whether to irrigate or not. Once the decision is made to irrigate, the next step is to decide the magnitude of the irrigation amount. The irrigation amount for the d^{th} irrigation decision within the i^{th} irrigation schedule can be generated as follows:

$$x_{i,d}^0 = \begin{vmatrix} 0 & \text{if U}(0{,}1) \leq 0.5 \\ x_{i,d,min}^0 + \left(x_{i,d,max}^0 - x_{i,d,min}^0 \right) (U(0{,}1) - 0.5)/0.5 & \text{otherwise} \end{vmatrix} \quad 3.6$$

where $U(0{,}1)$ represents a uniformly distributed random number in the range [0,1], $x_{i,d,min}^0$ and $x_{i,d,max}^0$ are the minimum and maximum irrigation amounts as constrained by the irrigation system design.

3.3.2.2 Fitness calculation

Improving the fitness of a population of candidate solutions with DE is equivalent to the optimisation of an objective function in standard MP applications. However, DE allows for a much more complex specification of the fitness function and the equations governing its behaviour. Optimising irrigation and salt management requires a model that can model the interactions between irrigation management decisions and the soil-water-plant-atmosphere continuum in the presence of salinity in order to quantify the impact on resulting crop yields. The energy costs and crop yields resulting from applying a specific irrigation schedule provide the necessary inputs to calculate the economic performance of the irrigation schedule, where the MAS of the pivot acts as a performance indicator. Following Equation 3.5, the calculation of the MAS for a specific irrigation schedule of a given generation is given by:

$$MAS_i^g = (prYa_i^g - ycYa_i^g - ac)A - \sum_d \sum_r H_{i,d,r}^g \, kWt_{d,r} \quad 3.7$$

MAS_i^g represents the MAS for the total irrigated area in Rands, where A is the irrigated area in hectares. Production income per hectare is calculated by multiplying the price of maize (pr) with the resulting maize yield (Ya_i^g). ac represents the area-dependent costs in Rands per hectare, while yield-dependent cost is calculated by multiplying the yield dependent costs (yc).

Energy costs are dependent on the amount of pumping hours necessary to irrigate the crop, the power requirement (kW) in kilowatts, and the Ruraflex time-differentiated electricity tariff ($t_{d,r}$) in Rands per kilowatt-hour. Before calculating the time-differentiated energy costs, it is necessary to allocate the pumping hours to a specific Ruraflex time-of-use time slot by using the following heuristics:

$$H_{i,d,off}^g = \begin{cases} PH_{i,d}^g & \text{if } PH_{i,d}^g \leq RH_{d,off} \\ RH_{d,off} & \text{otherwise} \end{cases} \quad 3.8$$

$$H_{i,d,std}^g = \begin{cases} PH_{i,d}^g - RH_{d,off} & \text{if } PH_{i,d}^g - RH_{d,off} \leq RH_{d,std} \\ RH_{d,std} & \text{otherwise} \end{cases} \quad 3.9$$

$$H_{i,d,peak}^g = \begin{cases} PH_{i,d}^g - RH_{d,std} & \text{if } PH_{i,d}^g - RH_{d,std} \leq RH_{d,peak} \\ RH_{d,peak} & \text{otherwise} \end{cases} \quad 3.10$$

where $H_{i,d,r}^g$ is the allocated hours to each Ruraflex time slot r with $r \in [off, std, peak]$, $RH_{d,r}$ is the available hours within a Ruraflex timeslot, and $PH_{i,d}^g$ is the number of hours necessary to apply $x_{i,d}^0$ on the whole area. $PH_{i,d}^g$ is dependant on the pumping rate of the irrigation system, which is calculated as $PH_{i,d}^g = 10x_{i,d}^g A/p$ where p is the pumping rate in m^3/hour.

3.3.2.3 Mutation and crossover

The initial population of irrigation schedules evolves through a process of mutation and crossover. For each target vector, X_i^g, a mutant vector V_i^g is created as follows:

$$V_i^g = X_{r1}^g + F \cdot \left(X_{r2}^g - X_{r3}^g\right) \quad 3.11$$

where $r1$, $r2$ and $r3$ are randomly chosen indexes from $i \in [1, \dots NP]$ which need to be different from the current generation index i and F is a constant scaling factor. The exploration capability of the mutant generation strategy employed is strong, since both the base and the difference vectors are randomly generated.

Crossover increases the diversity of the population by combining the mutant vector with the target vector to create a trail vector $U_i^g = \left[u_{i,1}^g,\ u_{i,2}^g\ \cdots\ u_{i,D}^g\right]$ where

$$u_{i,d}^g = \begin{cases} v_{i,d}^g & \text{if } \mathrm{U}(0,1) \leq \mathrm{CR} \\ x_{i,d}^g & \text{otherwise} \end{cases} \qquad 3.12$$

In standard applications of DE, the crossover rate (CR) is a constant. However, in our application, CR is assumed to be normally distributed, with a mean of 0.5 and a standard deviation of 0.15.

3.3.2.4 Stopping criteria

During the selection operation, the trial vector's MAS is compared with the target to determine which of the two schedules will carry forward to the next generation. Mutation, crossover and selection are repeated until the stopping criteria are met. The best solution in the last generation is the solution to the problem.

The VBA code for the bioeconomic optimisation procedure, which includes the economic model, is presented in Appendix A below.

3.4 MANAGEMENT ZONE DELINEATION

The next section will discuss the delineation procedure used to identify the management zones. Since the delineation of the management zones were achieved based on the soil characteristics, the discussion will begin with the soil thematic map characteristics.

3.4.1 SOIL THEMATIC MAP CHARACTERISTICS

It was decided to use two case studies in the bioeconomic model setup and simulations. To spatially characterise relevant soil properties for the model setup (silt plus clay and soil salinity), apparent soil electrical conductivity (ECa) readings were used, as obtained through electromagnetic induction (EMI) readings recorded by the project of Barnard *et al*. (2021), which was funded by the WRC. The standardised methodology (Corwin and Scudiero, 2016, as adopted by Barnard *et al*., 2021) was developed by researchers of the United States Department of Agriculture – Agricultural Research Service (USDA-ARS) at the United States (US) Salinity Laboratory over a number of decades to assist in the measuring and mapping of soil properties. The silt plus clay (s+c) and soil salinity maps for the two case studies were selected to represent contrasting, but still relevant, soils found in the study region, as described in Section 3.1.

The s+c map is important for noting soil-hydrological behaviour. For both case studies, three different levels (regions) of s+c were chosen. The s+c information was used to inform the crop growth model during the simulation. Another thematic map was developed, based on the measured soil-water electrical conductivity extract (ECe measured in mS/m). The ECe thematic map was used to inform the SWAMP model on the soil-water electrical conductivity at the beginning of the production season. The various maps and information (based on Section 3.1) to inform the SWAMP model are described in Section 3.5.

3.4.2 DELINEATION PROCEDURE

The study assumes that the producer can follow one of two responses to manage water and salt stress. The following section will discuss the two management responses.

3.4.2.1 Uniform irrigation applications

The first approach is to manage the field by using a uniform irrigation strategy. This strategy assumes that the decision-maker or farmer will treat the production area as a homogenous unit, irrespective of the presence of distinct management zones or hotspots that should be managed. The decision-maker would not adjust his or her management to “treat” hotspots. The irrigation strategy is developed based on the assumption that the soil's ECe is equal to the pivot's average ECe. Therefore, the decision-maker will adopt a homogenous strategy that would replace the amount of water transpired, once a pre-assumed depletion level is triggered. The irrigation decision for the uniform irrigation strategy is triggered once a predefined depletion level is reached. The trigger level was determined, based on GWK’s recommended irrigation amounts

3.4.2.2 Precision irrigation applications

The second scenario, which follows a heterogeneous production decision, assumes that the decision-maker can use precision management techniques or technology such as variable rate technology. Therefore, the assumption is that, based on predefined management zones, the decision-maker can treat every management zone or hotspot as a unique entity, and therefore manage that management zone separately from the other zones. Developing the variable rate strategy for each of the zones requires information on soil, water and salt information, and the area's size. The irrigation strategy (quantity and irrigation days) are determined endogenously, based on interaction between the water and salt budgets and the resulting crop yield.

Following consultation with a variable rate technology expert, the decision was made to divide the pivot into 36 equally sized management zones. As a result, the variable rate irrigation approach required an optimisation model to determine the optimal irrigation water strategy for each of the 36 zones.

Next, the SWAMP setup and the simulation approach will be discussed.

3.5 BIOECONOMIC MODEL SETUP

The discussion on the bioeconomic model setup will begin with a discussion of the setup procedures for the Vaalharts Irrigation Scheme before moving to the setup of the Orange-Riet Irrigation Scheme.

3.5.1 VAALHARTS IRRIGATION SCHEME

The SWAMP model was set up for a 39.9 ha pivot that is located in the Vaalharts Irrigation Scheme. The thematic map of the pivot is shown in Figure 3.4 below. From the map, three soils were identified as indicated by the blue, cream and brown colours. The size of the brown area (Soil1) is 0.35 ha, while the cream soil (Soil2) is 1.97 ha, and the blue soil (Soil3) is 37.65 ha.

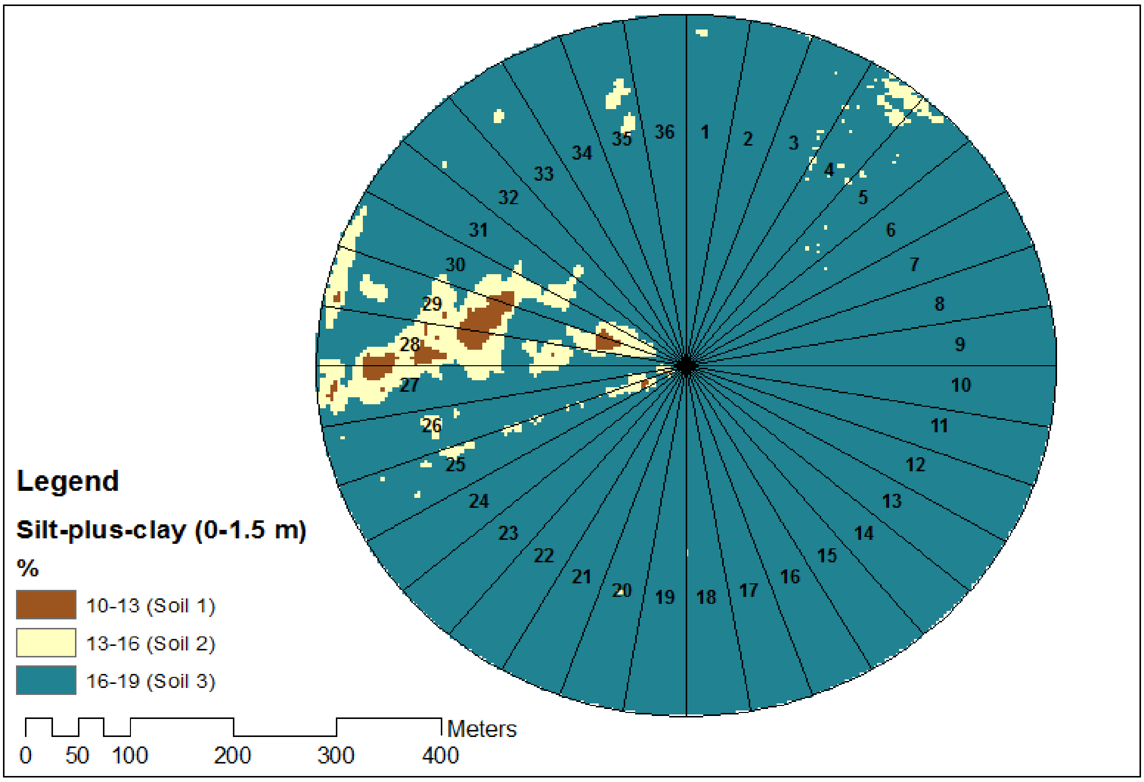


Figure 3.4: Thematic map of the soils of a 39.9 ha centre pivot in the Vaalharts Irrigation Scheme

The assumed soil, soil-crop and leaching information is shown in Table 3.5 below. The first soil, brown in Table 3.5, had a fairly low clay content (s+c) and volumetric soil water content (θ). Although the other two soils, cream and blue, show higher clay contents and volumetric soil water contents, the soil is homogenous, with s+c ranging from 13% to 19%.

Table 3.5: Soil, soil-crop and leaching parameter used to simulate water and salt stress on brown, cream and blue soils (Vaalharts)

	Parameter	**Soil1 (Brown)**	**Soil2 (Cream)**	**Soil3 (Blue)**
Soil	**(s+c)**	13	16	19
	θ_{sat} (mm/mm)	0.354	0.362	0.371
	θ_{fc} (mm/mm)	0.148	0.180	0.209
	θ_{a} (mm/mm)	0.022	0.025	0.029
	θ_{10} (mm/mm)	0.165	0.188	0.209
	θ_{1500} (mm/mm)	0.063	0.075	0.086
	C	5.191	5.424	5.663
	A	27.578	25.406	23.324
	b'	199.114	225.646	249.766
Soil-crop	L_m (mm/mm ^{2})	9.4	9.4	9.4
	RPR (mm/d^1)	23.53	23.53	23.53
	RGP (days)	85	85	85
	RootMax Default	2000	2000	2000
	RootMax Actual	1800	1800	1800
	Fsr	1.594E-05	1.536E-05	1.520E-05
	FB_{max}	100	100	100
	FB_1	0.013	0.013	0.013
	FB_2	12	12	12
	FB_3	7000	7000	7000
Leaching	1 mS/m=	0.075	0.075	0.075
	Soil factor	-17.353	-13.853	-10.325

It is assumed that the producer has a functioning centre pivot irrigation system of 39.9 ha, with an application efficiency of 90%. Assumptions were made with regard to the irrigation system pump rate, kilowatt and kilovar. The information on application efficiency, pump rate, kilowatt and kilovar is necessary for calculating the cost of applying irrigation water. The design parameters for the irrigation system are presented in Table 3.6 below.

Table 3.6: Design parameters for the irrigation system (Vaalharts)

Pivot size	39.9 ha
Application efficiency	0.9
Information required to calculate electricity cost	
Pump rate	250 m^3/ha
Irrigation Capacity	15 mm/day
Kilowatt	45 kW
Kilovar	14 kVar

The Vaalharts case study assumes that the producer begins the production season with an ECe that ranges between 71 mS/m and 191 mS/m. The thematic ECe map for the centre pivot is shown in Figure 3.5 below.

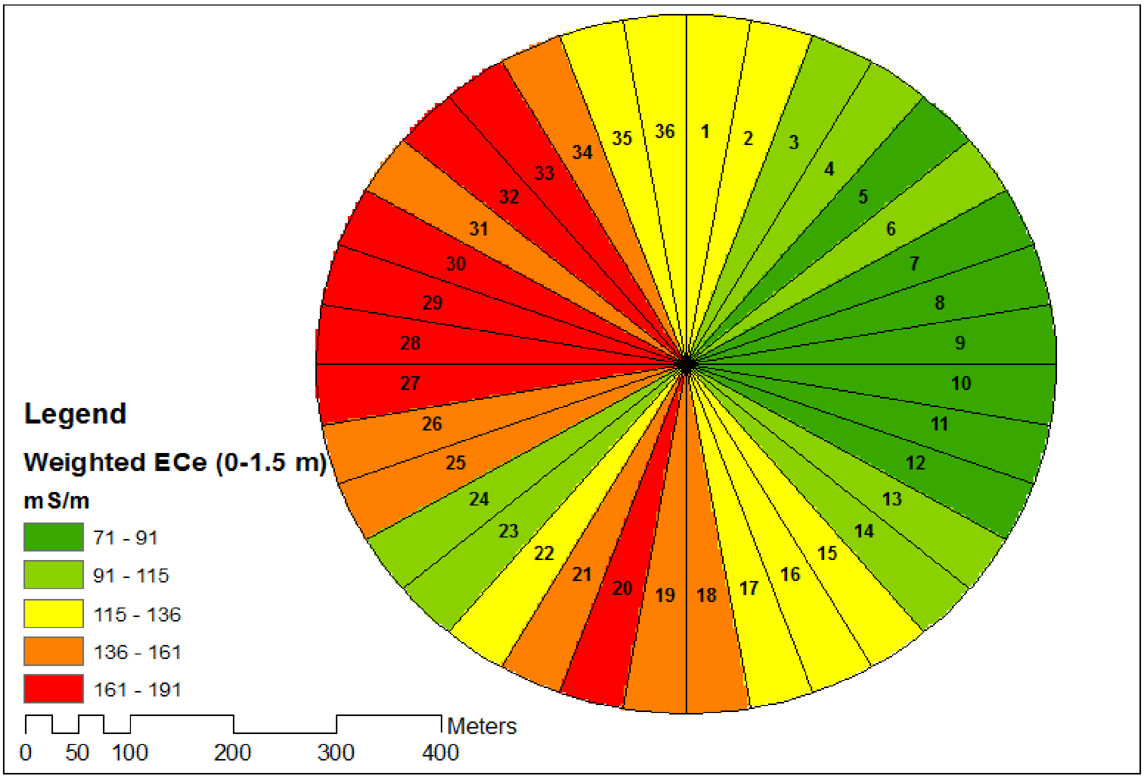


Figure 3.5: Thematic ECe map of the soils of a 39.9 ha centre pivot in the Vaalharts Irrigation Scheme

Notes: with ECe ranging from 71 mS/m to 191 mS/m

3.5.2 ORANGE-RIET IRRIGATION SCHEME

The SWAMP model was set up for a 25.1 ha pivot that is located in the Orange-Riet Irrigation scheme. The thematic map of the pivot is shown in Figure 3.6 below. Three soils were identified from the map and are indicated by the blue, cream, and brown colours in Figure 3.6. The size of the brown area (Soil1) is 9.11 ha, while the cream soil (Soil2) is 8.20 ha, and the blue soil (Soil3) is 7.20 ha.

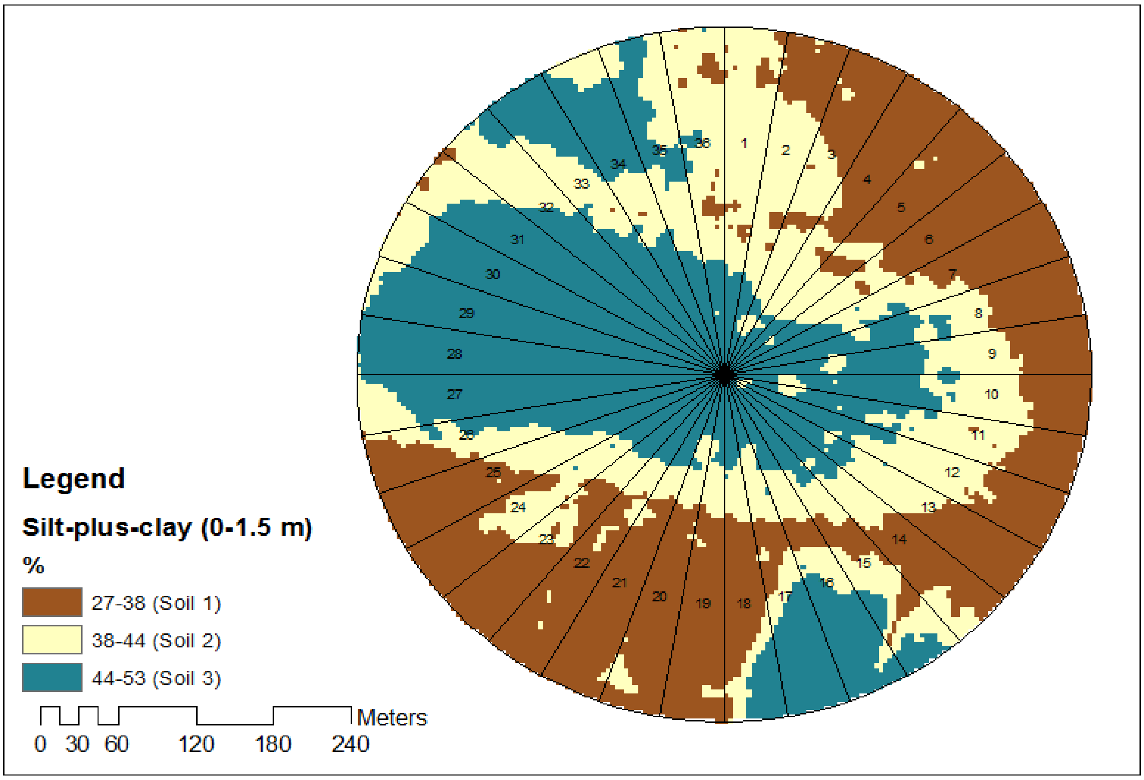


Figure 3.6: Thematic map of the soils of a 39.9 ha centre pivot in the Orange-Riet Irrigation Scheme

The assumed soil, soil-crop and leaching parameters are shown in Table 3.7 below. The first soil, brown, had a fairly low clay content (s+c) and volumetric soil water content (θ). Although Soil2 and Soil3, indicated by the cream and blue colours, show higher clay contents and volumetric soil water contents, the soil is homogenous, with s+c ranging from 27% to 44%.

Table 3.7: Soil, soil-crop and leaching parameter used to simulate water and salt stress on brown, cream and blue soils (Orange-Riet)

	Parameter	Soil1 (Brown)	Soil2 (Cream)	Soil3 (Blue)
Soil	**(s+c)**	27	38	44
	θ_{sat} (mm/mm)	0.394	0.426	0.444
	θ_{fc} (mm/mm)	0.277	0.332	0.347
	θ_{a} (mm/mm)	0.038	0.052	0.059
	θ_{10} (mm/mm)	0.259	0.319	0.348
	θ_{1500} (mm/mm)	0.117	0.159	0.182
	C	6.313	7.226	7.738
	A	18.212	12.228	9.474
	b'	302.294	346.514	356.966
Soil-crop	L_m (mm/mm ^{2})	9.4	9.4	9.4
	RPR (mm/d^1)	23.53	23.53	23.53
	RGP (days)	85	85	85
	RootMax Default	2000	2000	2000
	RootMax Actual	1800	1800	1800
	Fsr	1.489E-05	1.748E-05	1.999E-05
	FB_{max}	100	100	100
	FB_1	0.013	0.013	0.013
	FB_2	12	12	12
	FB_3	7000	7000	7000
Leaching	1 mS/m=	0.075	0.075	0.075
	Soil factor	-5.129	-5.129	-0.585

The assumption is that the producer has a functioning centre pivot irrigation system of 25.1 ha, with an application efficiency of 90%. Assumptions were also made regarding the irrigation system pump rate, kilowatt, kilovar and application efficiency for calculating the cost of applying irrigation water. The design parameters for the irrigation system are presented in Table 3.8 below.

Table 3.8: Design parameters for the irrigation system (Orange-Riet)

Pivot size	25.1 ha
Application efficiency	0.9
Information required to calculate electricity cost	
Pump rate	157 m^3/ha
Irrigation Capacity	15 mm/day
Kilowatt	45 kW
Kilovar	14 kVar

The Orange-Riet case study assumes that the producer begins the production season with an ECe that ranges between 109 mS/m and 240 mS/m. The thematic ECe map for the centre pivot is shown in Figure 3.7 below.

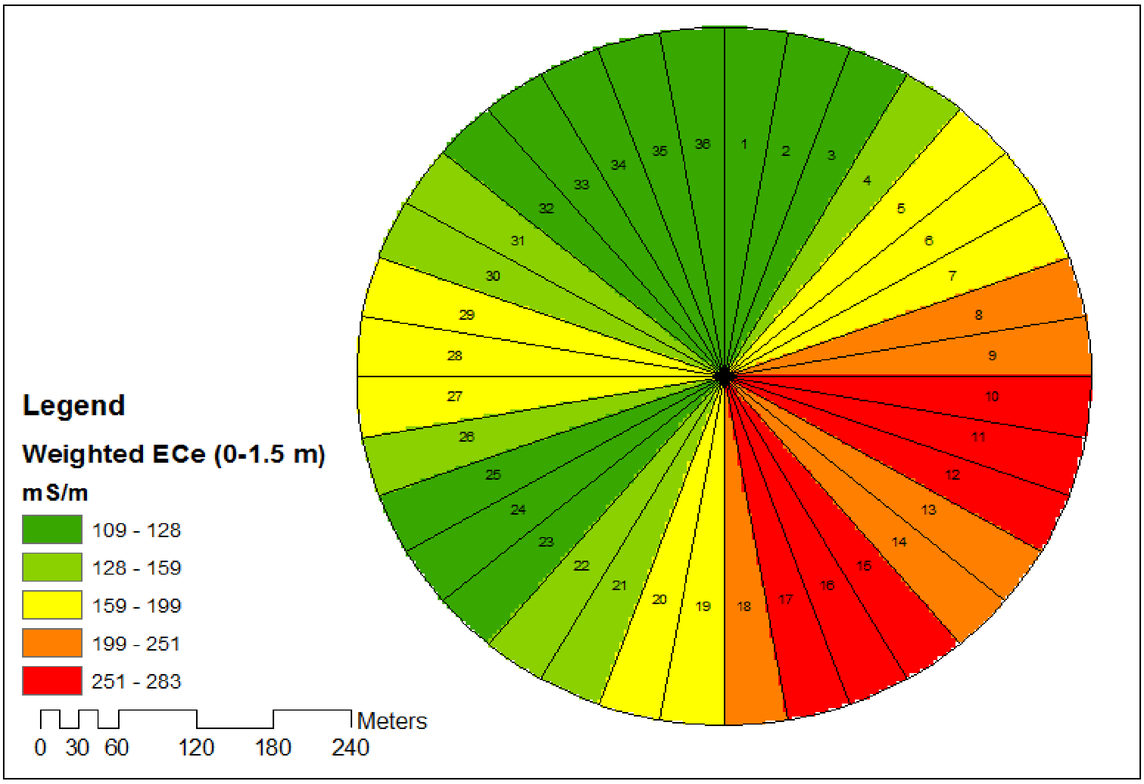


Figure 3.7: Thematic ECe map of the soils of a 25.1 ha centre pivot in the Orange-Riet Irrigation Scheme

Notes: with ECe ranging from 109 mS/m to 283 mS/m.

3.6 BIOECONOMIC MODEL APPLICATION

The economic benefit of using site-specific, precision salinity and water management is evaluated by comparing a uniform irrigation strategy with a site-specific irrigation strategy. The uniform irrigation strategy ignores the spatial variation of soil properties and salinity levels, and the same information is used to determine irrigation application rates for the pivot. The uniform irrigation strategy is applied to each soil under the pivot to determine the economic impact of using the wrong soil as a source of information to base irrigation decisions on. The uniform irrigation strategy applies 30 mm of irrigation when soil water is depleted to a predefined, management-allowed depletion (MAD) level. The impact of water quality is simulated by considering two irrigation water qualities, the first at 21 mS/m and the second at 200 mS/m.

Site-specific, precision water and salinity management is determined through the application of the optimisation algorithm to each of the 36 segments, with their own unique soil properties, to optimise water application rates with the objective of maximising the MAS of each segment. Generating the results is time consuming. On average, it takes about seven (7) hours for the optimisation algorithm to converge to a solution.

The value of site-specific, precision water and salt management is determined by comparing the uniform irrigation strategy with the optimisation results.

Next, the results of the bioeconomic model application are discussed.

CHAPTER 4: BIOECONOMIC SALINITY MANAGEMENT RESULTS

This chapter discusses the water and salinity management results for a uniform irrigation strategy and the precision management strategy for the two case studies. First, the results for the Vaalharts case study will be discussed, before moving to the results for the Orange-Riet case study.

4.1 VAALHARTS IRRIGATION SCHEME

The Vaalharts results comprise two main sections; the first section will discuss the uniform irrigation strategy results, before discussing the precision management strategy. The results were simulated for two irrigation water qualities, the first at 21 mS/m and the second at 200 mS/m.

4.1.1 UNIFORM IRRIGATION APPLICATIONS

The water and salt budget and the economic results for the uniform irrigation strategy for the Vaalharts case study are shown in Table 4.1 below. The results table show the simulated results for the three soils assuming an irrigation water quality of 21 mS/m and 200 mS/m. The results' discussion will start with the simulated results for production with an irrigation water quality of 21 mS/m on Soil3. We begin with production on Soil3 because the majority (94%) of the pivot consists of Soil3.

Maize production on Soil3 requires 638 mm of irrigation water to produce a crop yield of 14.85 ton/ha. The 14.85 ton/ha yield is produced under matric-, osmotic- and total potential conditions of -243.66 kPa, -209.21 kPa and -452.88 kPa, respectively. Even though nearly a ton of salts is added to the soil, the osmotic and total potential remains relatively high (close to zero) due to the amount of irrigation water used during production. Production on Soil3 results in a production income of R32 695/ha and a calculated MAS of R8 890.79/ha.

Table 4.1: Water budget, salt budget and economic information for the Farmer strategy on the three soils for the Vaalharts Irrigation Scheme

		ECi 21			ECi 200		
		Soil1	**Soil2**	**Soil3**	**Soil1**	**Soil2**	**Soil3**
Area	Ha	1	1	1	1	1	1
Yield	ton/ha	14.73	14.82	14.85	13.43	13.98	14.32
Net irrigation	mm	607	636	638	590	631	670
Drainage	mm	0	0	0	0	0	0
Delta WC	mm	233.74	272.83	291.43	265.85	301.07	335.10
Delta Salt	kg/ha	955.68	1 002.07	1 005.62	8 843.26	9 472.36	10 052.42
Matric potential	kPa	-275.20	-258.18	-243.66	-92.79	-96.19	-85.36
Osmotic potential	kPa	-279.71	-231.16	-209.21	-324.94	-275.91	-251.35
Total potential	kPa	-554.92	-489.34	-452.88	-417.73	-372.10	-336.71
MAS/ha	R/ha	8 685.18	8 844.07	8 890.79	6 399.03	7 325.35	7 869.54
Production Income	R/ha	32 407.55	32 613.22	32 659.32	29 549.22	30 755.90	31 513.35
Area Cost	R/ha	9 864.31	9 864.31	9 864.31	9 864.31	9 864.31	9 864.31
Yield Cost	R/ha	12 626.48	12 662.73	12 670.86	12 122.54	12 335.28	12 468.82
Electricity Cost	R/ha	1 211.80	1 221.36	1 212.53	1 144.11	1 210.37	1 288.82

Notes: Showing Soil1, Soil2 and Soil3 for an irrigation water quality of 21 mS/m and 200 mS/m for the Vaalharts Irrigation Scheme.

Both Soil1 and Soil2 have a lower s+c percentage than Soil3. Comparing the results for the three soils shows that, as the s+c percentage decreases (from 19% to 13%), the amount of irrigation water applied also decreases. The reduction in irrigation water applied results in a reduction of the simulated matric, osmotic and total potentials. The decrease in osmotic potential is not as expected because the amount of salts added to the soils decreases as the s+c percentage decreases. The reason for the osmotic potential decline is attributable to the reduction in irrigation water applied. Even though fewer salts are added to the soil, the concentration of salts is greater because of the decrease in the amount of irrigation water applied, and, therefore, the osmotic potential decreases.

The decreased potentials (matric, osmotic and total potentials) result in decreased crop yields and, therefore, a decrease in the MAS. The calculated MAS decreases from R8 844/ha to R8 685/ha (a difference of R159/ha) as the amount of irrigation water applied decreases from 638 mm (Soil3) to 607 mm (Soil1). The higher MAS is calculated for production on Soil3 because the irrigation strategy is associated with the highest yield and, therefore, the highest production income. Although the Soil3 strategy applies more amounts of irrigation water and shows an increase in production costs, the increase in production income outweighs the increase in production costs.

Production with an irrigation water quality (ECi) of 200 mS/m shows similar trends to the 21 mS/m scenario. The highest crop yield is produced on Soil3 with 670 mm of irrigation water. A movement to production on Soil1 or Soil2 produces lower crop yields (0.9 ton/ha and 0.34 ton/ha) with less irrigation water (80 mm and 39 mm). Similar to the 21 mS/m scenario, the highest MAS is calculated for production on Soil3 at R7 869.54/ha, and the lowest on Soil 1 (R6 399.03/ha). The R1 470.51/ha reduction in the MAS is in no small part due to the R1 964.13/ha reduction in production income.

Comparing the results for the two irrigation water quality scenarios shows that higher yields are simulated for the ECi 21 mS/m strategy. Production with the 200 mS/m irrigation water applies less irrigation water, but more salts are added to the soils because of the lower quality of the irrigation water. As a result, the osmotic potential for the 200 mS/m scenario is lower than for the 21 mS/m scenario. The reduced irrigation applications and crop yield for the ECi of 200 mS/m also leads to a reduction of R1 021/ha to R2 286/ha in the calculated MAS.

4.1.2 PRECISION IRRIGATION APPLICATIONS

This section will discuss the effect of using a precision irrigation strategy on the Vaalharts case study, as compared with using a uniform irrigation application strategy. The uniform irrigation strategy assumed that the decision-maker would irrigate according to the irrigation strategy for Soil1, Soil2 or Soil3. As a result, the three irrigation strategies are compared with the precision irrigation strategy for the Vaalharts case study, assuming an ECi of 200 mS/m. Next, the strategy for Soil3, which is the dominant soil for the case study, will be discussed, followed by the results for Soil1 and Soil2.

The matric, osmotic and total potentials (kPa), crop yield (ton/ha), irrigation water applied (mm), MAS (R/ha) for the management zones for the uniform irrigation strategy (Soil3), and the precision irrigation strategy are shown in Figure 4.1 below.

The irrigation water applied for the precision strategy is generally less than the irrigation water amount applied when using the uniform irrigation strategy. However, for segments (management zones) 27 to 30, the precision strategy's irrigation water exceeds the uniform strategy by about 50 mm. The reason for the increased irrigation water applied on these segments is that the segments have relatively high ECe (161 mS/m to 191 mS/m, as shown in Figure 3.5 above), and the segment consists of Soil1, Soil2 and Soil3 types. The matric potential is relatively higher (closer to zero), while the osmotic potential is relatively smaller (around -300 kPa). Segments 3 to 14 each have a relatively lower ECe; as a result, less irrigation water is applied (between 600 mm and 650 mm), the matric potential is relatively lower (between -80 kPa and -130 kPa), and the osmotic potential is relatively lower (-150 kPa to -250 kPa). The result for the matric potential may seem surprising, given that the uniform strategy applies more water (745 mm) than for the precision strategy (around 600 mm); however, this result could arise because the uniform strategy over irrigates, thus making it more difficult for the crop to extract water from the soil.

The matric, osmotic and total potentials experienced by the crop, when using the precision irrigation strategy, is higher when compared with the potentials for the uniform strategy. Because of the higher potentials, the crop yield for the precision strategy is higher than that for the uniform strategy. The crop yield for the uniform strategy ranges between 13.9 and 14.6 ton/ha, while the crop yield using the precision strategy ranges between 15 ton/ha and 15.6 ton/ha. The results in Figure 4.1 show that the simulated crop yield is the lowest for the management zones where the total potential is the highest.

Figure 4.1: Matric, osmotic and total potential (kPa), crop yield (ton/ha), water applied (mm) and MAS/ha (R/ha) for the uniform strategy for Soil3 and the variable rate irrigation strategy (precision) (Vaalharts)

Notes: showing production in Vaalharts, using irrigation water with a quality of 200 mS/m.

The calculated MAS for the management zones follows a similar pattern to that for the simulated crop yields. Overall production, using the precision strategy, results in MAS ranges from R9 116/ha to R10 425/ha. The MAS calculated for the uniform strategy follows a similar pattern to that of the precision strategy, but is about R2 000/ha lower.

Figure 4.2 below shows the matric, osmotic and total potentials (kPa), crop yield (ton/ha), irrigation water applied (mm), MAS (R/ha) for the management zones for the uniform irrigation strategy for Soil1, and the precision irrigation strategy. The uniform strategy applies around 90 mm less irrigation water, which has a relatively large effect on crop production. Because of the irrigation strategy used, the matric pressure range decreases from that shown in Figure 4.1 above. Although the osmotic potential also decreases from that shown in Figure 4.1, the effect of the reduction in irrigation water is seen predominantly in the simulated matric potential. The simulated crop yield follows the same pattern as for the matric potential. The simulated crop yield for production with the uniform irrigation strategy ranges between 12.97 kg/ha and 13.53 kg/ha, and is lower than that reported in Figure 4.1. The 90 mm reduction in irrigation water applied results in a 1 ton/ha reduction in crop yield. Because the Soil1 uniform strategy results in lower crop yields, the simulated MAS is also lower, with the MAS for the uniform strategy ranging from R5 562/ha to R6 568/ha. The difference in MAS between the precision strategy and the Soil1 uniform strategy is in the order of R3 000/ha to R4 000/ha, depending on the segment.

Figure 4.2: Matric, osmotic and total potential (kPa), crop yield (ton/ha), water applied (mm) and MAS/ha (R/ha) for the uniform strategy Soil1 and the variable rate irrigation strategy (precision) (Vaalharts)

Notes: showing production in Vaalharts, using irrigation water with a quality of 200 mS/m.

Figure 4.3: Matric, osmotic and total potential (kPa), crop yield (ton/ha), water applied (mm) and MAS/ha (R/ha) for the uniform strategy Soil2 and the variable rate irrigation strategy (precision) (Vaalharts)

Notes: showing production in Vaalharts using irrigation water with a quality of 200 mS/m

Figure 4.3 above show the matric, osmotic and total potentials (kPa), crop yield (ton/ha), irrigation water applied (mm), MAS (R/ha) for the management zones for the uniform irrigation strategy for Soil2, and the precision irrigation strategy. The strategy for Soil2 applies a constant 701 mm of irrigation water. The Soil2 uniform strategy results in a crop yield that ranges between 13.52 ton/ha and 14.13 ton/ha, and a MAS that ranges between R6 495/ha and R7 595/ha. The difference in MAS between the precision strategy and the Soil2 uniform strategy is between R2 000/ha and R3 000/ha, depending on the segment. Similar to the previous two irrigation scenarios, the matric, osmotic and total potentials are higher for the uniform strategy than for the precision strategy, resulting in the lower crop yield. More importantly, for some segments, the uniform strategy still over irrigates and for some, under irrigates.

The results presented in Figures 4.1 to 4.3 show the per-hectare results for crop production and the resulting MAS. The MAS shown in Figures 4.1 to 4.3 indicate that the placement of the probe, or the nature of the information (soil) on which the uniform strategy is developed, is important. The next step is to compare the calculated MAS for the three uniform strategies with the precision irrigation strategy for the pivot. The results for MAS calculated for the uniform and the precision strategies in the Vaalharts case study (39.96 ha pivot) are shown in Table 4.2 below.

Table 4.2: Calculated Margin Above Specified Costs for the Uniform strategies for the three soil types and the Precision irrigation strategy for the Vaalharts case study

	MAS Uniform	**MAS Precision**	**Difference**	
	R	**R**	**R**	**R/ha**
Precision		397 529		
Soil1	243 626		153 903	3 851
Soil2	283 680		113 849	2 849
Soil3	313 832		83 697	2 095

The calculated MAS for the 39.96 ha pivot, when using the precision irrigation strategy, is R397 529. The use of the uniform irrigation strategy designed for Soil3 will result in a reduction of R83 697 in the calculated MAS, while the strategies for Soil2 and Soil1 will reduce MAS by R113 849 and R153 903, respectively. It should be remembered that much of the pivot consists of Soil3; therefore, it should come as no surprise that Soil3 would result in the highest MAS when compared with the other uniform strategies. The reduction in MAS shows that the use of the Soil1 or Soil2 uniform strategy could severely impact upon the MAS of the farming operation. Therefore, it can be concluded that using the wrong information, when developing a uniform strategy, can have a relatively large effect on the MAS.

4.2 ORANGE-RIET IRRIGATION SCHEME

The discussion of the Orange-Riet results will begin with a discussion of the results for the uniform irrigation strategy, before discussing the precision management strategy. The uniform and precision irrigation results were simulated for two irrigation water qualities, a water quality of 21 mS/m and of 200 mS/m.

4.2.1 UNIFORM IRRIGATION APPLICATIONS

The water and salt budget and the economic results for the uniform irrigation strategy for the Orange-Riet case study are shown in Table 4.3 below. The results in the table record the simulated results for the three soils, assuming an irrigation water quality of 21 mS/m and 200 mS/m. The discussion of the results will begin with the simulated results for production with an irrigation water quality of 21 mS/m on Soil1. We start with production on Soil1 because, although the soil types seem fairly equal in size, Soil1 is relatively more dominant as compare with Soil2 and Soil3.

Production on Soil1 requires 61 8mm of irrigation water to produce a maize yield of 14.06 ton/ha. The 14.06 ton/ha yield result in a production income of R30 929/ha and a MAS of R7 431.15/ha. With an irrigation amount of 618 mm, the matric, osmotic and total potentials are -263.04 kPa, -164.87 kPa and -427.91 kPa, respectively.

Production on Soil2 and Soil3 requires an increase in irrigation water from 618 mm to 621 mm. The increase in irrigation water applied results in a reduction of the matric and total potentials, while the osmotic potential increased. The small increase in the amounts of salts added (5 kg/ha) is relatively small, compared with the soil-water content; thus, the effect of the added salts is not a concern. The reader should note that the s+c percentages for the three soils are 27%, 38%, and 44%; therefore, the soils' volumetric soil water contents at the beginning of the production season are different (increase with increased s+c percentage) and the amounts of irrigation water applied are different. The decrease in the total potential when comparing Soil2 and Soil3 with Soil1 results in decreases in production income and MAS (reduction of R87/ha and R563/ha, respectively).

Table 4.3: Water budget, salt budget and economic information for the Farmer strategy on the three soils (Soil1, Soil2 and Soil3) (Orange-Riet)

		ECi 21			**ECi 200**		
		Soil1	**Soil2**	**Soil3**	**Soil1**	**Soil2**	**Soil3**
Area	Ha	1	1	1	1	1	1
Yield	ton/ha	14.06	14.00	13.74	13.01	13.38	13.32
Net irrigation	mm	618	621	621	588	646	647
Drainage	mm	0	0	0	0	0	0
Delta WC	mm	413.33	481.40	513.94	425.63	517.88	540.62
Delta Salt	kg/ha	973.58	978.08	978.08	8 823.10	9 695.13	10 052.42
Matric potential	kPa	-263.04	-363.82	-495.10	-206.48	-295.66	-416.85
Osmotic potential	kPa	-164.87	-142.19	-137.75	-192.98	-165.70	-158.03
Total potential	kPa	-427.91	-506.01	-632.85	-399.47	-461.36	-574.88
MAS/ha	R/ha	7 431.15	7 344.39	6 868.46	5 651.59	6 159.80	6 048.78
Production Income	R/ha	30 929.01	30 791.71	30 235.66	28 629.87	29 444.64	29 298.76
Area Cost	R/ha	9 864.31	9 864.31	9 864.31	9 864.31	9 864.31	9 864.31
Yield Cost	R/ha	12 365.80	12 341.60	12 243.56	11 960.46	12 104.10	12 078.38
Electricity Cost	R/ha	1 247.58	1 221.17	1 239.08	1 134.34	1 295.35	1 286.18

Notes: as recorded for an irrigation water quality of 21 mS/m and 200 mS/m for the Orange-Riet Irrigation Scheme

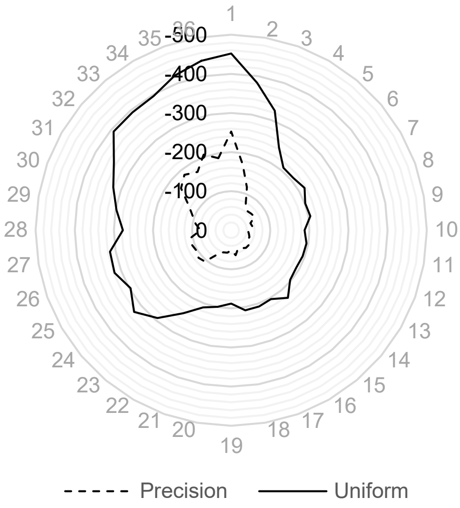
Production with irrigation water of quality 200 mS/m shows similar trends for irrigation water applied, and matric, osmotic and total potentials. Production on Soil1 uses 588 mm of irrigation water to produce a crop yield of 13.01 ton/ha. A switch to Soil2 and Soil3 requires a 58 mm increase in irrigation water to increase crop yield by 0.37 ton/ha. Although the difference in irrigation water use between Soil2 and Soil3 is 1 mm, the crop yield difference is 0.06 ton/ha. The highest crop yield of 13.38 ton/ha is realised for production on Soil2, resulting in the highest production income (R29 445/ha) and MAS (R6 159.80/ha).

Comparing the results of the two irrigation water qualities shows that irrigation with the lower ECi of 21 mS/m results in higher crop yields, and therefore higher MAS. It is interesting to note that the 21 mS/m strategy has lower matric potentials, but higher osmotic potentials, than the 200 mS/m strategy. Moreover, the 200 mS/m strategy applies more irrigation water compared with the 21 mS/m strategy, except for production on Soil1, where the amount of irrigation water applied is higher for the 21 mS/m strategy.

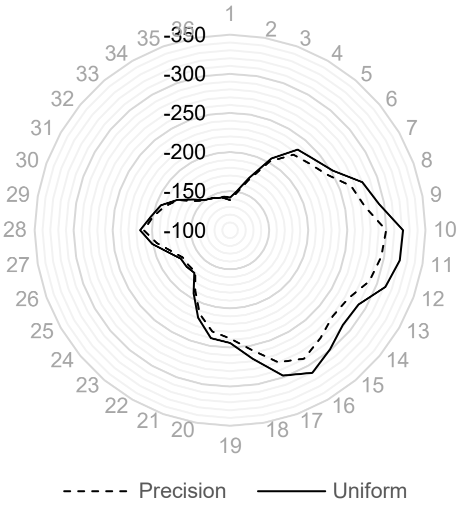
4.2.2 PRECISION IRRIGATION APPLICATIONS

This section will discuss the effect of using a precision irrigation strategy on the Orange-Riet case study, as compared with using a uniform irrigation application strategy. The uniform irrigation strategy assumed that the decision-maker would irrigate according to an irrigation strategy for Soil1, for Soil2, or for Soil3. Accordingly, the three irrigation strategies are compared with the precision irrigation strategy for the Orange-Riet case study, assuming an ECi of 200 mS/m. Next, the strategy for Soil1, which is the dominant soil for the case study, will be discussed, followed by the strategies for Soil1 and Soil3.

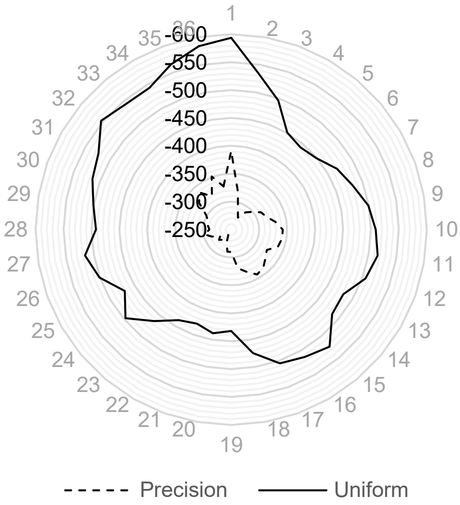
The irrigation water applied for the precision strategy (see Figure 4.4 below) ranges from 580 mm to 730 mm, while the amount applied for the uniform strategy is 650 mm. The precision strategy applied more water on the segments with the higher (199 mS/m to 283 mS/m) ECe at the beginning of the production season. For these segments, the uniform irrigation strategy tends to under irrigate. The segments with the lower ECe at the beginning of the season are the segments where less water is applied with the precision strategy. The uniform strategy is prone to under irrigating.



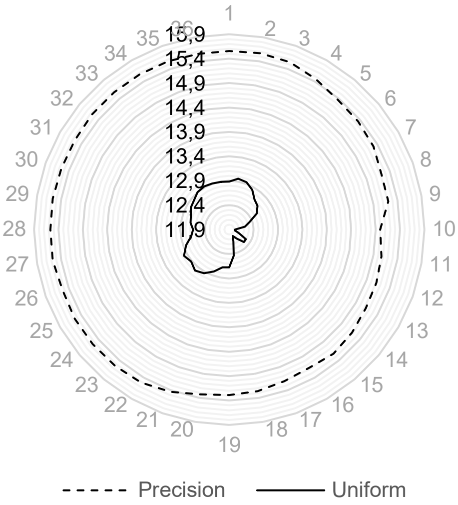
Matric potential



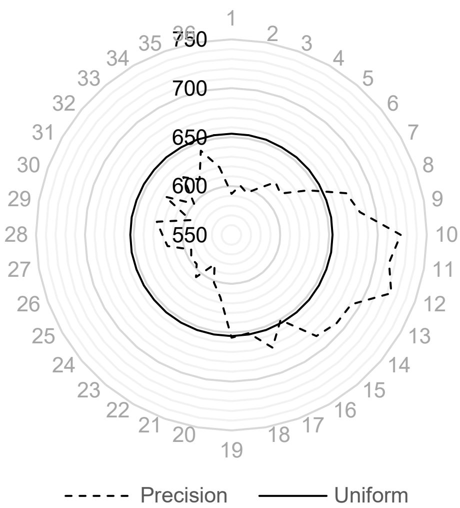
Osmotic potential



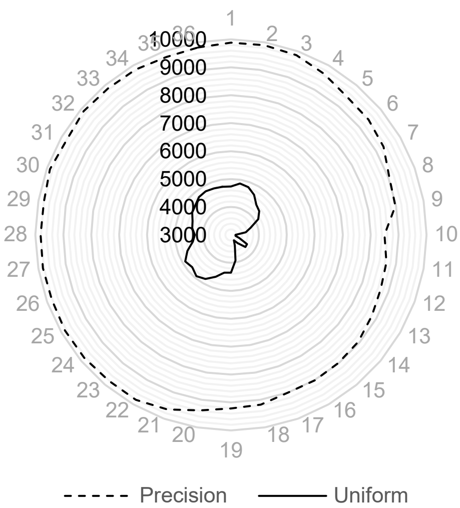
Total potential



Crop yield



Water applied



Margin Above Specified Costs per hectare

Figure 4.4: Matric, osmotic and total potential (kPa), crop yield (ton/ha), water applied (mm), and MAS/ha (R/ha) for the uniform strategy Soil1 and the variable rate irrigation strategy (precision) (Orange-Riet)

Notes: showing production in Orange-Riet, using irrigation water with a quality of 200 mS/m.

The results for the matric potential and osmotic potential can also be explained, based on the ECe shown in Figure 3.7 above. The segments with the lowest ECe values show the lowest matric potentials and the highest osmotic potentials for both the uniform strategy and the precision irrigation strategy. Comparing the matric, osmotic and total potentials for the two irrigation strategies shows that the matric, osmotic and total potentials are higher for the uniform strategy. The matric potential for the uniform strategy is between -100 kPa and -200 kPa lower than for the precision strategy. On the other hand, the difference in the osmotic potential never exceeds -30k Pa, with the lower osmotic potential being simulated for the uniform strategy. The difference in the total potential is as high as -200 kPa.

The simulated crop yield ranges between 12 ton/ha and 13 ton/ha, which is 2 ton/ha to 3 ton/ha less than for the precision strategy due to the high total potential. The calculated MAS follows the same trend as the crop yield. The estimated MAS ranges from a low of R3 167/ha to a high of R4 889/ha, while the MAS for the precision strategy ranges between R8 500/ha and R10 000/ha.

The results for production when using the uniform Soil2 strategy, as shown in Figure 4.5 below, shows that the uniform strategy applies a constant 720 mm water on all of the segments, while the precision strategy applies between 585 mm and 724 mm. The uniform strategy over irrigates, compared with the precision irrigation strategy. Although the Soil2 uniform strategy's matric potential follows the same trend as that for the Soil1 uniform strategy, the matric potential for the Soil2 strategy is slightly higher. As a result, the total potential for Soil2 is higher than for the Soil1 strategy. A surprising result is that the osmotic potential seems unchanged between the Soil1 and Soil2 uniform irrigation strategies. Therefore, the change in the total potential is attributable to the difference in the matric potential. The crop yield simulated for the Soil2 uniform scenario ranges between 12.4 ton/ha and 13.5 ton/ha, which is 2 ton/ha to 3 ton/ha less than for the precision strategy. As a result, the calculated MAS for the uniform strategy is more than R5 000/ha less than that for the precision strategy. For some segments, the difference is in the range of R6 000/ha.

Figure 4.5: Matric, osmotic and total potential (kPa), crop yield (ton/ha), water applied (mm) and MAS/ha (R/ha) for the uniform strategy Soil2 and the variable rate irrigation strategy (precision) (Orange-Riet)

Notes: showing production in Orange-Riet, using irrigation water with a quality of 200 mS/m.

Figure 4.6: Matric, osmotic and total potential (kPa), crop yield (ton/ha), water applied (mm) and MAS/ha (R/ha) for the uniform strategy Soil3 and the variable rate irrigation strategy (precision) (Orange-Riet)

Notes: showing production in Orange-Riet, using irrigation water with a quality of 200 mS/m.

The results for the Soil3 uniform strategy, as shown in Figure 4.6 above, do not show much of a difference from those simulated with the Soil2 strategy. The result is not surprising because the Soil3 strategy applies 1.11 mm more water than the Soil2 strategy does. The simulated crop yields for the Soil3 scenario range between 12.4 ton/ha and 13.5 ton/ha, which is about 0.009 ton/ha to 0.0123 kg/ha less than that for Soil2. The implication is that the Soil3 strategy gives lower crop yields when compared with the precision irrigation strategy and should, therefore, also show lower MAS. The calculated MAS results for production using strategy Soil3 range between R3 814/ha and R5 605/ha. The variation between the strategy and the precision strategy results gives a difference in MAS of between R4 305/ha and R5 088/ha.

The results calculated for MAS in the Orange-Riet case study's irrigation strategies (25.1 ha pivot) are shown in Table 4.4 below. The calculated MAS for the pivot when using the precision irrigation strategy is R237 742. The use of the Soil1 uniform irrigation strategy will result in a reduction of R130 692 in MAS, which is a reduction of R5 207/ha in the per-hectare MAS. The use of the Soil2 and Soil3 uniform strategies to irrigate the pivot will result in decreases of R4 549/ha and R4 514/ha, respectively, from the precision irrigation MAS. The results, therefore, indicate that the losses incurred where a decision-maker chooses to irrigate according to the Soil3 strategy would be less than if he or she chooses the Soil1 or Soil2 strategies.

Table 4.4: Calculated Margin Above Specified Costs for the Farmer strategy for the three soil types and the Precision irrigation strategy for the Orange-Riet case study

	MAS Farmer	MAS Precision	Difference	
	R	**R**	**R**	**R/ha**
Precision		237 742		
Soil1	107 050		130 691	5 207
Soil2	123 561		114 180	4 549
Soil3	124 429		113 312	4 514

Next, the daily changes to the matric, osmotic and total potentials will be discussed.

4.2.3 DAILY MATRIC, OSMOTIC AND TOTAL POTENTIALS

Figures 4.3 above to 4.6 above show the seasonal matric, osmotic and total potentials for the different segments (management zones). The purpose of this section is to discuss the daily potentials for a single segment for the precision irrigation strategy. The chosen segment was zone 10, one of the zones with the highest rates of water application, at 723 mm irrigation water. The results for the daily matric, osmotic and total potentials (kPa) for production on segment 10 are given in Figure 4.7 below.

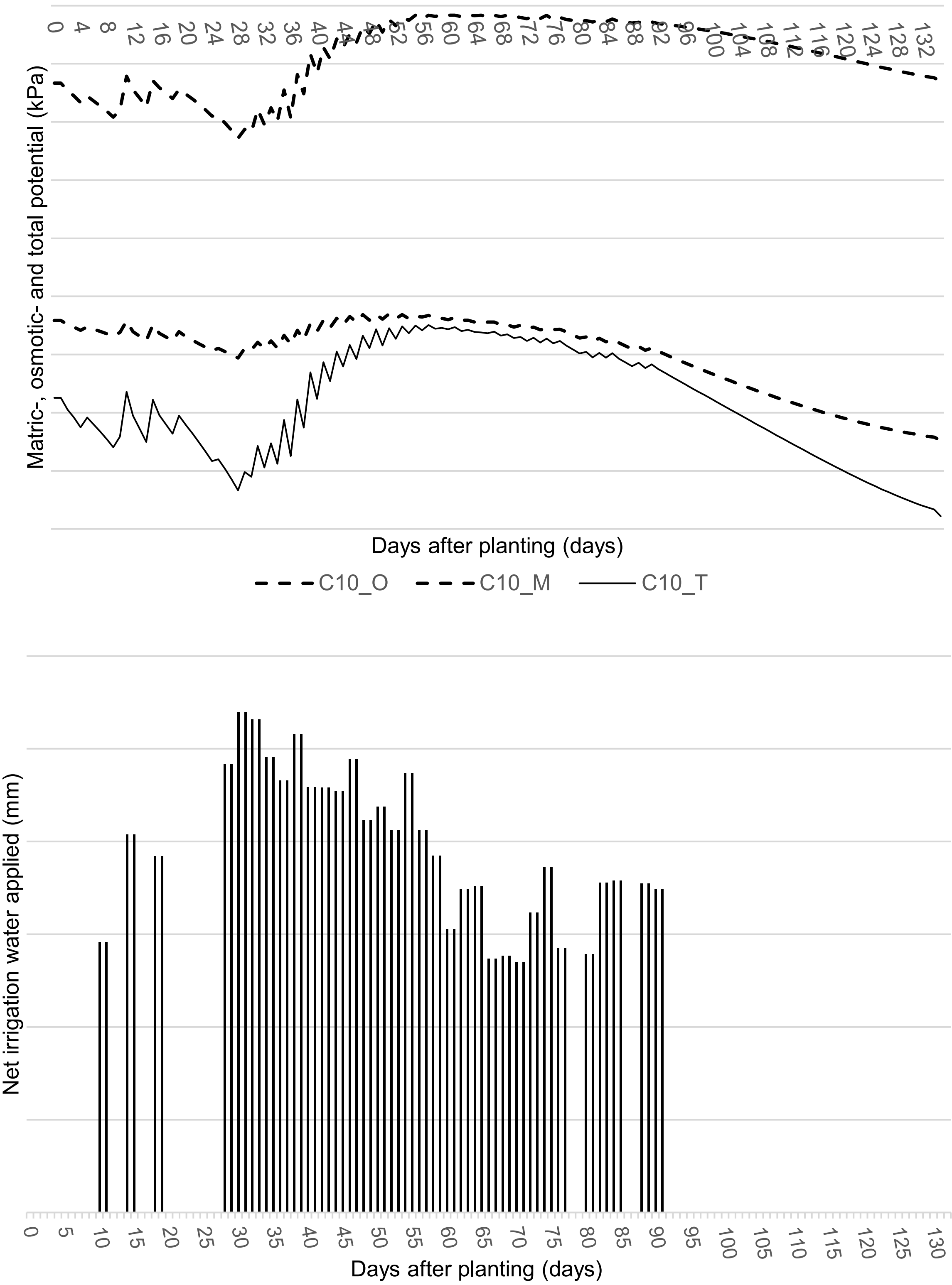


Figure 4.7: Daily matric (C10_M), osmotic (C10_O) and total potentials (C10_T) (kPa) and the net irrigation water applied (mm) (management zone 10, Orange-Riet)

Notes: showing production on management zone 10 for the Orange-Riet case study, using irrigation water with a quality of 200 mS/m

The daily matric potential (C10_M), as shown in Figure 4.7, shows that the matric potential follows a pattern very similar to the distribution of irrigation events during the production season. During the initial days after planting, the matric potential increases and decreases, depending on the occurrence of irrigation events. From day 29, the number of irrigation events increases and, although the amount of irrigation water applied move upwards and downwards, the matric potential is kept below -10 kPa. Later, the matric potential begins to decrease as the irrigation water applied decreases to zero, gradually.

The daily osmotic potential (C10_O) follows a pattern similar to the matric potential and is also driven by the irrigation decision. A noteworthy difference between the matric and osmotic potentials is that the matric potential shows minimal variation from day 54 to 90, as the osmotic potential decreases. The reason is that, although the matric potential is managed with irrigation events, the amount of water applied during an event fluctuates and even decreases. As a result, the osmotic potential decreases and, thereby, the ability of plants to extract water from the soil decreases.

CHAPTER 5: CONCLUSIONS, GUIDELINES FOR SALINITY MANAGEMENT, AND RECOMMENDATIONS FOR FURTHER RESEARCH

5.1 BACKGROUND

Irrigated agriculture experiences increased pressure to use water more efficiently by adopting better irrigation technology, irrigation scheduling methods, spatial management, and crop rotation strategies. Due to improved water use efficiency, the salt added to soils through irrigation water and fertilisers builds up in soils. The uncontrolled build-up of salts can cause salinity, which leads to a loss in crop yields.

The spatial management of water and salt stress is complex and requires having integrated information on the soil (i.e. soil salinity levels), the crop (i.e. crop water requirements and salinity tolerances), irrigation (i.e. quality of the irrigation water and information of the irrigation system) and economic information (i.e. information needed to calculate production income and production costs). A recent study conducted by Barnard *et al*. (2021) provides the information necessary to evaluate water and salinity management's spatial management through using a transient state crop growth model, SWAMP. The SWAMP model can simulate water and salt stress by using soil, crop and irrigation information. However, the existing SWAMP model does not consider the financial implications of the spatial management of water and salt stress. Previous studies on the economic management of salinity have used simplified steady state approaches to model the bioeconomic interactions within a constrained optimisation framework. The concern with using steady state approaches is that the impact of management decisions on dynamic changes in soil water content and osmotic pressure is assumed away. Therefore, an integrated modelling approach that links an economic model to a transient state soil-water-crop model is necessary to economically enhance spatial soil water and salinity management.

The purpose of this study is to develop an integrated bioeconomic model to economically manage site-specific water and salt stress in irrigated agriculture. To achieve the study's objective, the transient state soil-water-crop model, SWAMP, is linked to an economic model and an optimisation procedure to evaluate site-specific management of water and salinity.

5.2 SUMMARY OF RESULTS AND CONCLUSIONS

The Vaalharts results show that applying the same trigger level to initiate irrigation resulted in the same gross amount of irrigation being applied (686-690 mm), when the irrigation water quality is good (21 mS/m). Applying the increased amount of irrigation would decrease the matric and osmotic potentials simulated for the soils. When the irrigation water quality deteriorates to 200 mS/m, the same trigger shows a larger variability in the amount of irrigation water applied (590 mm to 670 mm). The simulated matric and osmotic potentials are also higher for the lower irrigation water quality scenario, resulting in lower crop yield and MAS. The results also indicated that, with changes in the irrigation strategy and resulting crop yield, the production income changes, although the production costs seem relatively constant. The changes in the calculated MAS for the soils are therefore more related to crop yield than to production cost changes. The same trends were observed for the Orange-Riet case study. The conclusion is that applying the same MAD percentage to the same soils with different irrigation water quality or to different soils may result in under irrigation or over irrigation.

The Vaalharts site-specific management strategy shows irrigation water amounts between 581 mm and 821 mm, with higher amounts being applied to areas with higher salinity levels. The areas of the pivot that receives a higher amount of irrigation water do leach some of the salt, but the osmotic potential is still relatively higher, and as a result, some crop losses occur. The use of the uniform irrigation strategy of the dominant soil (Soil3) shows reduced matric potential and osmotic potential, resulting in a lower crop yield than that for the site-specific strategy. The Soil1 and Soil2 uniform irrigation strategies show that, as the amount of irrigation water applied decreases, the matric and osmotic potentials decrease, resulting in even lower crop yields (12.7 ton/ha to 14.31 ton/ha). The conclusion is that the site-specific irrigation strategy is better able to manage matric and osmotic potentials, resulting in higher crop yields.

The comparison between the four irrigation strategies on the pivot shows that the site-specific management strategy results in large gains, when compared with the three uniform strategies (R153 903, R113 849 and R83 697). The results indicate that if a uniform strategy is developed, the information (in this case, soil information) on which the strategy is developed is critically important because using the incorrect information could result in either an under or over irrigation and a sub-economic management strategy.

The Orange-Riet case study results show much less variability in the irrigation amounts applied (585-724 mm), as compared with the Vaalharts case study. The Orange-Riet case study shows less drainage, even when the salinity levels of the segments are higher than those in Vaalharts. The irrigation strategy can keep the matric and osmotic potentials below -300 kPa. The strategy can maintain crop yields, even in segments where the salinity levels are higher. The uniform irrigation strategy developed based on Soil1, the dominant soil, shows higher matric and osmotic potentials and thereby lower crop yields than the site-specific strategy does. The Soil2 and Soil3 results indicated that, as more irrigation water is applied, the amounts of the matric and osmotic potentials are increased, thereby increasing the crop yields simulated for the case study. It is more important to ensure high production income to increase profitability, as the potential to reduce costs to improve profits is small. It can be concluded from the Orange-River results that the management of matric and osmotic stress on a crop requires that the decision-maker or researcher balance a highly complex system. However, balancing the complex system is not as easy as one would have hoped.

5.3 ECONOMIC MANAGEMENT OF WATER AND SALINITY

Developing economic guidelines for water and salinity management is difficult due to the interactive nature of economics with biophysical production decisions. However, economic theory provides us with some guidance on the economic management of water and salinity.

First, decision-makers have to maximise the MAS by maximising yield. Yields can be maximised or increased by increasing the factors of production, i.e. using more input to increase the amount of water applied during production. The first guideline is, therefore, that the producer should produce for maximum yield.

Decision-makers can also maximise the MAS by decreasing or minimising the production costs. However, given the current product prices and input prices, the return on increased input use is high. Therefore, the decision-maker should not decrease inputs to minimise production costs, but should rather apply inputs to maximise crop yield. A practical application of this is that the decision-maker should apply irrigation water during peak hours, when crop production would be negatively affected if the water is not applied.

Economic theory states that inputs are used efficiently, when the marginal factor cost (MFC) is equal to the value of the marginal product (MVP). The MFC is the cost of using one more unit of factor input, and the MVP is the increase in the value of the product produced due to a one-unit increase in a factor input. Typically, MVP is derived from a production function that captures the marginal physical product and the price of the product. In the absence of production functions, it is possible to use the prices of the input and the output ($\frac{P_{water}}{P_{maize}}$) to determine the increase in output necessary for a one-unit increase in input. Assuming that applying one additional millimetre of irrigation water costs R3.71/ha and that the maize price is R2 200/ton, it would then still be beneficial to apply 1 mm of irrigation water if the increase in crop yield is 1.68 kg/mm. The implication is that the decision-maker would always choose to irrigate for maximum yield.

The economic management of water and salinity requires that decision-makers manage a complex system. Therefore, the decision-maker must consider how complementary inputs such as fertilisers are used and the advantages of alternative cropping practices, such as increased crop yield attributable to ripping deeper into the soil. Management of the complex system requires having information, and the farmers are willing to pay for information that allows them to manage their production systems better.

Scarce resources should be protected. When water is the limiting input for the decision-maker, one of two strategies can be implemented. The decision-maker can reduce production by using smaller pivots (reducing hectares covered), or the decision-maker can produce on the same area and use technology to implement deficit irrigation techniques. When land is the limiting input, decision-makers should produce on the total available area and intensify production to ensure maximum yield. Alternatively, decision-makers can change to the production of high-value crops, assuming a market exists for those products.

The indirect measuring of water use also has a negative effect on the optimal use of water resources. Taking into account the facts that water is allocated to farmers based on the area in production, and that an increase in the area produced (even if the aggregate water consumption does not increase) would result in increased water tariffs being charged, the decision-maker has no incentive to use water optimally.

The decision to leach to manage salinity also requires that the decision-maker should make a trade-off between the cost of leaching and the gain in crop yield. Assuming that the MFC of leaching is lower than the MVP, it is beneficial for the decision-maker to leach. However, the decision-maker has to be sure that the soils are conducive to leaching. Alternatively, as the study results have shown, the decision-maker can reduce the need for leaching by ensuring that the soils remain wet.

5.4 RECOMMENDATIONS FOR FURTHER RESEARCH

- The site-specific variable rate irrigation strategy was developed on the assumption that complete information of the soil-water-crop status throughout the season would be available. The impact of incomplete information on the benefit of site-specific irrigation management should be quantified through using risk analysis.
- The benefit of the site-specific variable rate irrigation strategy strongly hinges on the baseline uniform irrigation strategy used. Research is necessary to represent actual farmer decision-making within soil-water-crop simulation models to better indicate the maximum benefits derivable from the site-specific variable rate irrigation strategy.
- The technical and financial feasibility of adopting the site-specific variable rate irrigation strategy should be further investigated.
- Information is key to the implementation of the site-specific variable rate irrigation strategy. More research is necessary to validate soil-water-crop simulation models under actual conditions faced by farmers.

- The research version of the bioeconomic model should be made operational and accessible to agricultural advisors.
- Parallel processing should be investigated to increase the solution time.
- Approaches to delineate management zones require further investigation, for example the use of multi-resolution image segmentation as a delineation approach.

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APPENDIX A: CODE: BIOECONOMIC SALINITY PROCEDURE

```
‘==========================================================================================
Public Sub Main()
‘==========================================================================================

numpop = 19
numday = 66
numsoil = 2
numstrat = 0
numcake = 0
numi = 1500
Dim BeginTime As Double
Dim YieldB(19) As Double
Dim PumpHourB(2, 19) As Double
Dim TarPumpHourB(2, 19) As Double
Dim TrialIrriB() As Double
Dim CumIB(19) As Double
ReDim Preserve Fitness(numpop, numstrat)
ReDim Preserve TrialIrriB(numday, numpop, numstrat)
Application.Calculation = xlManual
'=====================================================================
'GENERATE INITIAL POPULATION OF TRIAL SOLUTIONS AND DETERMINE FITNESS
'=====================================================================
'Call Initialise: Generate initial population of irrigation events
'---------------------------------------------------------------------------------
Initialise
'Call runSwampExcel: Simulate yields with SWAMP Excel and calculate output parameters
'------------------------------------------------------------------------------------------------------------------
runSwampExcel
'Write fitness to Excel for initial population
'---------------------------------------------------------
   For s = 0 To numstrat
      For y = 0 To numpop
         Sheet10.Cells(5 + y, 9 + s) = Mas(y, s)
      Next y
   Next s
'==================================
'TRACK THE FITNESS OF THE POPULATION
'==================================
'Assign fitness values and schedules to initial population
'--------------------------------------------------------------------------
For s = 0 To numstrat
    For y = 0 To numpop
          Fitness(y, s) = Mas(y, s)
        For d = 0 To numday
            TrialIrriB(d, y, s) = TrialIrri(d, y, s)
        Next d
    Next y
Next s
```

```
'==================
'EVOLVE POPULATION
'==================
' Set timer
BeginTime = Timer
'START MAIN LOOP
'===============
For i = 0 To numi
Calculate
   'Call Evolve: Evolve initial population of trial irrigation events
   '--------------------------------------------------------------------------------
   evolve
   'Call runSwampExcel: Simulate yields with SWAMP Excel and calculate new output
   '-----------------------------------------------------------------------------------------------------------
   runSwampExcel
'========================================
   'TRACK THE EVOLUTION OF THE POPULATION
'========================================
   'replace initial population with fit/better trials
   '-----------------------------------------------------------
  For s = 0 To numstrat
   For y = 0 To numpop
         If Mas(y, s) > Fitness(y, s) Then
            Fitness(y, s) = Mas(y, s)
            For d = 0 To numday
               Population(d, y, s) = MutantP(d, y, s)
               TrialIrriB(d, y, s) = TrialIrri(d, y, s)
            Next d
         End If
   Next y
  Next s
   'Write information to Excel for each iteration
   '----------------------------------------------------------
  Sheet10.Cells(1, 9) = Timer - BeginTime
  Sheet10.Cells(2, 9) = i + 1
  For s = 0 To numstrat
     For y = 0 To numpop
         Sheet10.Cells(5 + y, 9 + s) = Fitness(y, s)
     Next y
  Next s
'============================================
'WRITE FINAL POPULATION RESULTS TO Econ Results
'============================================
For s = 0 To numstrat
     For y = 0 To numpop
         Sheet11.Cells(4 + y, 2 + s) = Fitness(y, s)
         For d = 0 To numday
             Sheet11.Cells(4 + y + s * 20, 9 + d * 2) = TrialIrriB(d, y, s)
         Next d
     Next y
Next s
Calculate
'NEXT ITERATION
'==============
Next i
End
End Sub
```

```
'==========================================================================================
Public Sub Initialise()
'==========================================================================================
ReDim Preserve Population(numday, numpop, numstrat)
ReDim Preserve TrialIrri(numday, numpop, numstrat)
MutFactor = 0.25
CrossFactor = 0.5
AbsMinIrri = 0
MinIrri = 13.5
MaxIrri = 27
Prob_0 = 0.5
'delete previous values
'------------------------------
For d = 0 To numday
   For y = 0 To numpop
      For s = 0 To numstrat
          TrialIrri(d, y, s) = 0
      Next s
   Next y
Next d
'=================================================
'GENERATE INITIAL POPULATION OF IRRIGATION SCHEDULES
'=================================================
Randomize
For d = 0 To numday
  For y = 0 To numpop
    For s = 0 To numstrat
         Population(d, y, s) = Rnd()
         If Population(d, y, s) < Prob_0 Then
             TrialIrri(d, y, s) = 0
           ElseIf MinIrri + ((Population(d, y, s) - Prob_0) / (1 - Prob_0)) * (MaxIrri - MinIrri) < AbsMinIrri Then
             TrialIrri(d, y, s) = 0
         Else
             TrialIrri(d, y, s) = MinIrri + ((Population(d, y, s) - Prob_0) / (1 - Prob_0)) * (MaxIrri - MinIrri)
         End If
     Next s
   Next y
Next d
End Sub
```

```
'=========================================================================================
Sub runSwampExcel()
'=========================================================================================
Application.ScreenUpdating = False
Application.Calculation = xlManual
Dim rng As Range
ReDim Preserve soilha(numcake, numsoil)
ReDim Preserve MasCS(numcake, numsoil, numpop, numstrat)
ReDim Preserve YieldCS(numcake, numsoil, numpop, numstrat)
ReDim Preserve CumIrriCS(numcake, numsoil, numpop, numstrat)
ReDim Preserve TotalPumphourCS(numcake, numsoil, 2, numpop, numstrat)
ReDim Preserve Mas(numpop, numstrat)
'read pivot size ha
'-----------------------
PivotSize = Sheet8.Cells(6, 23)
'read cake slice size ha
'-----------------------------
For cake = 0 To numcake
        For soil = 0 To numsoil
                soilha(cake, soil) = Sheet2.Cells(4 + cake, 35 + soil)
        Next soil
Next cake
Set timer
'------------
BeginTime = Timer
'Delete previous values
'------------------------------
For y = 0 To numpop
   For s = 0 To numstrat
      Mas(y, s) = 0
      For cake = 0 To numcake
         For soil = 0 To numsoil
            MasCS(cake, soil, y, s) = 0
            YieldCS(cake, soil, y, s) = 0
            CumIrriCS(cake, soil, y, s) = 0
            For tar = 0 To 2
               TotalPumphourCS(cake, soil, tar, y, s) = 0
            Next tar
         Next soil
      Next cake
   Next s
Next y
'============================================================
'POPULATE SWAMP-ECON WITH PARAMETERS AND SIMULATE OUTCOME
'============================================================
For cake = 0 To numcake
        'populate model
        '---------------------
        Sheet4.Cells(13, 4) = Sheet2.Cells(4 + cake, 39).Value
        'populate soils
        For soil = 0 To numsoil
                 Set rng = Sheets("Soil" & soil + 1 & "-Parameters").Range("C2:S41")
                 Worksheets("Parameter").Range("C2").Resize(rng.Rows.Count,    rng.Columns.Count).Cells.Value    =
rng.Cells.Value
               For s = 0 To numstrat
                    For y = 0 To numpop
                         For d = 0 To numday
```

```
                    'read irrigation schedule
                    Sheet8.Cells(10 + d * 2, 2) = TrialIrri(d, y, s)
                Next d
                'Simulate results
                '----------------------
                 Calculate
                'read outputs
                '-----------------
                MasCS(cake, soil, y, s) = Sheet8.Cells(42, 29)
                YieldCS(cake, soil, y, s) = Sheet8.Cells(7, 33)
                CumIrriCS(cake, soil, y, s) = Sheet8.Cells(8, 33)
                For tar = 0 To 2
                     TotalPumphourCS(cake, soil, tar, y, s) = Sheet8.Cells(3 + tar, 29)
                Next tar
            Next y
        Next s
    Next soil
Next cake
'Calculate margin above specified cost
'--------------------------------------------------
For y = 0 To numpop
    For s = 0 To numstrat
        For cake = 0 To numcake
            For soil = 0 To numsoil
                Sheet16.Cells(5 + y, 3 + soil + cake * (numsoil + 1)) = MasCS(cake, soil, y, s) * soilha(cake, soil)
            Next soil
        Next cake
    Next s
Next y
Sheet16.Calculate
For y = 0 To numpop
    For s = 0 To numstrat
         Mas(y, s) = Sheet16.Cells(5 + y, 2)
    Next s
Next y
'Update time
'-----------------
Sheet8.Cells(1, 35) = Timer - BeginTime
'Update screen
'-------------------
Application.ScreenUpdating = True
End Sub
```

```
'=================================================================================
Sub evolve()
'=================================================================================
Dim random20() As Double
Dim SelectMut() As Double
Dim FinSelectMut() As Integer
ReDim Preserve random20(numpop)
ReDim Preserve SelectMut(5, numpop)
ReDim Preserve FinSelectMut(2, numpop)
Dim MutantA() As Double
Dim MutantB() As Double
Dim MutantC() As Double
ReDim Preserve MutantA(numday, numpop)
ReDim Preserve MutantB(numday, numpop)
ReDim Preserve MutantC(numday, numpop)
'delete previous values
'------------------------------
For d = 0 To numday
   For y = 0 To numpop

      TrialIrri(d, y, s) = 0
      MutantP(d, y, s) = 0
   Next y
Next d
'=====================================
'SELECT MUTANTS FROM INITIAL POPULATION
'=====================================
' generate random numbers
'------------------------------------
Randomize
For s = 0 To numstrat
   For y = 0 To numpop
        For yr = 0 To numpop
             random20(yr) = Rnd()
        Next yr
       For smr = 0 To 5
           aa = 0
           SelectMut(smr, y) = Application.WorksheetFunction.Small(random20, smr + 1)
          'randomly select 6 based on lowest values (use -1 with match because 0 - 19)
           aa = SelectMut(smr, y)
           SelectMut(smr, y) = Application.WorksheetFunction.Match(aa, random20, 0) - 1
       Next smr
      'randomly select 3 unique mutants without duplication in the population
      '-----------------------------------------------------------------------------------------------
      If SelectMut(0, y) = y Then
           FinSelectMut(0, y) = SelectMut(3, y)
           FinSelectMut(1, y) = SelectMut(4, y)
           FinSelectMut(2, y) = SelectMut(5, y)
      ElseIf SelectMut(1, y) = y Then
           FinSelectMut(0, y) = SelectMut(3, y)
           FinSelectMut(1, y) = SelectMut(4, y)
           FinSelectMut(2, j) = SelectMut(5, y)
      ElseIf SelectMut(2, y) = y Then
           FinSelectMut(0, y) = SelectMut(3, y)
           FinSelectMut(1, y) = SelectMut(4, y)
           FinSelectMut(2, y) = SelectMut(5, y)
      Else
```

```
            FinSelectMut(0, y) = SelectMut(0, y)
            FinSelectMut(1, y) = SelectMut(1, y)
            FinSelectMut(2, y) = SelectMut(2, y)
      End If
'========================================
'APPLY OPERATORS MUTATION AND CROSS OVER
'========================================
      For d = 0 To numday
            'assign values to selected mutants
            '-------------------------------------------
            MutantA(d, y) = Population(d, FinSelectMut(0, y), s)
            MutantB(d, y) = Population(d, FinSelectMut(1, y), s)
            MutantC(d, y) = Population(d, FinSelectMut(2, y), s)
            'Mutate
            '----------
            If Rnd() < Application.WorksheetFunction.NormInv(Rnd(), 0.5, 0.12) Then
                  MutantP(d, y, s) = MutantA(d, y) + MutFactor * (MutantB(d, y) - MutantC(d, y))
            Else
                  MutantP(d, y, s) = Population(d, y, s)
            End If
            'Clip mutant to comply with bounds
            '-----------------------------------------------
            If MutantP(d, y, s) < 0 Then
                  MutantP(d, y, s) = 0
            ElseIf MutantP(d, y, s) > 1 Then
                  MutantP(d, y, s) = 1
            Else
                   MutantP(d, y, s) = MutantP(d, y, s)
            End If
            'Crossover
'=====================================================
'GENERATE NEW TRIAL POPULATION OF IRRIGATION SCHEDULES
'=====================================================
            If MutantP(d, y, s) < Prob_0 Then
                  TrialIrri(d, y, s) = 0
            ElseIf MinIrri + ((MutantP(d, y, s) - Prob_0) / (1 - Prob_0)) * (MaxIrri - MinIrri) < AbsMinIrri Then
                  TrialIrri(d, y, s) = 0
            Else
                  TrialIrri(d, y, s) = MinIrri + ((MutantP(d, y, s) - Prob_0) / (1 - Prob_0)) * (MaxIrri - MinIrri)
            End If
      Next d
Next y

Next s
End Sub
```

APPENDIX B: KNOWLEDGE DISSEMINATION AND CAPACITY BUILDING REPORT

Published Papers:

Barnard, J.H., Matthews, N. and Du Preez, C.C. (2021). Formulating and assessing best water and salt management practices: lessons from non-saline and water-logged irrigated fields. *Agricultural Water Management*, 247: 106706.

Working Papers

Matthews, N Barnard, J.H. and Grove, B. (undated). Precision scheduling for water and salt management.

Matthews, N., Barnard, J.H. and Grove, B. (undated). The economic trade-offs between allocating water for crop production and leaching for salinity management.

Farmers' Day Presentation

Grové, B, Matthews N and Barnard JH. Precision scheduling for water and salt management. Gariep and Orange-Riet Farmers, 18-19 February 2021.

Conference and Symposium Presentations

Lunguza, ZP and Matthews, N. (2019). Economic trade-offs of allocating water for leaching where water tables are present. Paper presented at the 57th Annual Conference of the Agricultural Economics Association of South Africa, 8-10 October 2019, Bloemfontein, South Africa.

Matthews, N and Grové, B. (2018). Precision scheduling for water and salt management. Paper presented at the 8th South African National Commission on Irrigation and Drainage (SANCID) Symposium. White River, Mpumalanga, 14-15 November 2018.

Marcill Venter
Degree: PhD (Agricultural Economics)
Status on study: Continuation from 2020
Proposed date of completion: December 2021
Title: Development of the SWIP-S model to determine the economic value of information under decision making for irrigated agriculture

Abstract:
The main objective of this research is to include a salinity management model in the SWIP-E programming model which is an integrated non-linear programming model that unifies the interrelated linkages between the timing of irrigation events and the electricity tariffs to improve water, salt and energy management. Risk will be included in the model by optimising different states of nature, which includes mainly different weather circumstances.

The Soil Water Irrigation Planning and Energy Management (SWIP-E) programming model (Venter and Grové, 2016) will be further developed to address the main objective of the research. The model will include a risk model, a salinity management model, soil water budget calculations, and an energy accounting component to model the interaction between salt management, irrigation management and time-of-use electricity tariff structures while taking the risk under decision making into account. The Soil Water Irrigation Planning and Salinity Management (SWIP-S) model will firstly be applied to a scenario where perfect information about soils (water holding capacity, soil type, etc.) and irrigation system specifications (variable rate irrigation) are available. Secondly, the model will be applied to a scenario where perfect information about the above-mentioned factors is not available. The different scenarios will be compared to determine the economic value of information for decision-making in irrigated agriculture.

Penelope Languza
Degree: M.Sc. Agric
Status on study: Continuation from 2020
Proposed date of completion: December 2021
Title: The Economic evaluation of irrigation strategies that prevent excessive salinisation at the Vaalharts Irrigation Scheme

Abstract:

This research aims to evaluate the irrigation strategies that prevent excessive salinisation at the Vaalharts Irrigation Scheme (VIS). This is one of the five management practices that were introduced by soil scientists at the department of Crop, Soil and Climate sciences at the University of Free State. The irrigation management practices currently employed by irrigation farmers are investigated for fitness to supply the crop with the required water, for crop growth, and the ability to manage salt accumulation in the soils. The Soil Water Management Program (SWAMP) model is used to simulate the effect of alternative irrigation strategies on crop growth, while an economic model determines the financial implication of farmers' irrigation decisions. Furthermore, a meta-heuristics model is used to evaluate the near optimal irrigation management strategy that manages water and salt stress. Determining this optimal management strategy allows the irrigator to move towards precision management of water and salt stress.

Anje Erasmus
Degree: M.Sc. Agric
Status on study: Continuation from 2020
Anje started on the project while doing her undergraduate degree. She has been very helpful in obtaining data and running scenarios.

Name: Mzwandile Dayimane
Degree: B.Sc Agric (Hons)
Status of study: 2019
Zwai worked on the project while he was doing his honours in Agricultural Economics. At the end of 2019, Zwai was offered employment elsewhere.

During the course of the project, the Research Team attended the following courses.

2017	Attended the "Modelling and Optimising with GAMS (combined basic and advanced)" course, presented by GAMS Software GmbH in Weissenheim am Berg. (6-10 November 2017).
2019	Successfully completed a summer school course, "Risk Analysis and Management in Agriculture: Updates on Modelling and Application", presented by Wageningen School of Social Sciences, Wageningen University. (26-30 August 2019)

APPENDIX C: ARCHIVING OF DATA

The models and data will be archived within the Department of Agricultural Economics. The models and data will also automatically be backed up on the University backup system.

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