MODELLING THE ECONOMIC TRADE-OFFS OF IRRIGATION PIPELINE INVESTMENTS FOR IMPROVED ENERGY MANAGEMENT

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DECLARATION

I, Marcill Venter, hereby declare that this dissertation submitted for the degree of *Magister Scientiae Agriculturae* in the Faculty of Natural and Agricultural Sciences, Department of Agricultural Economics at the University of the Free State, is my own independent work, and has not previously been submitted by me to any other university. I furthermore cede copyright of the thesis in favour of the University of the Free State.

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Date

DEDICATION

This dissertation is dedicated to my parents and grandmother,
Johan and Adeleen Venter and Marthie Cilliers,
to whom I will always be grateful for this life opportunity and support.

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"Through hard work, perseverance and a faith in God, you can live your dreams."

Benjamin Carson

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ABSTRACT

The main objective of this research is to develop an integrated non-linear programming model that unifies the interrelated linkages between mainline pipe diameter choice and the timing of irrigation events in conjunction with electricity tariff choice to facilitate better evaluation of the economic trade-offs of irrigation pipe investments for improved energy management.

The Soil Water Irrigation Planning and Energy Management (SWIP-E) programming model was developed to address the main objective of the research. The model includes an irrigation mainline design component, soil water budget calculations and an energy accounting component to model the interaction between irrigation system design, irrigation management and time-of-use electricity tariff structures. The SWIP-E model was applied in Douglas to evaluate the impact of different electricity tariff structures and irrigation system designs on the optimal pipe diameter of an irrigation mainline, electricity costs and profitability.

The results showed that Ruraflex is more profitable than Landrate which is a direct result of higher electricity costs associated with Landrate. The large center pivot resulted in higher net present values than the smaller center pivot and the lower delivery capacities were more profitable than higher delivery capacities. More intense management is necessary for delivery capacities lower than 12 mm/day to minimise irrigation during peak timeslots. Variable electricity costs are highly dependent on the interaction between kilowatt requirement and irrigation hours. For the large center pivot the interaction is dominated by changes in kilowatt whereas the effect of irrigation hours in relation to kilowatts is more important for smaller pivots. Landrate with relatively higher electricity tariff charges resulted in a change in the optimal pipe diameter at lower delivery capacities compared to Ruraflex. Optimal pipe diameters will increase for a breakeven percentage of between 0.6% and 0.66% for Ruraflex and between 0.4% and 0.6% for Landrate which is much lower than the design norm of 1.5%.

The overall conclusion is that the SWIP-E model was successful in modelling the complex interrelated relationships between irrigation system design, management and electricity tariff choice that influence the trade-off between main pipeline investment decisions and the resulting operating costs. Electricity tariff choice has a significant impact on the results which suggest that economic principles are important and that it should be included in the design process. A shortcoming of the model is that the risk of lower irrigation system delivery capacities was not included in the model. The conclusion that lower delivery capacities are more profitable should therefore be interpreted with care. The low breakeven friction percentages optimised in this research suggest that the norm of 1.5% friction is too high and a lower norm should be considered.

Future research should focus on extending the model to include a combination of irrigation systems and the inclusion of risk to evaluate the risk associated with low irrigation delivery capacities in combination with load shedding.

Keywords: Non-linear programming, economic trade-off, electricity costs, irrigation system investment costs, water management, net present value

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CHAPTER 1
INTRODUCTION

1.1 Background and Motivation

The South African agricultural sector plays an important role in the South African economy and is a key contributor to rural development and employment creation. Two of the most important crops produced in South Africa are maize and wheat serving as a food source for humans and animals, an input provider to other sectors, a source of job creation, a contributor of value added to the national economy and an earner of foreign exchange (Vink and Kirsten, 2000). In 2012 South Africa produced an average of 1 870 000 tons and 5 090 000 tons of wheat and maize, respectively. The majority of wheat is planted in the Western Cape, Free State and Northern Cape while the majority of maize is planted in the Free State, Mpumalanga, North West and Northern Cape. The largest producer of irrigation wheat and maize is the Northern Cape, producing an average of 272 600 tons and 580 500 tons of wheat and maize, respectively. The production under irrigation constitutes 14.5% and 11.4% of total production of wheat and maize, respectively (GrainSA, 2012).

Ever increasing production costs are a serious threat to the sustainability of the wheat and maize industry. Over the past 15 years, production costs of wheat and maize under irrigation increased significantly. The major contributors towards the increase in production costs are fertilizer, seed and irrigation costs. Increases in irrigation costs are due to ever increasing electricity costs. The recent increases in electricity tariffs have created serious problems for irrigation farmers. According to Bazilian, Rogner, Howells, Arent, Gielen, Steduto, Mueller, Komor, Tol and Yumkella (2011), electricity tariffs increased by 31% from 2009 to 2010, and NERSA has allowed Eskom to increase their average annual electricity tariffs with 13% for the next few years (Eskom, 2013/14). Increasing electricity costs, which constitute a significant part of operating costs (Breytenbach, Meiring and Oosthuizen, 1996, and BFAP, 2010), will increasingly require from irrigators to balance the cost of applying irrigation water with the expected economic benefit from doing so. Thus, the old paradigm with the biological objective of applying irrigation water to sustain maximum production will be replaced with the new paradigm where water use is optimised to increase profitability (English, Solomon and Hoffman, 2002). Irrigations farmers will need to evaluate different options to manage energy and water use in the future.

Significant opportunities exist for irrigation farmers to reduce energy costs through irrigation system design, renewable energy resources and operating practices to improve profitability. Renewable energy resources (wind energy, hydroelectricity and solar panels) require a large amount of capital and are not always affordable to irrigation farmers with a cash flow constraint. The design of an irrigation system and the operating practices needs to be evaluated in order to reduce energy costs. Potential energy savings can be achieved by adopting new technologies (variable speed drives, high efficiency motors) while taking cognizance of the trade-off between investment and operating costs. Operating costs (electricity costs) include variable and fixed electricity costs. Fixed electricity costs are constant and can only be changed by the electricity supplier, Eskom. Irrigation farmers are left with the option to manage their variable electricity costs. The variable electricity cost is the product of irrigation hours, kilowatt (kW) requirement and electricity tariff. These three components constitute the areas that should be investigated to manage variable electricity costs. Irrigation hours are determined by irrigation management, systems capacity and the limits that are placed on irrigation hours during the week when using time-of-use electricity tariffs. Irrigation management will determine the timing of an irrigation event as well as how much water to apply. The electricity tariff is obtained from Eskom's available tariff structures and is beyond the control of the irrigator apart from the choice of a specific tariff structure. The kW requirement is closely linked to the irrigation system layout and design. The kilowatt requirement is a function of total pressure required by the system, flow rate and the efficiency of the pump and motor.

An important strategy to minimise variable electricity cost is to design irrigation systems that require the minimum amount of kilowatts to drive the water through the system (Lamaddalena and Khila, 2011 and Moreno, Medina, Ortega and Tarjuelo, 2012). A design factor that has an impact on the required amount of kilowatts is the choice of the diameter of the mainline through which water is pumped from the water source to the infield irrigation system. Pipes with larger diameters result in less friction loss which reduces the kilowatt requirement. However, an economic trade-off exists between reducing the kilowatt requirement by means of increasing the diameter of the pipes to lower operating costs and the increasing cost of buying pipes with larger diameters. General practice in the design of the mainline is to select the pipe diameter such that the friction loss represents less than 1.5% of the length of the pipe (Burger, Heyns, Hoffman, Kleynhans, Koegelenberg, Lategan, Mulder, Smal, Stimie, Uys, Van der Merwe, Van der Stoep and Viljoen, 2003). Important to note is that the norm may not select the optimal pipe diameter. In the past, irrigation systems were designed to minimize the investment costs because energy was cheap and irrigators did not mind the higher electricity costs. Recent increases in electricity costs have renewed the importance of energy cost in irrigation farming. As a result irrigation farmers are increasingly focusing on the economic trade-off between investment costs and operating costs when deciding on an irrigation system design.

The question, however, is not whether irrigators should adopt practises to improve energy and water management. Rather, the problem is how to evaluate the interrelated linkages between irrigation management, irrigation system design and choice of electricity tariffs simultaneously to improve energy and water management. Together these factors will determine the extent of water and energy savings in irrigated agriculture. A need exits for an integrated decision support model that includes optimal irrigation management (irrigation hours), irrigation system design aspects (kilowatt requirement) and time-of-use electricity tariffs.

1.2 Problem Statement and Objectives

Irrigators are currently unsure about the trade-off between irrigation system investment costs and the resulting energy costs as well as the optimal management requirements of irrigation system investments. The unavailability of an integrated model that is able to model the interaction between irrigation management, irrigation system design and the choice of electricity tariffs further hamper decision support for improved energy and water management in irrigated agriculture.

A large number of research studies have been done in South Africa to support energy management. Meiring (1989) built on the procedure developed by Oosthuizen (1985) to develop a method to calculate irrigation cost for a center pivot irrigation system (Spilkost). During the research irrigation system capacities and static head were identified as important factors that influence irrigation cost. Breytenbach (1994) adjusted the method of Meiring (1989) to calculate irrigation cost for a dragline-irrigation system. The procedure was used to evaluate the impact of two alternative electricity tariffs on irrigation costs for representative irrigation systems in the Winterton area. Oosthuizen, Botha, Grové and Meiring (2005) extended previous research through the development of a cost estimating procedure for a combination of irrigation systems.

None of the above research was concerned with the optimal design of the irrigation mainline and the adoption of new technologies (variable speed drives, high efficiency motors) to minimise energy costs. Radley (2000) developed an irrigation mainline optimisation procedure with the objective to select the optimal pipe diameter by minimising total investment and operating costs over the lifespan of the irrigation system. The linear programming model is highly efficient in choosing economic pipe diameters while assuming a flat rate electricity tariff and a seasonal amount of applied water. As a result the model is not applicable to time-of-use electricity tariffs where the timing of irrigation events within the season determines electricity costs. Determining the timing of irrigation events requires an evaluation of the soil water budget and the status of the crop.

Grové, Van Heerden and Venter (2012) did a study with the objective to determine whether it is possible to include the SAPWAT (Crosby and Crosby, 1999) soil water budgeting routine into a non-linear programming (NLP) framework to facilitate crop water use optimisation. Results showed that the SAPWAT optimisation model is able to optimise the distribution of irrigation events over the growing season while taking cognisance of a daily soil water budget and the effect on crop yield. However, the model is not concerned with energy accounting and the optimal design of an irrigation system.

The review of the South African literature shows that no integrated modelling framework exists to evaluate the interrelated linkages between irrigation system design, irrigation management and restrictions placed by time-of-use electricity tariffs.

The main objective of this research is to develop an integrated non-linear programming model that unifies the interrelated linkages between mainline pipe diameter choice and the timing of irrigation events in conjunction with electricity tariff choice to facilitate better evaluation of the economic trade-offs of irrigation pipe investments for improved energy management.

In order to achieve the main objective of the research the following specific programming objectives were identified to facilitate model development and integration:

- Development of pipeline investment model.

  The optimal pipeline investment model of Radley (2000) is used to determine optimal pipe diameters. The investment model is based on an Excel© linear programming model with a fixed system layout that could not be changed. The model was reformulated in GAMS (Brooke, Kendrick, Meeraus, Raman*,* 1998) to allow for different layouts and to facilitate model integration.

- Further development of the SAPWAT optimisation model (Grové *et al.,* 2012) to model timing of irrigation events for multiple crops in conjunction with electricity tariff choice.

  In order to achieve the above specific programming objectives the calculation of the soil water budget was expanded to model the soil water budget for a crop rotation system. An energy accounting routine was also developed and integrated with the water budget routine to facilitate modelling of time-of-use electricity tariffs and the restrictions thereof.

- Model component integration

  The pipeline investment model and the water budget optimisation model were integrated within the GAMS environment to create the Soil Water Irrigation Planning and Energy management (SWIP-E) model.

The SWIP-E model was applied to answer the following research questions:

- What is the economically optimal pipe diameter for Ruraflex and Landrate electricity tariffs while considering a small and large center pivot with high and low irrigation system delivery capacities under optimal irrigation management?

- What are total electricity costs (variable and fixed) for Ruraflex and Landrate electricity tariffs while considering a small and large center pivot with high and low irrigation system delivery capacities under optimal irrigation management?

- What is the most profitable irrigation system for Ruraflex and Landrate electricity tariffs while considering a small and large center pivot with high and low irrigation system delivery capacities under optimal irrigation management?

1.3 Research Area

The research was done in the Douglas, Northern Cape area. The area has some unique features that support the development and application of mathematical programming models to improve water and energy management and irrigation system designs. Crop rotation systems are prevalent in the area where maize and wheat are the most dominant cash crop rotation system. Douglas is located in the semi-arid part of the Northern Cape, where evaporation is higher than the natural precipitation. Annual evaporation in the Douglas district is more than 2 400mm and rainfall varies between 200mm and 500mm per year. Climate plays a direct role in the amount of rainfall and evapotranspiration. The climate in the area is mostly hot and dry. The area has hot summers with temperature above 30ºC and even temperatures in the low 40ºC’s. The high temperatures cause evapotranspiration to be higher than the average rainfall, which means that crop production is only possible under irrigation. In contrast to the hot summers, cold winters with daily average temperatures in the low 20ºC’s with cold nights below 0ºC are observed in the area. The temperatures for wheat production range from 40ºC to lower than 0ºC, with an average temperature of more or less 21ºC (Haarhoff, 2014). Furthermore, the two main types of soil in the district are Clovelly and Hutton soils (Haarhoff, 2014). The most common irrigation systems in the area are more or less 30ha center pivots with 12mm/day delivery capacities. Larger center pivot sizes do occur in the area but are in the minority compared to smaller center pivot sizes (Myburgh, 2014).

1.4 Outline of the study

The study is presented in the following format: Chapter 2 contains a literature review related to irrigation system design process, agricultural water use, electricity tariffs and previous energy management studies. The methodology of the integrated model and description of data are presented in Chapter 3. Chapter 4 includes all the results, discussions and conclusion of the application of the model developed in this research. The last chapter consists of a summary and recommendations of the research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter a literature review is done on the importance of energy and water management in irrigated agriculture. The design of an irrigation system is an important aspect for improved water and energy management. The first part of this chapter consists of a theoretical framework of the irrigation system design process, more specifically the irrigation main pipeline design and a literature review on the methods used in the designing process of an irrigation main pipeline. The second part focuses on methods used to optimise agricultural water use. The third part of this chapter includes a description of electricity tariffs used in irrigated agriculture and the last section includes previous research studies on energy management.

2.2 Irrigation System Design Process

The irrigation system design process is an integrated process and requires a balanced approach that results in both technically and financially acceptable designs for the irrigator. Various variables influence the irrigation system design process. According to Burger *et al.* (2003) a survey of all relevant factors related to the design of an irrigation system must be done. The factors include evaluation of the soil, the crop water requirement, climate, water source, the management aspects of the irrigator and the economics of the system (Burger *et al.,* 2003). Once the survey has been done the irrigation design process can follow. The irrigation design manual (Burger *et al.,* 2003) proposes that the irrigation system design process takes place in the following three phases: (1) the infield irrigation system design, (2) water supply system design (conveyance) and (3) pumping station design.

2.2.1 Infield Irrigation System Design

The aim of the infield irrigation system design is to design a system which meets the required system working pressure and system discharge. Next the variables affecting system discharge and working pressure will be discussed in more detail.

2.2.1.1 Flow Rate

The flow rate of the infield irrigation system is determined from a series of variables which include the net irrigation requirement, irrigated area, the soil's infiltration rate, available time to irrigate and system efficiency.

The amount of water required by the crop is the most basic input in the irrigation system design process (Grové, Venter, Van der Stoep and Van Heerden, 2013). The most widely recognised method of determining crop irrigation requirement in South Africa is the SAPWAT3 (Van Heerden, Crosby, Grové, Benadé, Schulze and Tewolde, 2009) program. The model is an enhanced and improved version of the SAPWAT (Crosby and Crosby, 1999) program. SAPWAT3 uses the basic methodology proposed in FAO-56 (Allen, Pereira, Raes and Smith, 1998) to calculate crop water requirements based on a reference evapotranspiration rate. Most commonly irrigation systems are designed to meet the peak irrigation requirement of the crop which can be calculated with SAPWAT3 (Van Heerden *et al.,* 2009).

Once the peak irrigation requirement is determined, the next step is to decide on the duration during which the peak requirement must be applied. The duration (hours) together with the area irrigated will determine the required system discharge (Q). The principle is that the longer it takes to apply the peak demand the smaller the system discharge will be and therefore the power requirement (Burger *et al.,* 2003). Eskom's time-of-use tariff structure needs to be taken into account when determining the available irrigation hours per week. According to Burger *et al.* (2003), irrigation hours for a center pivot design should be less than 144 hours/week. According to the irrigation design manual (Burger *et al.,* 2003), allowance in the capacity of the irrigation system must be made for unforeseen delays during peak demand as well as moving time of the infield irrigation system when working hours are determined.

The aim of the designer is always to strive for a system design with the maximum attainable efficiency. The uniformity with which an irrigation system applies water has an effect on the efficiency of the system (Ascough and Kiker, 2002,) and therefore the discharge. The designer should strive to achieve maximum uniformity when designing an irrigation system in order to ensure that the majority of the crop receives an adequate amount of water (Letey, Dinar, Woodring and Oster, 1990, Ascough and Kiker, 2002, Valin, Cameira, Teodoro and Pereira, 2012, Montero, Martinez, Valiente, Moreno and Tarjuelo, 2013). An infield irrigation system that performs well in a uniformity perspective will benefit energy management as the irrigator will be assured that the largest part of the field receives the optimum amount of water.

2.2.1.2 Irrigation System Working Pressure

System pressure is the output of the hydraulic infield design process and defines the total pressure required to deliver the discharge (Q) to the desired area. The system working pressure is the sum of the sprinkler (end) pressure, static height to the highest point of the field, friction through the infield irrigation system and the pressure regulators and the height of the inlet of the infield irrigation system. The sprinkler pressure is the pressure at which the sprinkler operates. The static height is determined from the difference in height between the inlet of the infield irrigation system and the highest point on the field. Pressure regulators are necessary to maintain a constant flow through all sprinklers where static height differences are present. The friction losses through the infield irrigation system are determined by the roughness of the pipe walls, pipe diameter, flow velocity, pipe length, discharge rate and direction changes in the pipeline (Burger *et al.,* 2003).

2.2.2 Mainline Design

The design of the water conveyance system (main pipeline) is the second step in the irrigation system design process. Different design methods are available for the design of the main pipeline. Some of the available pipe sizing models do not take the economic trade-off between investment and operating costs into account, while other models include an economic objective (minimising total costs or maximising net present value) to determine the optimal pipe diameter. Another distinction can be made based on whether the design process results in a theoretical (continuous) or practical (discontinuous) pipe diameter (Dercas and Valiantzas, 2012).

2.2.2.1 Economic Models

According to Dercas and Valiantzas (2012), a designer of an irrigation system should design the main and submain pipelines with the objective to minimise total costs (investment and operating costs). The reason is that an economic trade-off exists between reducing the power requirement by means of increasing the diameter of the pipes to lower operating costs and increasing costs of buying pipes with larger diameters. The optimum pipe diameter or most economical diameter can be determined through economic analysis of the economic trade-off between investment and operating costs for a range of possible pipe diameters that can be used. Figure 2.1 illustrates the economic trade-off between investment and operating costs for different pipe diameters. An inverse relationship between investment and operating costs exists. As investment costs increase, operating costs decrease, due to the fact that the power requirement decreases. The most economical pipe diameter will be the pipe diameter with the lowest total costs (Figure 2.1).

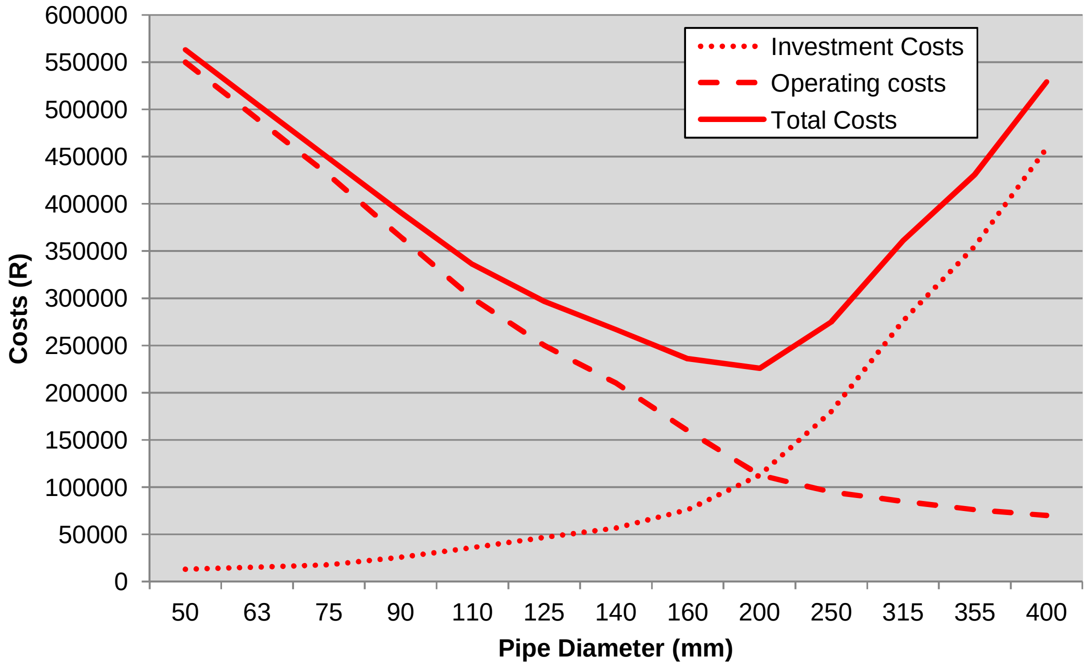

Figure 2.1: Economic trade-off between investment and operating costs for different pipe diameters

Modelling the economic trade-off is complicated by the fact of time value of money. Thus, economic profitability analysis is necessary to determine if the investment will result in long run profits. According to Boehlje and Eidman (1984), the four most common methods available to evaluated economic profitability are the payback period, the simple rate of return, net present value and the internal rate of return. Most researchers (Radley, 2000, Planells, Ortega and Tarjuelo, 2007, Pedras, Pereira, Concalves, 2009, Theocharis, Tzimopoulos, Sakellariou-Makrantonaki, Yannopoulos and Meletiou, 2010 and Dercas and Valianthas, 2012) include economic profitability of investments using the net present value method expressed as an annuity.

Various international researchers have developed and applied methods that include the economic trade-off between investment and operating costs for determining the optimal pipe diameter. Planells *et al.* (2007) developed a procedure which takes into account both the system layout and pipe sizing of a water network in order to obtain the lowest costs. The optimisation process is structured in three stages. In the first stage the cost of the pipes is determined using simultaneously both the network layout and pipe size for the worst operating point. Secondly, the energy and the annual pumping investment costs are evaluated. Lastly, the lowest total cost is determined. The researchers applied the model to a system layout in a main ring network. The results lead to the optimum branched irrigation network. After the optimum network layout was established, a linear programming optimisation method was used to determine the optimum pipe diameter.

Pedras *et al.* (2009) developed a decision support model to support the design of micro irrigation systems. The model is based on the integration of technical, economic and environmental objectives. The model is mainly developed to select the pipe diameters and emitters for an irrigation system. Pipe sizing in the model aims at finding pipe diameters that best achieve the user's performance targets relative to pressure variation within the operating system and the resulting target uniformity of water applications. The researchers argued that the model is not only able to solve typical pipe sizing problems but also to deal with maximizing economic results and minimizing environmental impacts due to more uniform designs.

Theocharis *et al.* (2010) did a comparative calculation of the pump head as well as the corresponding economic pipe diameters, using Laybe's optimisation method, linear programming and Theocharis simplified nonlinear programming method. All of the above methods include an objective function which includes the total cost of the network pipes that are optimised according to specific constraints relating to the length, friction loss and non-negativity constraints. The researchers applied all of the above methods to a given network layout in order to determine the optimal pipe diameters and therefore the optimal costs of the network. Results indicated that the three methods conclude to the same result and therefore can be applied with no distinction in the studying of hydraulic networks.

Dercas and Valiantzas (2012) used economic criteria to determine the optimal pipe diameter of a system layout with different nodes. The objective of the study was to choose a pipe diameter such that total costs (investment and operating costs) are minimised. The investment costs include the costs of the main pipeline as well as the costs of the pumping station. The operating costs are a function of the power requirement at the pumping station, energy costs and the annual operating time. The operating time was based on an assumed energy demand. The researchers did mention that time-of-use electricity tariffs should be included in the energy costs calculation, however, they argued that a weighted average electricity rate can be used. In order to calculate the weighted average electricity rate, an assumption of energy demand in the time-of-use timeslots are necessary to calculate electricity costs.

In South Africa, Radley (2000) developed a linear programming model that is able to model the economic trade-off between investment and operating cost. The first step in using the calculation procedure is to define the layout of the mainline in terms of length of the pipes, static heights and the flow rate in each of the pipe sections. Next an equation is developed to determine the hydraulic gradient at each of the irrigation system outlets given a certain combination of the pipe diameters. Linear programming is then used to determine the pipe diameters and the lengths that will produce the required head at the lowest total costs. Radley (2000) calculated friction loss over the length of the mainline for each pipe diameter that is considered in the optimisation through the use of the Darcy-Weisbach (Burger *et al.,* 2003) equation in combination with the Hazen-Williams (Burger *et al.,* 2003) equation. The linear programming model chooses the most economic pipe diameter in each phase considered in the model with the objective to minimise total cost for a given energy demand and flat energy rate.

All of the above mentioned studies assume the operating time of the irrigation system and uses a flat energy rate to calculate operating costs. Thus, the procedures reviewed are not conducive to a holistic approach which integrates irrigation system design with irrigation management under different electricity tariff structures.

2.2.2.2 Non - Economic Models

The available methods that do not include the economic trade-offs are constant hydraulic slope, maximum velocity, recommended velocity (Gonzalez-Cebollanda and Macarulla, 2012), Mougnie velocity (Perez, Vidal and Izquirerdo, 1993), and maximum friction (Burger *et al.,* 2003). The constant hydraulic slope method chooses a commercial pipe diameter that produces the appropriate head loss for each phase while keeping the hydraulic slope constant. The maximum and recommended velocity consists of setting a maximum and recommended velocity for water circulation (Gonzalez-Cebollanda and Macarulla, 2012). The Mougnie method uses the Mougnie formula (Perez *et al.,* 1993) to establish a relationship between the maximum velocity of water circulation in the pipeline and the diameter of the pipes. The established relationship determines the maximum flow that each commercial pipe is capable of transporting so that each phase of the water distribution network can be assigned with the cheapest pipe of transporting its design flow. With the maximum friction method a pipe diameter is selected such that the friction loss represents less than 1.5% of the length of the pipeline (Burger *et al.,* 2003). All of the above methods with exception of the maximum friction method are continuous methods since they obtain theoretical pipe diameters that must be modified to adjust them to available diameters (Gonzalez-Cebollanda and Macarulla, 2012 and Dercas and Valiantzas, 2012).

2.2.2.3 Integrated Pipe Optimisation Approach

The following section describes an integrated approach which includes crop irrigation scheduling models and electricity accounting models to model the economic trade-off between investment and operating costs to determine the optimal pipe diameter of an irrigation main pipeline. The section includes the work done by Allen and Brockway (1984) and Otterman (1988).

Allen and Brockway (1984) developed a linear programming (LP) framework for irrigation system design and costs estimating procedures for the design and planning of irrigation systems. The LP framework includes five different models, namely the ETSM, APSYS, NWRKLN, CANAL and

PUMP model. The ETSM model simulates crop water use. The simulation model uses historical evapotranspiration and precipitation recordings for a specific area as well as inputs such as soil properties and crop characteristics. The crop growth simulation results are used to estimate multiple linear regression equations which relate average expected half-monthly evapotranspiration rates, ending soil moisture levels, antecedent soil moisture and effective application rates to half-monthly periods of water use throughout the growing season. The APSYS program models sprinkler irrigation designs and management. The APSYS program models the hydraulics, economics and irrigation system management for different irrigation systems. The program sizes all laterals and main pipelines using life-cycle cost analyses where equivalent annual marginal costs for energy are balanced against annual marginal capital costs for the pipe. The program includes the costs of valves and water measurement meters. Output from the model is used to develop linear cost functions for alternative irrigation system application rates. The NWRKLN program applies life-cycle cost analysis in which incremental costs for pumping systems and energy are set equal to incremental costs for pipe investments. Inputs consist of economic parameters, energy, pump and pipe costs. Linear regression of pipe costs against effective application rates are repeated for several flow rates. The CANAL program sizes lined and earthen canals and estimates construction and maintenance costs for various flow rates. The costs are linearly regressed against effective application rates to be included in the linear programming optimisation. The PUMP program is concerned with the sizing of individual pumps and evaluates alternative pump combinations or booster pumps. All the linear regression equations that were developed with each of the models are included in a linear programming model to determine the overall optimal irrigation system design and layout.

Otterman (1988) adjusted the method of Allen and Brockway (1984) for South African conditions. Due to limited time, Otterman (1988) only adjusted two of the models that were used in the LP framework, namely the ETSM and APSYS programs. Otterman (1988) applied the reduced LP framework to an irrigation farm and found that the framework is a useful tool to help with the planning of irrigation systems. Recently Jumman (2009) developed a framework to assess irrigation design and operating strategies. The researcher used alternative irrigation system design to calculate capital and operating expenses. A water scheduling strategy was linked to the model, however, the assumption was made that the water scheduling strategy has no effect on the capital costs of an irrigation system. Thus, although an integrated approach was followed to determine capital and operating costs of an irrigation system, the model is not unified.

All of the above researchers concluded that a crop irrigation scheduling model which determines the operating time of the system needs to be included in the irrigation system design process. Therefore, an integrated approach is needed to enhance irrigation system design and operation to improve energy and water management in irrigated agriculture (Allen and Brockway, 1984, Otterman, 1988, and Jumman, 2009).

2.2.3 Pumping Station Design

The objective in a pumping system is to transfer water from a source to the infield irrigation system. A pressure and flow rate is required at the inlet of the infield irrigation system. The operating point or duty point of a pumping station is determined by the head and flow rate requirement of an irrigation system. The operating point will always be where the pump and system curve intersect. Each pump is characterized by the relationship between the flow rate (Q) it produces and the pressure (H) at which the flow is delivered. A pump is selected based on how well the pump and efficiency curve match the most extreme operating point in an irrigation system design (Burger *et al*., 2003). The design of the pumping station is the last step in the designing process and is treated independent of the infield design and the main pipeline design by designers. Exceptions include the work done by Moreno, Medina, Ortega and Tarjuelo (2012) who included a theoretical pump curve to represent the pump for a groundwater pumping system.

2.2.4 Discussion and Conclusion

The design of an irrigation system is an integrated approach and all relevant factors that influence the design process need to be considered. An important step in the design process is the design of the main pipeline. The mainline design is important because it is the origin of the trade-off between higher investment costs and lower operating costs and vice versa. Various methods are available to design the main pipeline but not all the methods include the economic trade-off between investment and operating costs of an irrigation mainline. The South African norm whereby the design of the mainline is done such that the friction loss represents less than 1.5% of the length of the main pipeline should be challenged since it is not based on economic principles. Economic trade-off methods such as Laybe's method, Lagrange multipliers, linear programming, dynamic programming, non-linear programming and recursive programming have been developed and applied by numerous researchers (Laybe, 1981, Radley, 2000, Theocharis *et al.,* 2010, Planells *et al.,* 2007, Pedras *et al.,* 2009, Gonzalez-Cebollanda and Macarulla, 2012 and Dercas and Valianthas 2012). Although good results were obtained from the methods the following critical assumptions were made:

1. The irrigation system network layout must be known.
2. A flat energy rate is used to calculate energy costs of an irrigation system.
3. The annual operating time of an irrigation system is assumed.

Under a flat rate electricity tariff structure the timing of irrigation events is unimportant because the irrigator is unable to manage electricity cost through adjustments to the timing of irrigation events. Timing of irrigation events is of the utmost importance when considering time-of-use electricity tariffs because the irrigator is able to manage electricity costs by changing the timing of irrigation events. The conclusion is that a daily crop irrigation scheduling model is needed in order to determine the daily timing of irrigation applications in order to link it with time-of-use electricity tariffs. The economic trade-off between pipeline investment cost and operating costs requires an integrated approach because optimal pipe diameters are chosen while considering time-of-use operating costs.

2.3 Agricultural Water Use Optimisation

Various researchers (Hancke and Groenewald, 1972, Symington and Viljoen 1997 and Van Rooyen, 1979) modelled crop water use using crop water production functions which relate a seasonal water application to crop yield. Thus, the assumption is made that the allocated water is optimally distributed over the growing season without any consideration of the interaction between different irrigation water applications in different time periods. Bernardo (1985) argued that if such assumptions are made technically efficiency is met. As a result intra-seasonal water supply constraints and water allocation between multiple crops as well as the economic theory of water use are ignored. Economic theory suggests that water allocation does not need to be technically efficient when water allocation between multiple crops is of concern and intra-seasonal water supply is constraining (Bernardo, 1985).

Only methods that are able to model the interdependency of water applications in different time periods are reviewed in this section, since the timing of water applications has a significant impact on electricity costs when using time-of-use electricity tariffs. The last section is devoted to a review of methods to model irrigation efficiencies using uniformity of irrigation applications.

2.3.1 Interdependent Time Period Optimisation

Irrigation water management is a dynamic process over the growing season involving a choice when to irrigate as well as how much water to apply. As a result irrigation timing has a significant impact on evapotranspiration and crop yields even for a given total volume of applied water (Muralidharan and Knapp, 2009). Grové *et al.* (2012) argued that a daily soil water budget routine needs to be taken into account when irrigation scheduling is optimised because the amount of irrigation applied in one time period has an effect on the availability of water that the crop can extract in the next time period due to the fact that water can be stored in the soil. Thus, if the availability of water in the next time period is less than the crop requirement, no yield reduction will occur due to water stored in the soil. Various researchers modelled irrigation timing through dynamic programming (Shangguan, Shao, Horton, Lei, Qin and Ma, 2002, and Prasad, Umamahesh and Viswanath, 2006), linear programming approximations (Grové and Oosthuizen, 2010, Bernardo, Whittlesey, Saxton and Basset, 1987, and Scheierling, Young and Cardon, 2004), explicitly incorporating soil water budget calculations into mathematical programming models (Grové *et al*., 2012, Ghahraman and Sepaskhah, 2004, Kanooni and Monem, 2014, Garcia-Vila and Fereres, 2012 and Muralidharan and Knapp, 2009) and simulation optimisation

(Botes, Bosch and Oosthuizen, 1996, Oosthuizen, Botes, Bosch and Breytenbach, 1996, Brown, Cochrane and Krom, 2010, Darshana, Pandey, Ostrowski, and Pandey, 2012 and Haile, Grové, Barnard and Van Rensburg, 2014). Next these approaches are reviewed in more detail.

2.3.1.1 Dynamic Programming

Dynamic programming (DP) is a method for solving complex problems by means of backward recursion (Sengupta and Fox, 1975). Application of dynamic programming requires specification of stage and state variables. For an irrigation water allocation problem the stages will correspond to the time interval at which irrigation decisions are made. State variables are required to keep track of the soil water status and area irrigated. Increasing the number of stage and state variables will increase the dimensionality of the model. In order to overcome the “curse of dimensionality” researchers have simplified their problems through the adoption of a multi-tier approach (Shangguan *et al.,* 2002, Prasad *et al.,* 2006).

Typically, a multi-tier approach consists of using DP to develop seasonal crop water production functions that are technically efficient. In the next tier the production functions are used to optimise water use between multiple crops. With such a multi-tier approach irrigation water is not optimally distributed between multiple crops since the water allocation of a single crop is determined independently of other crops and intra-seasonal water constraints. Thus, the assumption of technically efficiency is met for a single crop. However, Bernardo (1985) argued that when water allocation between multiple crops is of concern and intra-seasonal water supply is constraining, economic theory suggests that water allocation does not need to be technically efficient.

2.3.1.2 Linear Programming Approximations

Bernardo *et al.* (1987) developed a two-stage simulation and optimisation model to approximate the dynamics of water use optimisation between multiple crops with linear programming as an alternative to DP. In the first stage, crop growth simulation was used to estimate yield response to alternative ways of distributing water over the growing season. A crop simulation model is used to relate meteorological, crop and soil moisture relationships on a daily basis throughout the growing season to crop yield. In the second stage, the generated irrigation activities were included in a linear programming model to optimise irrigation management under limited water supply conditions. The procedure requires approximately 1 200 discrete irrigation activities to ensure that the approximation of the dynamics is close to the global optimal solution given a continuous formulation of the problem. Internationally, Scheierling *et al.* (2004) provide support for the procedure by applying it to determine price responsiveness of demands for irrigation water deliveries and consumptive use. Locally, the procedure is applied by Grové (2006), Grové (2008) and Grové and Oosthuizen (2010). In all instances the local researchers used the SAPWAT model to determine the timing of irrigation applications. Crop yields were estimated using relative evapotranspiration deficits in combination with crop yield reduction coefficients (Ky-factors).

2.3.1.3 Soil Water Budget Mathematical Programming Models

An alternative method to determine economically efficient solutions is to include explicit water budget calculations into a mathematical programming model. Such an approach was followed by Ghahraman and Sepaskhah (2004) who developed a non-linear programming (NLP) optimisation model with an integrated soil water balance routine to determine optimal irrigation scheduling of single and multiple cropping patterns. The soil water budget calculations are essential to determine the timing of irrigation applications. Results from the analyses showed that the model was unable to model the soil water balance correctly due to incorrect deep percolation calculations. Such a result is expected because the model formulation is based on a single mass balance equation without any constraints that govern the magnitude of deep percolation. Despite the shortcomings of the model formulation, Kanooni and Monem (2014) adopted the same formulation to optimise water management for a canal command system.

Grové *et al.* (2012) conducted research to determine the feasibility of including explicit water budget calculations into a mathematical programming model. The water budget calculations use the simple cascading water budget included in SAPWAT (Crosby and Crosby, 1999) to model crop water use based on the basic methodology proposed in FAO-56 (Allen *et al.,* 1998). Internationally, Muralidharan and Knapp (2009) applied a similar procedure to model deep percolation in the soil water budget by including constraints sets to model deep percolation in a non-linear programming model. Both models were formulated in GAMS (Brooke *et al.,* 1998) solved using CONOPT (Drud, 1998).

2.3.1.4 Simulation Optimisation

Botes *et al.* (1996) developed a simulation optimisation model to optimise irrigation scheduling to determine the value of irrigation information strategies. A crop growth simulation model was linked to an economic model to optimise irrigation scheduling for maize under uncertain weather conditions using the Nelder-Mead simplex algorithm (Nelder and Mead, 1965). The crop growth simulation model starts by initializing soil, crop and weather variables. These variables are then linked to an irrigation scheduling routine where an irrigation information strategy is selected first and then the trigger level for the specific plant growth stage is selected. The soil water level is calculated and compared to the selected trigger level. An irrigation amount of 10mm is applied if the calculated soil water is less than the selected trigger level. Irrigation takes place over two days due to the irrigation application capacity constraints of the center pivot. Irrigation water is applied until all the available water has been used; after that the application amount is set to zero. The economic sub-model contains the simulated yield and the amount of irrigation water applied.

Random output prices for the maize enterprises are selected. The gross income, variable cost and gross margin resulting from the specific yield and irrigation amount are then calculated. Oosthuizen *et al*. (1996) adjusted the model develop by Botes *et al*. (1996) to evaluate the impact of energy load management in the Winterton area while considering risk, different application capacities and soil types. The results indicated that adoption of irrigation scheduling can increase the economic efficiency of irrigation farmers under load management.

More recently, genetic algorithms (GA) are increasingly used to search for the optimal irrigation scheduling strategy. GA refers to a near optimal global optimisation technique which is based on a population based approach to optimisation (Schütze and Schmitz, 2010, Rana, Khan and Rahami, 2008, Spall, 2003). The main reasons for using GA is their ability to deal with non-linear complex optimisation problems and their broad applicability and flexibility (Schütze, De Paly and Shamir, 2012; Van Dijk, Van Vuuren and Van Zyl, 2008, Rana, Iet al., 2008).

Darshana *et al.* (2012) assembled simulation and optimisation models for optimal planning of cropping patterns through the maximisation of net benefits and minimisation of irrigation water requirements. The researchers used the CROPWAT simulation model to estimate crop water requirements, timing and depth of water applications. Since the objective function is multi-objective, the researchers used evolutionary algorithms (GANetXL) to maximise the net benefit function and to minimise irrigation applications. The evolutionary algorithm is a genetic add-on for Microsoft Excel© supporting single and multi-objective optimisations. Application of the GANetXL requires some form of computer programming when the simulation model is not constructed in Excel©.

Haile *et al.* (2014) developed a model which optimises irrigated water taking into consideration water stress, salt stress and the possibility of water uptake from shallow water table with the objective to find the best irrigation strategy to manage water and salt balances. The researchers used the SWAMP model to optimise irrigation applications. The model simulates daily changes in water content of a multi-layer soil. Simulation and genetic algorithms were used to optimise the irrigation strategy of a field.

2.3.2 Discussion and Conclusion

Various methods are available to optimise the interdependency between irrigation applications in different time periods. Dynamic programming is preferred by various researchers (Shangguan *et al.,* 2002, Prasad *et al.,* 2006, Bernardo *et al.,* 1987, Grové, 2006, Grové, 2008 and Grové and Oosthuizen, 2010) to optimise water use. However, simplifying assumption is necessary to keep the model tractable because adding too much detail will quickly result in a too large model. The conclusion is that the amount of stages and stage variables will determine the suitability of using DP in agricultural water use optimisation since increasing the amount of stages and state variables will quickly result in a too large model. Furthermore, simplifying assumptions should be carefully considered to ensure that economic optimality is achieved. Linear programming approximations are an alternative method to DP to optimise water use. However, the accuracy with which the dynamic optimisation problem is approximated with multiple linear programming activities is highly dependent on the number of activities. The number of irrigation decision time intervals has a significant bearing on the dimensionality of the model since the number of irrigation activities necessary to approximate the problem will increase with an increase in the time intervals. The conclusion is that linear programming approximations are able to model intra seasonal water supply constraints and water allocation between multiple crops; however, the results stay an approximation of the optimal solution. An alternative method to determine optimal irrigation scheduling is to include water budget calculations into mathematical programming models. Grové *et al.* (2012) and Muralidharan and Knapp (2009) demonstrate the ability of modern solvers to optimise agricultural water use between multiple crops given appropriately specified soil water budget model formulations. Simulation optimisation is an alternative method to DP and linear programming approximation to optimise water use. The reviewed studies show that it is possible to optimise detailed irrigation scheduling models through externality linked algorithms. However, only near optimal solutions are possible since these algorithms are not based on optimality conditions.

2.3.3 Modelling Non–Uniformity of Irrigation Applications

According to Ascough and Kiker (2002), efficient and equitable use of water is of utmost importance due to the limited amount of water resources. The uniformity with which water is applied has an effect on the efficiency of water use. Two methods exist to model the uniformity of applied water.

The first approach simulates spatial variability in soil depths, water holding capacities, infiltration rates and distribution of applied water by dividing the irrigated fields into sectors with randomly assigned values using Monte Carlo simulation (Hamilton, Green and Holland, 1999, Lopez, Tarjuelo, De Juan, Ballesteros and Dominguez, 2010). Hamilton *et al.* (1999) integrated the CropSyst (Cropping Systems Simulation Model) and IEM (Irrigation Efficiency Model) to produce crop water production functions to simulate changes in cropping patterns and irrigation practices. CropSyst is a multiyear, multi-crop, daily time-step growth simulation model that examines effects of crop-systems management on crop productivity and the environment. The model has an irrigation management component, but it does not differentiate between irrigation technologies and assumes constant irrigation uniformity. The researchers integrated the model with an irrigation efficiency model (IEM) which models non-uniform water applications to simulate inefficiencies. The IEM model simulates changes in crop yield resulting from non-uniform water applications by dividing the field into different sectors with each receiving a different amount of water. The integration of the two models enables the researchers to model inefficiencies associated with applying irrigation water. A similar approach was used by Lopez *et al.* (2010) to simulate the effect of non-uniform water applications on crop yield and the repercussion on gross margin.

The second approach assumes a statistical distribution to simulate non-uniform water distribution for irrigation systems based on the Christiansen's Uniformity coefficient (CU) (Reca, Roldan, Alciade, Lopez, Camacho, 2001, Ortega, De Juan and Tarjuelo, 2005, Sepaskhah and Ghahraman, 2004). The approach calculates the average area that is respectively under-irrigated and over-irrigated while quantifying the production functions.

Locally, Lecler (2004) demonstrated how the statistical uniformity could be modelled with detailed water budget calculations through the use of multiple water budgets. The researcher evaluated water use efficiency of alternative irrigation schedules and irrigation technologies by simulating several water budgets with ZIMshed (Zimbabwe Irrigation Scheduling Model) to incorporate non-uniformity of water application on sugar yield. Grové (2006), Grové (2008) and Grové and Oosthuizen (2010) used the same procedure as Lecler (2004) to model the impact of water applications on crop yield while taking inefficiencies resulting from non-uniform water application into account.

The conclusion is that the non-uniformity with which irrigation systems apply water provides a powerful way of modelling the non-linear relationship between applied water and crop yield through the inclusion of multiple water budgets. Failure to model the non-uniformity of water applications will result in over-estimation of the crop yield resulting from irrigation applications.

2.4 Electricity Tariffs

In the past energy accounting was not an important factor for irrigation farmers due to the fact that electricity was relative cheap and affordable. However, this has changed dramatically over the last few years. Electricity prices increased significantly and South Africa's electricity supplier, Eskom has the intention to further increase the price of electricity. The increases in electricity tariffs have a significant impact on the profitability of irrigation farmers due to the fact that farmers depend on electricity to pump water for irrigation. Eskom has designed a number of tariff options for irrigation farmers. The tariff options that are used by irrigation farmers are Ruraflex, Landrate and Nightsave. Next these tariff structures are discussed in more detail.

2.4.1 Ruraflex

Ruralfex was designed to create the incentive to use electricity during low demand season 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 from time to time and which accept supply from 400 volt (V) to 22 kilovolt (kV).

Ruraflex's fixed costs consist of a network access charge, service charge, administration charge and reactive energy charge. The network access charge (R/KVA/month) combines the transmission and distribution network access charge based on the voltage of the supply, the transmission zone and the annual utilised capacity measured at the point of delivery (POD) applicable during all time periods. The service charge (R/account/day) is based on the voltage of the supply applicable during all time periods. The administration charge (R/POD/day) is based on the monthly utilised capacity of each POD linked to an account. The reactive energy charge (c/KVArh) supplied in excess of 30% of the kilowatt-hour (kWh) recorded during the entire billing period is applicable. The excess reactive energy is determined using the billing period totals and will only be applicable during the high-demand season (Eskom, 2014/15).

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 demand for electricity is the lowest and comprises 82 hours/week. Peak time on the other hand covers the time of the day when electricity demand is the highest and comprises 25 hours/week. Figure 2.2 illustrate the different time-of-use periods for the Ruraflex tariff structure. From Figure 2.2 it is observed that time-of-use hours differ between weekdays and weekends and are not consecutive during weekdays.

Variable costs consist of active energy charge, reliability energy charge and network demand charge. Active energy charges (c/kWh) differ between seasons and time-of-use periods and it is based on the voltage of supply and the transmission zone. The reliability energy charge (c/kWh) is based on the voltage of supply applicable during all time periods. The network demand charge (c/kWh) is based on the voltage of the supply and the energy measured at the POD during all the time-of-use periods.

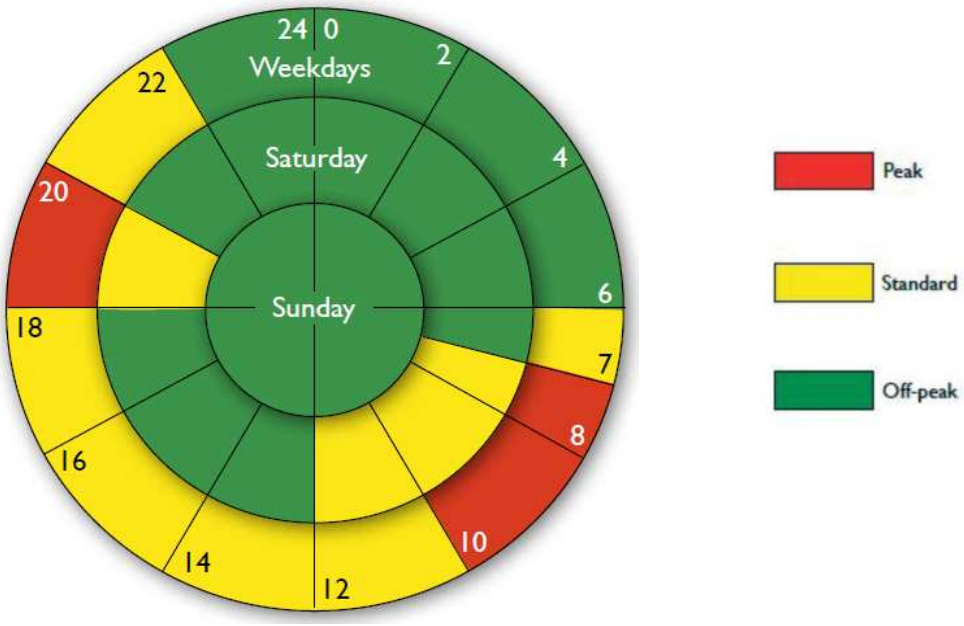

Figure 2.2: Ruraflex's time-of-use periods

Source: Eskom (2014/15)

Different rates apply for the distances from Johannesburg to the farm. The four different categories of distances from Johannesburg are (1) 0 to 300km; (2) 301 to 600km; (3) 601 to 900km; (4) further than 900km (Eskom, 2014/15).

2.4.2 Landrate

Landrate is available for rural customers with single, dual or three-phase conventionally metered supplies with a notified maximum demand (NMD) up to 100 kilovolt-ampere (kVA) with a supply voltage of less than 500V. Landrate is a flat rate, dependent on the size of supply. The size of supply determines the Landrate (Landrate 1,2,3,4 and Dx) option that farmers will use.

Landrate's fixed costs include a network access charge, service charge and administration charge. The network access charge (R/day) is based on the NMD of the supply. The service charge (R/day) for each POD is based on the applicable daily rate and the number of days in the month. Variable costs include an active energy charge, a network demand charge and a reliability service charge. The active energy charge (c/kWh) is a single charge measured at the POD. The network demand charge (c/kWh) and the reliability service charge (c/kWh) are based on the active energy measured at the POD. The Landrate Dx option is a non-metered supply with a fixed charge based on the Landrate 4 option, typically suited to small telecommunication installations where the electricity usage is low enough not to warrant metering for billing purposes (Eskom, 2014/15).

2.4.3 Nightsave

Nightsave is an electricity tariff for high load factor rural customers, with an NMD from 25kVA at a supply voltage of less than 22kV (or 33kV where designated by Eskom as Rural). Nightsave is divided into fixed and variable costs. The variable costs consist of an active energy charge, a distribution network demand charge and a reliability service charge. The active energy charge (c/kWh) is a seasonally differentiated charge, based on the voltage of the supply and the transmission zone. The distribution network demand charge (c/kWh) is based on the voltage of the supply and the energy measured at the POD. The reliability service charge is based on the voltage of the supply applicable during all time periods. The fixed costs consist of an energy demand charge, service charge, administration charge and a network access charge. The energy demand charge (R/kVA) is a seasonally differentiated charge based on the voltage of the supply, the transmission zone and is charged on the chargeable demand in peak periods. The service charge (R/account/day) and the administration charge (R/POD/day) are based on the monthly utilised capacity of each POD linked to an account (Eskom, 2014/15).

2.5 Previous Energy Management Studies

The following section consists of a review of previous energy management studies. The section is divided into electricity cost estimation procedures (IRRICOST, IRRI-ECON) and electricity management of irrigation farmers.

2.5.1 Electricity Cost Estimation Models

An important step in analysing the economics of irrigation is to estimate the costs of an irrigation system. It is very important for irrigators to have irrigation cost estimates under various operating conditions to evaluate efficient and profitable water-use techniques. Capital and operating costs are the main factors that need to be considered in irrigation system design. Operating costs are important during the replacement or upgrading of a new or existing irrigation system.

Numerous electricity cost estimation procedures are available to calculate electricity costs for irrigation systems. However, this review concentrates on two selected electricity costs estimation procedures (IRRICOST and IRRI-ECON) that can be found in the South African literature.

2.5.1.1 IRRICOST (Irrigation Cost) Model

The IRRICOST program was developed from SPILKOST 2.0 (Meiring, 1989) and it was used for the management of irrigation costs for several irrigation systems in combination (Meiring, Oosthuizen, Botha and Crous, 2002). The primary objective of the development of the IRRICOST program was to establish a computerised cost-accounting program for the satisfactory calculations of the cost of different types of irrigation systems. The secondary aim was to facilitate and enhance the execution of economic analyses regarding irrigation.

Only irrigation costs are estimated and typically the output of the model is used in other economic models to evaluate the profitability of irrigation farming systems. In order to allocate the costs appropriately the model makes a distinction between the costs associated with the mainline that distributes water to the different irrigation systems and the irrigation system itself. The fixed costs associated with the mainline are allocated to each irrigation system based on the area of the system. The variable costs associated with pumping water are allocated to each irrigation system based on the proportional share of the kilowatts required to pump the water to each system when operated individually. The total amount of water pumped is assumed. A node network system is used to present the layout of the system and to facilitate the inputs of the pipe characteristics of each phase. Knowing the precise layout of the irrigation system design allows for the calculation of the pressure at each node which is beneficial to check whether the sufficient pressure is available.

2.5.1.2 IRRIECON (Irrigation Economics) Model

Due to increasing pressure to manage water use for improved irrigation efficiency in the sugarcane industry, researchers from SASRI worked with sugarcane growers to develop the IRRIECON model (Armitage, Lecler, Jumman and Dowe, 2008). IRRIECON was developed to determine detailed capital, operating and marginal costs of various irrigation scenarios. The model is a detailed economic analysis tool to assess farm specific scenarios related to irrigation, such as system design specifications, repairing or upgrading irrigation systems, comparing Eskom tariff structure options, and/or changing farm and water management approaches relating to irrigation.

A critical assumption that is made while estimating the irrigation costs with IRRICOST and IRRIECON is that all the irrigation systems are used to irrigate their respective fields simultaneously. In essence only one operating point is considered. Due to differences in the water requirements of different crops and soil variations such an assumption may not be justifiable all of the time.

2.5.2 Electricity Management Studies

Botes and Oosthuizen (1994) did a study on the effect of pumping restrictions on irrigation efficiency if Eskom’s time-of-use electricity supply is adopted in rural areas. The researchers evaluated two scenarios to determine the effect on net return flows if time-of-use electricity tariffs are used. The first scenario assumes no interruptions, the irrigation farmer can apply irrigation water 168 hours per week. The second scenario assumes that irrigation farmers have 81 hours per week (Eskom's Ruraflex load management programme) available for applying irrigation water. The researchers adjusted the SIMCOM model to search for alternative combinations of depletion levels to find an irrigation management strategy that maximises the expected utility for each load management scenario. The analysis was done for a 50ha center pivot with an application capacity (flow rate) of 135m^3/h and the analyses were repeated for a higher system capacity of 200m^3/h. A 1050mm deep Hutton/Deverton soil and an 800mm deep Avalon/Bergville soil were included in analysis. The results indicated that load management programmes can potentially increase the economic efficiency of irrigation farming. However, the importance of proper irrigation scheduling will increase under load management conditions. The results further indicated that irrigation farmers with lower application capacities, poor quality soils, high risk aversion and the inability to adjust irrigation management to load management programmes will be worst of if they adopt time-of-use load management programmes. The study highlights the effect of irrigation management and irrigation timing on the management of electricity costs for irrigation farmers.

Breytenbach, Meiring and Oosthuizen (1996) did a study on the importance of electricity costs in the Winterton area. The extent to which electricity was used, the influence of the irrigation system design on electricity costs and the contribution of electricity costs to total variable costs of irrigation and production were estimated. The results indicated that static pumping height is the major attribute of the irrigation system design influencing the electricity costs of applied water. Electricity costs accounted for an average of 75% of total variable irrigation costs for center-pivot systems. Electricity costs varied between 10% and 29% of total variable costs at enterprise level. The total annual kilowatt hour (kWh) usage of an irrigation system is mainly determined by the design of the irrigation system and the amount of irrigation. Thus, the more irrigation is applied, the greater the contribution of electricity costs to total variable cost will be.

In 2010 the Bureau for Food and Agricultural Policy (BFAP) did a similar study as Breytenbach *et al*. (1996). A typical irrigation farm in the Northern Cape Province was identified. The BFAP system of linked models was used to analyse the impact of electricity costs. The results indicated that electricity costs are the second and fourth largest cost components, respectively in the production of maize and wheat under irrigation for the typical irrigation farm investigated. Electricity costs have never exceeded eight percent of total variable costs, but it is projected that it will contribute almost 20% of total variable cost in 2014 and 2015. The results indicated that electricity costs will increase to more than 18% of wheat variable costs from 2012 onwards. The increases in electricity costs will put irrigation farmers under enormous pressure to realise sustainable profits.

Troskie (2012) did a study on the economic impact of electricity tariff increases on the potato industry in South Africa. The main objective of the study was to quantify the true impact of higher electricity tariffs on production and market prices within the potato industry. Troskie (2012) adjusted the supply response model developed by the Bureau for Food and Agricultural Policy to evaluate the impact of increased electricity tariffs on potato production and prices in South Africa. To illustrate the impact of the electricity cost component in production cost was shocked to reflect an increase at the set rate of an average of 25% per annum for the 2010, 2011 and 2012 production year. The results indicated that the three regions investigated (Sandveld, Limpopo and South Western Free State) will experience a decrease in hectares planted over the period 2013 until 2020 as a result of the increased electricity tariffs, but the decrease in hectares planted will be very small. Troskie (2012) introduced the adoption of the Ruraflex tariff option as a costs saving technique for farmers in the three regions. He made the critical assumption that all available off-peak hours will be used first without testing the feasibility from an irrigation scheduling point of view. The study concluded that the impact of higher electricity tariffs on potato production and market prices in the three regions are of a small nature which will most likely be absorbed by the farmers.

2.5.3 Discussion and Conclusion

Electricity tariffs have increased rapidly over the past years and constitute a significant part of irrigation farmers' operating costs (Breytenbach *et al.,* 1996, BFAP, 2010). Eskom has created different electricity tariff structures which farmers can adopt. However, various variables will have an effect on the economic benefit that farmers will receive from adopting different electricity tariff structures (time-of-use electricity structures). According to Botes and Oosthuizen (1996), irrigation farmers with low application capacities, poor quality soils, high risk aversion levels and the inability to adjust irrigation management to time-of-use electricity tariff structures will not increase the economic efficiency of the farm. Decision on irrigation applications and time-of-use electricity should be integrated in order to improve the management of electricity costs.

The operating (electricity) costs of irrigation are mainly determined by the design of the irrigation system (Breytenbach *et al.,* 1996). Thus, the calculation of electricity costs for a new irrigation system and if an old system is evaluated should be based on time-of-use electricity tariffs. The expected increases in electricity tariffs should be included in the design process of an irrigation system in order to design the most efficient system over the lifetime of the system.

2.6 Overall Conclusion

The literature review shows that the interaction between irrigation system design (kilowatt), irrigation management (hours) and time-of-use electricity tariffs is not integrated into one optimisation model to enhance water and energy management in irrigated agriculture. As a result, the results may be biased due to assumptions made regarding the interaction between irrigation management hours and electricity tariff choice. The main conclusion is that a unified optimisation model is necessary to model the interaction simultaneously between irrigation system design, irrigation management and time-of-use electricity tariffs. The unified model needs to consist of the following components:

- Irrigation mainline design model

  An irrigation mainline design model is necessary to calculate investment costs and kilowatt requirements. The literature review indicated that the linear programming pipe optimisation model developed by Radley (2000) is able to model the economic trade-off between pipeline investment cost, kilowatt requirement and operating costs, but requires the inclusion of a soil water budget routine and time-of-use electricity tariffs.

- Daily soil water irrigation planning model

  The SAPWAT optimisation model (Grové et al., 2012) is able to model the soil water budget which is a requirement to determine irrigation timing. The modelling procedure provides assurance that the soil water budget is calculated correctly and includes the non-uniformity of which irrigation systems apply water.

- Energy accounting model

  Timing of irrigation events is of utmost importance since the irrigator should manage irrigation timing in collaboration with time-of-use electricity tariffs and the restrictions thereof. Thus, an energy accounting model is necessary to model the time-of-use electricity tariffs as well as the restrictions thereof.

CHAPTER 3
METHODOLOGY AND DATA

3.1 Introduction

Chapter 3 comprises of two sections. The first section specifies the mathematical formulation and parameters used for the Soil Water Irrigation Planning and Energy management (SWIP-E) programming model which calculates the economic trade-off between pipeline investment cost and operating costs to determine the optimal pipe diameter for an irrigation main pipeline design. The second section discusses the methods of data collection and calculation of input parameters for the programming model.

3.2 Soil Water Irrigation Planning and Energy Management (SWIP-E) Programming Model

The following section describes the Soil Water Irrigation Planning and Energy management programming model (SWIP-E) that is used to model the trade-off between pipeline investments and energy operating costs. The SWIP-E programming model is based on the SAPWAT optimisation (SAPWAT-OPT) (Grové, 2008) model that optimises a daily soil water budget for a single crop. The SAPWAT-OPT model was further developed to facilitate inter-seasonal crop water use optimisation. Detailed electricity cost calculations and a mainline pipe optimisation model (Radley, 2000) were included in the model to facilitate electricity energy management in an integrated way.

Next the SWIP-E model specification is described following the convention whereby variables are indicated with capital letters and data parameters with small letters.

3.2.1 Objective Function

The objective function maximises the net present value of an irrigation system investment. Equation (3.1) represents the objective function used in the SWIP-E model:

$$MAX: NPV = \sum_{c,y} \frac{PI_c\,(1-t)}{(1-d_y)^{y-1}} - \sum_{c,y} \frac{YDC_c\,(1-t)}{(1-d_y)^{y-1}} - \sum_{c,y} \frac{ADC_c\,(1-t)}{(1-d_y)^{y-1}} - \sum_{c,y} \frac{IDC_c(1-t)}{(1-d_y)^{y-1}} - INV \tag{3.1}$$

Where:

PI_c	Total production income for crop *c* (R)
YDC_c	Total yield dependent costs for crop *c* (R)
ADC_c	Total area dependent costs for crop *c* (R)
IDC_c	Total irrigation dependent costs for crop *c* (R)
INV	After tax investment costs for an irrigation system (R)
t	marginal tax rate (%)
d_y	real discount rate in year *y* (fraction)

The first four terms of the objective function calculate the net present value of the margin above specified costs for a specified crop rotation. The margin above specified costs (cash flow) is calculated by subtracting the yield, area and irrigation dependent costs from the production income. The cash flow with an exception of electricity costs is calculated by using constant prices; thus, real prices are used. Electricity costs are increased by using a real increase in electricity tariffs (increase rate above inflation). The real discount rate is calculated using the formula proposed in Boelhje end Eidman (1984). The NPV is calculated by subtracting the after-tax investment costs of an irrigation system from the margin above specified costs.

The following sections describe the calculation procedures to calculate each of the components of the objective function in more detail.

3.2.1.1 Production Income

Production income is a function of yield and area planted for each crop and the price of the crop. The following equation is used to calculate the production income for each crop considered in the model:

$$PI_c = \frac{\sum_{wb} Y_{wb,c}}{5} \times p_c \times A_c \tag{3.2}$$

Where:

$Y_{wb,c}$	Yield for water budget *wb* for crop *c* (tons/ha)
p_c	Crop price for crop *c* (R/ton)
A_c	Area planted for crop *c* (ha)

Production income is calculated by multiplying the crop yield with the crop price and area planted. The crop price is an input in the model while the crop yield and area planted are endogenously determined in the model. Crop yield is estimated for each of the water budgets that were included in the model to model the impact of non-uniform water applications. The sum of the yields obtained in each water budget is divided by the number of water budgets to calculate the average crop yield that is used to calculate production income.

3.2.1.2 Yield Dependent Costs

The calculation of yield dependent costs is based on a cost reduction method (Grové, 1997). Equation (3.3) is used to calculate yield dependent costs:

$$YDC_c = vym_c - \left(ym_c - \frac{\sum_{wb} Y_{wb,c}}{5}\right) vy_c \qquad (3.3)$$

Where:

vym_c	Total yield dependent costs for crop *c* at maximum yield (R/ha)
ym_c	Maximum yield for crop *c* (ton/ha)
vy_c	Scaling factor for a less than proportional reduction in yield dependent costs for crop *c* (R/ton)

The first part of the equation represents total yield dependent costs at maximum crop yield. The second part of the equation calculates the less than proportional reduction in yield dependent costs for the difference between the maximum and actual yield by multiplying the difference with a scaling factor (vy_c). The scaling factor for a less than proportional reduction in yield dependent costs for each crop included in the model is calculated in Excel©. The following example is used to explain equation (3.3). Suppose the yield dependent costs to produce 17tons/ha of maize is R 13,506.66, thus the yield dependent cost per ton is R 794.51 (13,506.66/17). Suppose the cost to produce 13tons/ha is R 9,123.18/ha, therefore the yield decrease with 4ton/ha resulting in a cost saving of R 4,383.52/ha, but due to the non-proportional decrease, the yield dependent costs decrease with R 9, 123.18/ha (Equation 3.3).

3.2.1.3 Area Dependent Costs

Area dependent costs include all input costs which will change with the area planted. The area dependent costs are calculated for each crop considered in the model using Equation (3.4):

$$ADC_c = A_c \times va_c \qquad (3.4)$$

Where:

A_c	Area planted to crop *c* (ha)
va_c	Area dependent cost for crop *c* (R/ha)

3.2.1.4 Irrigation Dependent Costs

The following section explains the calculation of irrigation dependent costs which is a function of the pumping hours or irrigation water applied. Equation (3.5) represents the formula to calculate irrigation dependent costs:

$$IDC_c = EC_c + LC_c + RMC_c + WC_c \tag{3.5}$$

Where:

EC_c	Total electricity costs for crop *c* (R)
LC_c	Total labour costs for crop *c* (R)
RMC_c	Total repair and maintenance costs for crop *c* (R)
WC_c	Total water costs for crop *c* (R)

Irrigation dependent costs (IDC) include electricity costs, labour costs, repair and maintenance costs and water costs of the irrigation system. Total electricity costs depend on the type of electricity tariff. All tariff options include a fixed cost and variable cost. Fixed costs have to be paid every month irrespective of whether electricity was used or not while variable costs have to be paid for electricity consumption. Variable electricity costs are a function of management (hours pumped), electricity tariffs and irrigation system design (kW). The following equation is used to calculate total electricity costs:

$$EC = \sum_{i,t}\left(ta_{i,t} + rc_{i,t} + dc_{i,t}\right) kWPH_{i,t} + \sum_{i,t} tra_{i,t} kvarPH_{i,t} + fec \tag{3.6}$$

Where:

$PH_{i,t}$	Pumping hours on day *i* in timeslot *t* (hours)
kW	Kilowatt (kW)
$kvar$	Kilovar (kVAR)
$ta_{i,t}$	Active energy charge on day *i* in timeslot *t* (R/kWh)
$tra_{i,t}$	Reactive energy charge on day *i* in timeslot *t* (R/kVARh)
$rc_{i,t}$	Reliable energy charge (R/kWh)
$dc_{i,t}$	Demand energy charge (R/kWh)
fec	Fixed electricity costs (R)

The electricity tariffs are divided into different charges, active, reliable and demand energy charge, which is dependent on the product of the *kW* requirement of an irrigation system and the pumping hours. The *kW* requirement is closely linked to irrigation system layout and design. Pumping hours (*PH*) are determined by irrigation management and the limits that are placed on irrigation hours during the irrigation cycle when using time-of-use electricity tariffs. The reactive energy charge is dependent on the kilovar (kVAR) and pumping hours of an irrigation system.

The *kVAR* is calculated from the power factor (PF) of the pump (kVAR = $\cos^{-1}$ PF). Each pump has a unique power factor which can be obtained from the manufacturer. The user pays for 70% of the *kVARh* used. The fixed electricity costs (fec) are an input parameter in the model and depend on the type of electricity tariff.

Equation (3.7) and (3.8) represent the formulas to calculate labour costs and repair and maintenance costs of the irrigation system, respectively. The calculation procedures for labour and repair and maintenance costs are based on formulas proposed by Meiring (1989).

$$LC_c = \sum_{i,t} \frac{PH_{i,t}}{24} \, lh \, lw \qquad (3.7)$$

Where:

lh Labour hours needed per 24 hours irrigation for a given size center pivot (hours)

lw Labour wage (R/hour)

Labour costs for permanent labourers can be considered as a fixed cost. However, labour costs obtain a variable character once labour is employed in a specific enterprise because labour costs can then be allocated between different enterprises. Labour costs for center pivot irrigation is variable because the amount of labour hours required is determined by the hours that the system is operated. The amount of labour that is required per operating hour is influenced by the size of the system and the type of task being performed. The model calculates the labour demand for every 24 hours that the system is operated. The calculated labour demand is multiplied with the total pumping hours and the labour wage to calculate total labour costs.

Repair and maintenance costs depend on the conditions (climate) under which the system operates. The pump's repair and maintenance cost is directly linked to the use of the pump, through expressing the repair and maintenance tariff as a percentage per 1000 hours pumped. The repair and maintenance costs of the motor, pivot and pipe are not included in the model since it is independent of the use of the system and will decrease the profit linearly (Meiring, 1989).

$$RMC_c = \sum_{i,t} PH_{i,t} \, rt \qquad (3.8)$$

Where:

rt Repair and maintenance tariff per 1000 hours pumped for an irrigation system (R/1000hours)

Equation (3.9) represents the formula to calculate water costs:

$$WC_c = \sum_{c,i} IR_{c,i} \; A_c wt \qquad (3.9)$$

Where:

$IR_{c,i}$	Irrigation for crop *c* on day *i* (mm)
wt	Water tariff (R/mm)

Water charges are a function of the irrigation water applied, area planted and the water tariff charged by the water user association. The water tariff includes the totality of payments that an irrigator makes for the irrigation service and is calculated on a volumetric basis. The volumetric-based charges is a fixed rate per unit water received, where the charge is related directly to and proportional to the volume of water received. The charge per millimetre water was calculated by dividing the total charge by the volume water allocated.

3.2.1.5 Investment Costs

The section describes the calculation procedures used to calculate the net after tax investment costs of an irrigation system. The calculation procedure of the main pipeline is based on the formulas used in the linear programming pipe optimisation model developed by Radley (2000). The pivot and pump investment costs are collected from a manufacturer and are inputs in the model. The following equation represents the calculation procedure for investment costs of an irrigation system:

$$INV = \sum_p PRO_p\, r_p\, l - \sum_{ty,p} \frac{(PRO_p \times r_p \times l)ty\_per_{ty}}{(1 - d_{ty})^{ty-1}} + i_{pivot} + i\_pump - \sum_{ty} \frac{(i\_pivot + i\_pump)ty\_per_{ty}}{(1 - d_{ty})^{ty-1}} \quad (3.10)$$

Where:

PRO_p	Proportion of pipe *p* used (fraction)
r_p	Costs of the pipe *p* (R/m)
l	Length of the main pipeline (m)
ty_per_{ty}	Tax deduction in tax year *ty* (%)
d_{ty}	Real discount rate in tax year *ty* (fraction)
i_pivot	Investment costs of the pivot (R)
i_pump	Investment costs of the pump (R)
$tb_{ty,p}$	Tax benefit received in tax year *ty* for a pivot and pump investment (R)

The main pipeline can be designed by choosing the pipe diameter such that the sum of the operating and investment costs are minimised. Calculations are done with consideration of the investment of the pipe, the tax benefit that the irrigator will receive from investing in a new pipeline and electricity costs (operating costs). Investment costs are depended on the pipe costs, length of the pipe and can be considered as a lump sum. The costs of the pipes and the length of the main pipeline are inputs in the model. The tax benefit that the irrigator will receive from investing in a new irrigation system was included in the calculation of the investment costs of the main pipeline, center pivot and pump. The tax benefit calculations are based on a 50%, 30% and 20% in year one, two and three, respectively, tax deduction. The present value of the tax benefit was calculated by using the same procedure as in the objective function. The tax benefit for the center pivot and pump investment is calculated in Excel© and is an input parameter in the model.

Equation (3.11) is included in the model to ensure that sum of the proportions of the pipes used must be equal to one:

$$\sum_p PRO_p = 1 \tag{3.11}$$

3.2.2 Constraint Set

The following section describes the constraint set of the SWIP-E model. The section is divided into crop yield and water budget calculations, pumping hours, kilowatt requirement calculation and resource constraints.

3.2.2.1 Crop Yield and Water Budget Calculations

Crop yield is calculated with the use of crop yield response factors (ky) which relate relative yield decrease (1-Y/Ym) to relative evapotranspiration deficit (1-ETA/ETM). The Stewart multiplicative (De Jager, 1994) relative evapotranspiration formula was used to calculate crop yield taking the effect of water deficits in different crop growth stages into account. Equation (3.12) is used to calculate crop yield:

$$Y_{wb,c} = ym_c \times \prod_{g=1}^{4} \left(1 - ky_{c,g}\left(1 - \left(\frac{\sum_i ETA_{wb,c,i}}{\sum_i etm_{c,i}}\right)\right)\right) \tag{3.12}$$

Where:

$ky_{c,g}$	Yield response factors for crop *c* in growth stage *g*
$ETA_{wb,c,i}$	Actual evapotranspiration in water budget *wb* for crop *c* on day *i* (mm)
$etm_{c,i}$	Maximum evapotranspiration for crop *c* on day *i* (mm)

Crop yields were estimated for each of the water budgets included in the model. Actual evapotranspiration is based on simple cascading water budget calculations in SAPWAT (Crosby and Crosby, 1999). SAPWAT uses the basic methodology proposed in FAO-56 (Allen *et al.,* 1998) to calculate crop water requirements based on a reference evapotranspiration rate. The basic idea is that while the crop does not experience any water deficits the actual evapotranspiration is equal to the potential.

Irrigation systems do not apply water with perfect uniformity. Due to the lack of the uniformity a part of the field is adequately irrigated while others are not. An excess amount of water can increase the costs of pumping, lower yields and water logging of soils in inadequately irrigated areas. In contrast, a shortage of water decrease yields, which result in a decrease in profit. Various researchers (Hamilton *et al.,* 1999, Grové, 2008 and Lecler, 2004) modelled the impact of non-uniformity by dividing the irrigation field in different water budgets. The relationship between applied water and crop yield was explicitly incorporated in the water budget calculations by modelling several different water budgets simultaneously in GAMS. Thus, all the water budget formulas are defined in terms of wb.

The water budget routine included in the SWIP-E model distinguishes between water in the root zone and below the root zone. The total available moisture (TAM) in the soil that potentially can be used by the crop is a function of the water holding capacity (WHC) of the soil and the rooting depth (RD) of the crop. Only a portion of TAM is readily available for crop consumption (RAM). RAM is a function of RD, WHC and the P-value, which indicates the proportion of the water that is readily available for crop consumption. The P-value calculation is based on a formula proposed in Dominguez, De Juan, Tarjelo, Martinez and Martinez-Romera (2012). If soil moisture deficits (SMD) are greater than RAM, the rate at which the crop consumes water is reduced from its potential level and ETA is only a fraction of ETm. Given these conditions ETA is calculated using equation (3.13):

$$ETA_{wb,c,i} = min \left| \begin{array}{l} etm_{c,i} \\ etm_{c,i}\left(\frac{RWC_{wb,c,i}}{TAM_{wb,c,i} - RAM_{wb,c,i}}\right) \end{array} \right. \qquad (3.13)$$

Where:

$RWC_{wb,c,i}$	Root water content in water budget *wb* for crop *c* on day *i* (mm)
$TAM_{wb,c,i}$	Total available moisture in water budget *wb* for crop *c* on day *i* (mm)
$RAM_{wb,c,i}$	Readily available moisture in water budget *wb* for crop *c* on day *i* (mm)

Soil moisture deficit defines the difference between the water holding capacity in the root zone (RWCAP) and the actual water content in the root zone (RWC). RWCAP is a function of the WHC of a specific soil and the RD of the crop. RWC is a function of the RWC of the previous day, ETA, rainfall, irrigation and any additions made to RWC due to root growth (TR). The irrigation amount is calculated for the average water budget and multiplied with a scaling factor (cu_scale) to calculate an irrigation amount for each of the water budgets included in the model. Water that drains below the root zone is not explicitly accounted for in the calculation of RWC but indirectly because it is capped to a maximum of TAM. Equation (3.14) is used to determine RWC:

$$RWC_{wb,c,i} = min \left| \begin{array}{l} RWC_{wb,c,i-1} - ETA_{wb,c,i-1} + r_{c,i-1} + IR_{c,i-1} cu\_scale_{wb} + TR_{wb,c,i} \\ rwcap_{wb,c,i} \end{array} \right. \qquad (3.14)$$

Where:

$r_{c,i}$	Rainfall for crop *c* on day *i* (mm)
$IR_{c,i}$	Irrigation for crop *c* on day *i* (mm)
cu_scale_{wb}	Scaling factor for water budget *wb*
$TR_{wb,c,i}$	Additions made to RWC due to root growth in water budget *wb* for crop *c* on day *i* (mm)
$rwcap_{wb,c,i}$	Water holding capacity in the root zone in water budget *wb* for crop *c* on day *i* (mm)

The water content of water below the root zone (BRWC) is determined by:

$$BRWC_{wb,c,i} = min \left| \begin{array}{l} BRWC_{wb,c,i-1} + BR_{wb,c,i} - TR_{wb,c,i} \\ (rd_{max} - rd_i)whc \end{array} \right. \tag{3.15}$$

Where:

$BRWC_{wb,c,i}$	Water below the root zone in water budget *wb* for crop *c* on day *i* (mm)
$BR_{wb,c,i}$	Water that drains below the root zone in water budget *wb* for crop *c* on day *i* (mm)
rd_i	Root development on day *i* (m)
rd_{max}	Maximum root depth (m)
whc	Water holding capacity (mm/m)

Where BR and TR are calculated as:

$$BR_{\,wb,c,i} = max \left| \begin{array}{l} RWC_{wb,c,i-1} + BR_{wb,c,i} - TR_{wb,c,i} \\ 0 \end{array} \right. \tag{3.16}$$

$$TR_{wb,t} = \left| \begin{array}{ll} (rd_{c,i} - rd_{c,i-1})/\big(rd_{max} - rd_{c,i-1}\big)BRWC_{wb,c,i-1} & if\; rd_{c,i} = rd_{g=2} \\ 0 & if\; rd_{c,i} \neq rd_{g=2} \end{array} \right. \tag{3.17}$$

The last equation indicates that TR is directly attributed to root growth and the availability of water below the root zone (BRWC). Thus, TR will only occur in the crop development growth stage and TR will be zero in the initial, mid-season and late-season growth stages.

To initialize the whole water budget the user has to specify the water holding capacity (WHC) and the water content in percentage terms. RWC and BRWC are then adjusted accordingly to give the same water content in terms of a percentage.

3.2.2.2 Pumping Hours

According the Burger *et al.* (2003) pumping hours can be calculated on an annual basis for all the fields or systems supplied from one pumping station with equation (3.18).

$$PH_{i,t} = \frac{\frac{\sum_c IR_{c,i}}{\eta_s} A_c 10}{q} \qquad (3.18)$$

Where:

q	Flow rate (m^3/h)
η_s	System efficiency (%)

The irrigation amount is calculated in the model, while the flow rate and system efficiency are input parameters in the model. The irrigation amount is based on the average irrigation of the water budgets included in the model. The system efficiency is based on the spray losses of the irrigation system (wind drift).

Eskom's time-of-use electricity tariffs are designed to create the incentive for irrigation farmers to use electricity during low demand season and off-peak hours. The time-of-use tariffs are divided in three time slots with different rates applicable to each time-slot. Pumping hours needs to be restricted to the available hours within an irrigation cycle and time-of-use. Equation (3.19) illustrates the equation used to restrict the pumping hours within the available hours in an irrigation cycle.

$$PH_{i,t} \leq thc_{i,t} \qquad (3.19)$$

Where:

$thc_{i,t}$	Available irrigation hours within each irrigation cycle on day *i* in timeslot *t* (h)

The basic idea is that pumping hours in a specific time-slot cannot exceed the available irrigation hours in that specific time-slot.

3.2.2.3 Kilowatt Requirement

Kilowatt (kW) is determined endogenously in the model and quantifies the kilowatts required to drive the water through the system. Kilowatt is a function of the flow rate of the pump, total pressure required by the system and the efficiency of the pump and motor (Burger *et al.,* 2003). Equation (3.20) is used to calculate the kilowatt requirement at the pumping station:

$$kW = \frac{H \times q}{0.0036 \times \eta_m \times \eta_p} \qquad (3.20)$$

Where:

H	Total pressure required by the system (m)
η_m	Motor efficiency (%)
η_p	Pump efficiency (%)

Total pressure in the system is the sum of the operating pressure of the pivot, static head and friction in the main pipeline. The pivot pressure represents the required pressure at the center of the pivot in order to apply a designed irrigation amount per day. Static head is a constant which represents the height difference between the water source and the irrigation system. Equation (3.21) is used to determine the total operating pressure of the system which the pump must supply:

$$H = centre\ pressure + hs + \sum_p PRO_p\, f_p \tag{3.21}$$

Where:

hs	Static head (m)
f_p	Friction loss in each of the pipe diameters for a given flow rate (m)

Friction in the mainline is a function of the proportion of the pipe diameter that has been used in the mainline and the friction that was calculated through the use of the Darcy-Weisbach (Burger *et al.,* 2003) equation for a given flow rate.

3.2.2.4 Area

The following equation is used to restrict the area planted of a certain crop to the pivot size:

$$A_c \leq Pivot\ Size \tag{3.22}$$

The model is developed for a crop rotation system consisting of maize and wheat. Thus, the available area for each crop must be equal or smaller than the designed center pivot size. Important to note is that the model does not model intra-seasonal competing crops since the crop rotation consists of maize and wheat only.

3.2.2.5 Water

The maximum water allocation depends on the area and the allocation of water determined by the water user association. The basic idea of the equation is that the amount of irrigation applied (average water budget) for the total area planted cannot exceed the allocation of the total area available.

$$\frac{\sum_c IR_{c,i}}{\eta_s} A_c \leq Alloc \times Pivot\ Size \tag{3.23}$$

Where:

$Alloc$ Allocation of water (m^3/ha)

Equation (3.24) represents the maximum irrigation application within an irrigation cycle. The user has to specify the length of an irrigation cycle. Thus, the irrigation cycle determines the day an irrigator can decide to apply irrigation. Furthermore, the assumption is made that the maximum irrigation application within an irrigation cycle cannot exceed the maximum irrigation amount per irrigation cycle. The irrigation amount is based on the average irrigation applications of the water budgets.

$$\frac{\sum_c IR_{c,i}}{\eta_s} \leq irc_i \tag{3.24}$$

Where:

irc_i = Irrigation amount per cycle for crop *c* on irrigation day *i* (mm/cycle)

The above resource constraints are explicitly included in the modelling process.

3.2.3 Model Application

The maximum (MAX) and minimum (MIN) functions used in the water budget calculations result in discontinuous derivatives which reduce the ability of non-linear solvers to solve these models satisfactorily. Drud (1998) provides smooth approximations for the MIN and MAX functions with values close to the original functions, but with smooth derivatives. A smooth approximation for MIN(f(x),g(y)) is given by:

$$(f(x) + g(y) - SQRT\left(SQR\big(f(x) - g(y)\big) + SQR(delta)\right))/2 \tag{3.25}$$

The delta scalar are very small and the value of delta can be used to control the accuracy of the approximation and the curvature around f(x) = g(y). The approximation error is delta/2 when f(x) = g(y) and decreases with the difference between the two terms. The error is equal to delta which is the largest with delta closer to zero. A similar smooth approximation for the MAX(f(x),g(y)) function is given by:

$$(f(x) + g(y) + SQRT\left(SQR\big(f(x) - g(y)\big) + SQR(delta)\right))/2 \tag{3.26}$$

All the above minimum and maximum equations (ETA, RWC, BRWC and BR) that are used to calculate the water budget are modelled with smooth approximation formulas in GAMS, with the value of delta equal to 0.001 (Drud, 1998).

Before applying the SWIP-E model the user needs to decide on the number of water budgets that needs to be included to model non-uniformity of irrigation applications. The number of water budgets was determined graphically by plotting the optimised production functions with different number of water budgets. The results are shown in Figure 3.1.

The Christian Coefficient (CU) of the one water budget was taken as 100%, thus, no inefficiencies are modelled. The relationship between applied water and crop yield is linear if inefficiencies are ignored. However, inefficiencies are present due to deep percolation if water is applied non-uniformly since a portion of the field will receive more than the average amount of water. Inefficiencies were taken into account by dividing the area into three, five and seven water budgets. Each water budget received a different amount of water based on a uniform distribution and a CU of 88%. Important to note is that the relationship between water consumption and crop yield is linear up to about 50% of full irrigation where the relationship becomes non-linear. The accuracy between applied water and crop yield is represented by a different number of water budget increases. However, the difference between seven and five water budgets was insignificant. As a result five water budgets were included in the analysis.

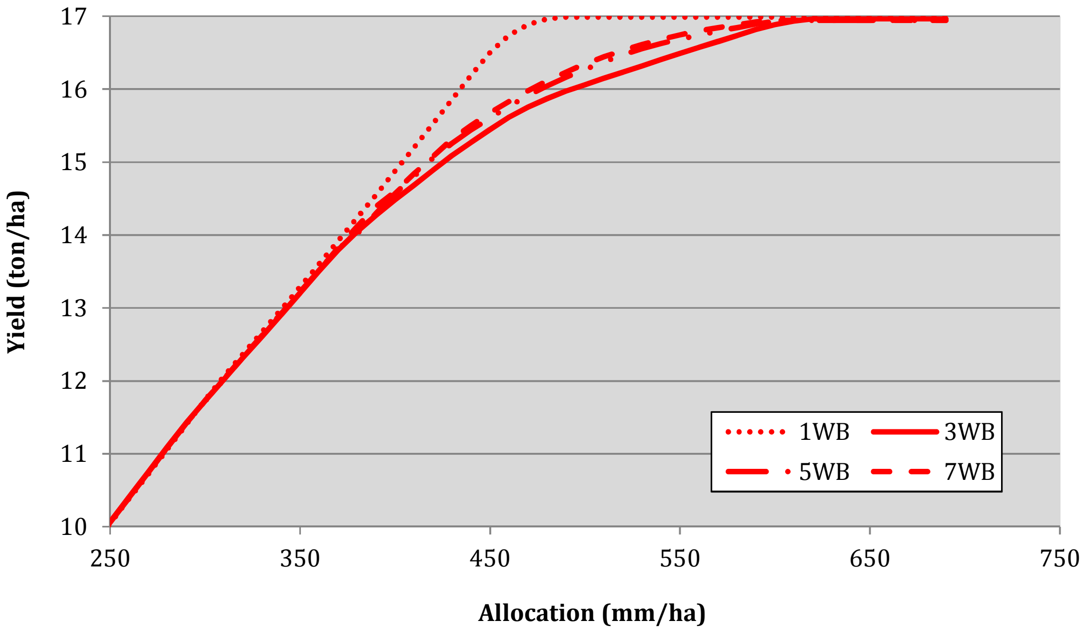

Figure 3.1: Relationship between applied water, water in the water budget, rainfall and crop yield for one, three, five and seven water budgets

3.3 Data Requirements

In order to setup the SWIP-E model the decision maker needs to specify certain inputs. The required inputs can be divided into four groups, namely economic parameters, irrigation dependent parameters, irrigation system design data and water budget input parameters.

3.3.1 Economic Input Parameters

Economic data include input costs data for maize and wheat, crop price data, yield and area dependent costs and all costs related to the investment of the main pipeline. The calculation of yield and area dependent costs for maize and wheat are based on the “Griekwaland-Wes Korporatief” (GWK) input costs guide for November 2013 (GWK, 2013). The calculation of yield dependent costs is based on a formula proposed by Grové (1997). Equation (3.27) is used to calculate the scaling factor for the change in yield dependent costs expressed on a rand per ton basis:

$$vy_c = \frac{ydc\_ym_c - ydc\_ya_c}{ym_c - ya_c} \tag{3.27}$$

Where:

vy_c	Actual yield dependent costs for crop *c* (R/ton)
ydc_ym_c	Maximum yield dependent costs for crop *c* (R/ton)
ydc_ya_c	Target yield dependent cost for crop *c* (R/ton)
ym_c	Maximum yield for crop *c* (ton/ha)
ya_c	Target yield for crop *c* (ton/ha)

The above equation calculates the actual yield dependent costs by dividing the difference between maximum and target yield dependent costs with the difference in yield between maximum and target yield. Table 3.1 represent the crop prices, area and yield dependent parameters for maize and wheat. The average spot prices for maize and wheat over a period of 10 years were used. Price data for the period 2007 until 2014 were downloaded from the JSE website.

Table 3.1: Economic input parameters and maximum and target yield for maize and wheat in the Douglas area, 2014

	Maize	Wheat
Crop Price (R/ton)	*1 896*	*3 011*
Maximum Yield Costs (R/ha)	*13 506.66*	*9 040.80*
Target Yield Costs (R/ton)	*9 123.10*	*8 118.90*
Scaling Factor (R/ton)	*1 095.88*	*921.91*
Area dependent costs (R/ha)	*7 315.81*	*4 898.63*
Maximum Yield (ton/ha)	*17*	*8.5*
Target Yield (ton/ha)	*13*	*7.5*

Source: Eskom (2014/15)

Price data for different pipe diameters are necessary to calculate the investment costs of each pipe diameter. The data are collected from the manufacturer and included in the model as a parameter. The tax benefit for the main pipeline and pivot was calculated on a 50%, 30%, 20% in year one, two and three of the initial investments. The tax rate was assumed at 28% and the lifetime of the pipeline 20 years.

A real discount rate of 2.7% was used in the calculations and was calculated by using an interest rate of 9.25% and an inflation rate of 6.4%. NERSA allowed Eskom to increase electricity tariffs with 13% for 2015 (Eskom, 2014/15) which results in a real increase in electricity costs of 6.2%. These rates were used in the model to calculate the net present value of margin above specified costs and investment costs of an irrigation system.

3.3.2 Irrigation Dependent Input Parameters

Irrigation dependent input parameters include all the data needed to calculate the irrigation dependent costs in the SWIP-E model. These inputs include electricity tariffs, labour, water and repair and maintenance data.

3.3.2.1 Electricity Tariffs

Electricity costs relate to Eskom tariffs and charges booklet for the period 2014 to 2015 (Eskom, 2014/15). The electricity tariffs options (Ruraflex and Landrate) applicable to the Dougals area are used to calculate electricity costs. Table 3.2 illustrates the Ruraflex charges used in the analysis. The active energy ($ta_{i,t}$) and network access charges (fixed charge) are based on the 300km to 600km range transmission zone and a voltage of smaller than 500V. Reliability ($rc_{i,t}$) and network demand ($dc_{i,t}$) charge are also based on a voltage smaller than 500V. Reactive energy charge ($tra_{i,t}$) is only applicable on wheat, due to the fact that wheat is irrigated in the high season. Fixed electricity costs were calculated using 50 kilovolt ampere (KVA) for all the irrigation systems included in the analysis with an exception of the large center pivot with a 12mm/day and 14mm/day delivery capacity which used 75KVA to calculate fixed electricity costs. Kilovar hours are calculated for each irrigation system design and is a function of the power factor of the pump.

Table 3.2: Variable and fixed electricity tariffs for the Ruraflex electricity tariff structure in the Douglas area, 2014/15

Variable Electricity Costs Tariffs			
Active Energy Charge (c/kWh)	**High (June – August)**	**Off-Peak**	*38.01*
		Standard	*69.99*
		Peak	*231.03*
	Low (September – April)	**Off-Peak**	*32.91*
		Standard	*51.87*
		Peak	*75.36*
Reliability service Charge (c/kWh)			*0.29*
Network Demand Charge (c/kWh)			*18.8*
Reactive Energy Charge (c/kVArh)	**High (June – August)**		*6.35*
	Low (September – April)		*0*
Fixed Electricity Costs Tariffs			
Network Access Charge (R/KVA/month)			*13.25*
Service Charge (R/Account/day)			*44.32*
Administration Charge (R/POD/day)			*20.54*

*POD: Point of delivery

Source: Eskom (2014/15)

Option 2 was used for the calculation of electricity costs for the Landrate electricity tariff structure. According to Bezuidenhoudt (2012), the Landrate 2 option is the most popular amongst irrigation farmers, thus this option was used in the study. Table 3.3 illustrates the charges applicable to the Landrate 2 option.

Table 3.3: Variable and fixed electricity tariffs for the Landrate electricity tariff structure in the Douglas area, 2014/15

Variable Electricity Costs Charges	
Energy Charge (c/kWh)	*75.27*
Reliability Service Charge (c/kWh)	*0.29*
Network Demand Charge (c/kWh)	*18.8*
Fixed Electricity Costs Charges	
Network Access Charge (R/POD/day)	*30.9*
Service Charge (R/POD/day)	*16.69*

*POD: Point of delivery

Source: Eskom (2014/15)

The tariffs that will have the biggest effect on variable electricity costs are active energy for Ruraflex and energy charge for Landrate. Ruraflex's active energy charge is divided into a high and low season as well as time-of-use tariffs. Ruraflex's active energy charge in the low season during peak time is more or less the same as Landrate's energy charge, whereas the active energy charge in high season during peak time is three times Landrate's energy charge. Ruraflex consists of reactive energy charge during the high season. The other two variable electricity tariffs are exactly the same for both of the tariffs. Ruraflex has three fixed electricity tariffs compared to the two of Landrate. Ruraflex's network access charge is 2.3 times smaller than Landrate's network access charge, but the service charge of Ruraflex is 2.6 times greater the service charge of Landrate. Ruraflex also has an additional administration charge.

The available irrigation hours in each timeslot as well as the total irrigation hours during a growing season for maize and wheat are given in Table 3.4. The available irrigation hours for wheat are more than maize due to the longer growing season.

Table 3.4: Available irrigation hours in each time-of-use timeslot for maize and wheat grown in the Douglas area, 2014

	Maize	Wheat
Off-Peak	*960*	*1 184*
Standard	*1 048*	*1 292*
Peak	*430*	*530*
Total	***2 438***	***3 006***

Source: Eskom (2014/15)

3.3.2.2 Other Irrigation Dependent Input Parameters

A minimum wage of R 12.41/hour is used in the application of the model (DOL, 2014). The labour requirement for every 24 hours that the irrigation system operates is based on the data proposed in Meiring (1989) and account to a value of 0.58 labour hours per 24 hours. The repair and maintenance tariff calculated depends on the irrigation system design and is based on a method proposed by Meiring (1989). The tariff is a function of the initial investment of the pump and is expressed as per 1000 hours pumped. The water tariff is based on the Van der Kloof water user association which is based on a volumetric-based charge with an allocation of 10 000 m^3/ha. The tariff per millimetre water applied is calculated by dividing the tariff with the water allocation and is equal to R 0.716/mm.

3.3.3 Irrigation System Design Data

Irrigation system design data are collected for eight center pivot designs from Myburgh (2014). The irrigation systems are designed with one center pivot on the main pipeline. Thus, only one operating point exists. The analysis is done for center pivots consisting of pivot sizes of 30.1ha and 47.7ha, with capacities ranging from 8mm/day to 14mm/day. The 30.1ha center pivot is a five tower system that consists of three towers of 55m, two towers of 61m and an overhang of 22.56m. The 47.7ha center pivot is a six tower system of 61m and an overhang of 25.08m. The irrigation systems are designed for a 750m main pipeline at a static height of 12m. Table 3.5 shows the design and initial investment of different elements of the irrigation systems. Flow rate depends on the size of the pivot and the designed capacity of the center pivot and will determine the irrigation hours of the irrigation system. Center pressure, pump rate and efficiency of the pump are necessary to calculate kilowatt requirement in the model. The center pressure, pump rate and the efficiency of the pump depend on the size and capacity of the center pivot and will vary between different center pivot designs.

Table 3.5: Design parameters and initial investment costs of the infield irrigation system for two center pivot sizes (small and large) and four irrigation system delivery capacities

	Center Pivot Size (ha)							
	Small (30.1)				**Large (47.7)**			
	Irrigation System Delivery Capacity (mm/day)				**Irrigation System Delivery Capacity (mm/day)**			
	8	**10**	**12**	**14**	**8**	**10**	**12**	**14**
	Design Parameters							
Flow Rate (m^3/h)	*100.5*	*125.5*	*150.5*	*178*	*158.9*	*198.6*	*239*	*278*
Center pressure (m)	*21.1*	*22.4*	*24.1*	*22.9*	*22.9*	*25.2*	*28*	*31.1*
Efficiency of pump (fraction)	*0.747*	*0.755*	*0.775*	*0.784*	*0.778*	*0.797*	*0.814*	*0.817*
Center pivot rotation on 100% (hours)	*7.69*	*7.69*	*7.69*	*7.67*	*9.77*	*9.77*	*9.77*	*9.77*
Kilovar (kVAR)	*10*	*13*	*14*	*16*	*14*	*24*	*30*	*38*
Kilovolt-ampere (KVA)	*50*	*50*	*50*	*50*	*50*	*50*	*75*	*75*
	Initial Investments							
Pivot (R)	*638 482*	*668 999*	*723 185*	*739 653*	*815 452*	*835 239*	*842 405*	*930 818*
Pump (R)	*14 368*	*21 655*	*20 661*	*20 661*	*20 661*	*22 216*	*22 216*	*22 216*

Source: Myburgh (2014)

Friction in the main pipeline is included as a parameter in the model. Table 3.6 represents a data table consisting of the friction loss over the length of the mainline for each pipe diameter as well as the flow rates that are considered in the optimisation. Equation (3.28) was used to calculate friction in the main pipeline through the use of the Darcy-Weisbach (Burger *et al.,* 2003) equation in combination with the Hazen-Williams (Burger *et al.,* 2003) equation.

$$\frac{1}{\sqrt{f_p}} = 1.14 - 2\log\left(\frac{k}{d} + \frac{21.25}{Re^{0.9}}\right) \tag{3.28}$$

Where:

f_p	Friction loss for pipe *p* (m)
k	Pipe roughness (mm)
d	Inside pipe diameter (mm)
Re	Reynolds number

Table 3.6 represents the friction in each diameter pipe that is included in the SWIP–E model. Friction in the smaller diameter pipes is much greater than in the larger diameter pipes. The friction (m) ranges from 3342.02m in a 50mm diameter pipe to 0.086m in a 400mm diameter pipe for a flow rate of 100.5m^3/h. As flow rates increase the friction in the main pipeline increase. For example, the friction for a 250mm pipe diameter with a flow rate of 100.5m^3/h is 1.007m and 6.548m for a flow rate of 278m^3/h.

Table 3.6: Friction values used for friction parameter in the SWIP–E model

Outside Pipe Diameter (mm)	Flow Rate (m^3/h)							
	100.5	125.5	150.5	178	158.9	198.6	239	278
47	*3 342.024*	*5 158.283*	*7 364.452*	*10 241.252*	*8 193.188*	*12 704.937*	*18 304.088*	*24 673.224*
63	*963.495*	*1 481.341*	*2 108.786*	*2 925.388*	*2 344.180*	*3 623.777*	*5 208.858*	*7 009.536*
75	*383.322*	*587.368*	*834.011*	*1 154.409*	*926.427*	*1 428.060*	*2 048.308*	*2 751.977*
90	*153.473*	*234.322*	*331.776*	*458.088*	*368.237*	*565.794*	*809.509*	*1 085.536*
110	*56.456*	*85.848*	*121.156*	*166.789*	*134.341*	*205.618*	*293.286*	*392.352*
125	*29.973*	*45.463*	*64.028*	*87.975*	*70.952*	*108.322*	*154.188*	*205.933*
140	*17.139*	*25.941*	*36.469*	*50.025*	*40.391*	*61.527*	*87.417*	*116.580*
160	*8.895*	*13.431*	*18.843*	*25.799*	*20.857*	*31.690*	*44.929*	*59.812*
200	*2.974*	*4.475*	*6.259*	*8.545*	*6.922*	*10.475*	*14.801*	*19.648*
250	*1.007*	*1.510*	*2.107*	*2.869*	*2.328*	*3.511*	*4.946*	*6.548*
315	*0.271*	*0.406*	*0.565*	*0.767*	*0.623*	*0.937*	*1.316*	*1.738*
355	*0.152*	*0.228*	*0.317*	*0.430*	*0.349*	*0.525*	*0.736*	*0.971*
400	*0.086*	*0.128*	*0.178*	*0.241*	*0.196*	*0.294*	*0.412*	*0.544*

Source: Radley (2000)

3.3.4 Water Budget Input Parameters

All relevant input parameters that are necessary in the calculation of the water for maize and wheat are included in this section. Maize is a short grower with a growing period of 120 days while a spring type wheat cultivar is used with a growing period of 148 days. Weather data for 49 years are obtained from Van Heerden (2012). The data of the C92B weather station are used in the SWIP-E model to calculate crop water use of maize and wheat. The weather station is situated in a dry and hot climate in the Douglas, Northern Cape area. The weather data include rainfall and potential evapotranspiration (ET0) on a daily basis for maize and wheat. However, rainfall is assumed to be zero in the analysis, because if the rainfall is included in the analysis the critical assumption is made that the decision maker knows exactly when and how much it is going to rain during the planning period. The implication is that the optimised irrigation schedules will be based on 100% effective rainfall. Ultimately, effective rainfall is determined by the soil water status which is determined during optimisation. Thus, it is difficult to include rainfall in the model. Some form of stochastic programming is necessary to incorporate rainfall into the model. Given the size and complexity of the model, it was decided to assume zero rainfall. The average ET0 and rainfall for a period of 49 years is used. Potential evapotranspiration (ET0) together with the Kc values are used to calculate maximum evapotranspiration in Excel©. Equation (3.29) is used to calculate maximum evapotranspiration (ETM) for each crop considered in the model:

$$etm_{c,i} = et0_{c,i} \times kc_c \tag{3.29}$$

The SWIP-E model uses the single crop coefficient (Kc) to calculate maximum evapotranspiration. The single crop coefficient approach combines the effect of crop transpiration and soil evaporation into a single Kc coefficient. The dual crop coefficient (basal crop coefficient and soil water evaporation coefficient) values were collected from Van Heerden (2012). In order to calculate the single crop coefficient, the average daily Kc value of a 49 year period was used. The Kc value is constant in the initial and mid-season growth stages. In the crop development and late-season growth stages the Kc value was calculated using interpolation.

In addition to weather data inputs regarding the soil, root development, yield response factors and water allocation are also required. A high and low water holding capacity soil with a depth of 1.2m is used in the analysis with water holding capacity (WHC) of 100mm/m and 130mm/m, respectively. The initial depletion of both of the soils was taken as 50% depletion to calculate the RWC and BRWC on the first day of the water budget. Only a portion of TAM is readily available for crop consumption therefore the P-value (Dominguez *et al.,* 2012) of maize and wheat was calculated on a daily basis. Table 3.7 illustrates the parameters for calculating the P-value of the different crops. Wheat and maize are in group three and four, respectively.

Table 3.7: Parameter inputs for calculating P-value of different crops

Group	Crops	A	B	C
1	**Onion, Pepper, Potato**	*0.85*	*1.585*	*0.405*
2	**Banana, Cabbage, Grape, Pea, Tomato**	*0.786*	*3.501*	*0.472*
3	**Alfalfa, Bean, Citrus, Groundnut, Pineapple, Sunflower, Watermelon, Wheat**	*0.692*	*6.657*	*0.542*
4	**Cotton, Maize, Olive, Safflower, Sorghum, Soybean, Sugar beet, Sugarcane, Tobacco**	*0.606*	*11.86*	*0.602*

Source: Dominguez, De Juan, Tarjelo, Martinez and Martinez-Romera (2012)

The root development of the maize and wheat was collected from Van Heerden (2012). The root growth for maize and wheat was 0.3m for the initial stage and developed from 0.3m to 1.2m between the crop development and mid-season stage which is the maximum root growth for maize and wheat. As the roots of the crop develop the ground cover, crop height and the leaf area change. The growing period can be divided into four distinct growth stages, namely, initial, crop development, mid-season and late season.

Yield response factors are crop specific and vary over the growing season according to the growth stages. If Ky is greater than one the crop response is very sensitive to water deficit with proportional larger yield reductions when water is reduced because of stress. If Ky values are smaller than one the crop is more tolerant to water deficits and recovers partially from stress resulting in less than proportional reductions in yield with reduced water use. If Ky values equal to one the yield reduction is directly proportional to reduced water use. The yield response factors (Ky coefficients) and the length of the stages (Ky days) are based on values proposed in Doorenbos and Kassam (1979). Table 3.8 represents the yield response factors (Ky-factors) and the length of the Ky and Kc days for maize and wheat in each growth stage. Potential yield in the Douglas area for maize and wheat cultivated under irrigation is assumed as 17ton/ha and 8ton/ha, respectively.

Table 3.8: Length of Kc and Ky days and yield response factors for the different growth stages of maize and wheat grown in the Douglas area

		Initial	Crop development	Mid-season	Late-season
Length of Kc-days	**Maize**	*21*	*26*	*63*	*10*
	Wheat	*28*	*47*	*63*	*10*
Length of Ky-days	**Maize**	*50*	*15*	*45*	*10*
	Wheat	*91*	*17*	*30*	*10*
Ky-Factors	**Maize**	*0.4*	*1.5*	*0.5*	*0.2*
	Wheat	*0.2*	*0.6*	*0.5*	*0.1*

Source: Van Heerden (2012)

Non-uniformity of irrigation applications are modelled through the inclusion of five water budgets. Two water budgets received more than the average while two received less than the average amount of water. The applied irrigation for each of the five water budgets was calculated by multiplying the average applied water with a scaling factor (cu scale). Table 3.9 represents the scaling factors that were used in the water budgets.

Table 3.9: Scaling factors for adjusting irrigation applications for modelling non-uniformity with the SWIP-E model

Water Budgets	Scaling Factor
Lower2	*0.76*
Lower	*0.88*
Normal	*1*
Upper	*1.12*
Upper2	*1.24*

Source: Van Heerden (2012)

The water allocation for the Douglas area is 1 000mm/ha (10 000m^3/ha). The assumption is made that the calculated irrigation amount will not exceed 15mm/cycle within an irrigation cycle of two days, due to the infiltration ratio of the soils and the application ratio of the pivot at the overhang.

CHAPTER 4

RESULTS, DISCUSSIONS AND CONCLUSIONS

4.1 Introduction

In this chapter, the procedures described in Chapter 3 are applied to model the economic trade-off between investment and operating costs to determine the optimal pipe diameter of an irrigation system main pipeline. The first section describes the economic trade-off between investment and operating costs for Ruraflex and Landrate. The second section describes management implications of using Ruraflex and Landrate. The analysis was done for two electricity tariffs, eight different irrigation system designs and a high and low water holding capacity soil for a crop rotation system consisting of maize and wheat. The results for the high water holding capacity soil were very similar to the low water holding soil and are not reported as part of this chapter. The results are provided in Appendix B.

4.2 Economic Trade-off between Investment Costs and Operating Costs

The results obtained from the economic evaluation for pipe investments are presented in this section. The section includes the results obtained for Ruraflex and Landrate as well as a comparison between Ruraflex and Landrate.

4.2.1 Ruraflex

Table 4.1 shows the design parameters, investment and electricity costs as well as the profitability of Ruraflex for the eight different irrigation systems included in the analysis for a low water holding capacity of 100mm/m. The irrigation systems include a small (30.1ha) and large (47.7ha) center pivot with irrigation system delivery capacities ranging from 8mm/day to 14mm/day. If irrigation system delivery capacities increase from 8mm/day to 14mm/day the flow rates increase from 100.5m^3/h to 178m^3/h for the small center pivot and from 158.9m^3/h to 278m^3/h for the large center pivot. Low system delivery capacities (8mm/day and 10mm/day) resulted in thinner optimal pipe diameters when compared to higher system delivery capacities (12mm/day and 14mm/day). For example, the most economical pipe diameter for the low system delivery capacities for the small center pivot is 200mm while a 250mm pipe diameter is optimal for the higher system delivery capacities. Larger pipe diameters are optimal for the large center pivot compared to the small center pivot when comparing systems with the same delivery capacities. The optimal pipe diameters increase by 50mm and 65mm respectively for low and high system delivery capacities

Table 4.1: Optimised design parameters, investment and electricity costs for different irrigation systems using Ruraflex for a 100mm/m water holding capacity, 2014

	Center Pivot Size (ha)							
	Small (30.1)				Large (47.7)			
	Irrigation System Delivery Capacity (mm/day)				Irrigation System Delivery Capacity (mm/day)			
	8	10	12	14	8	10	12	14
	DESIGN PARAMETERS							
Flow Rate (m^3/h)	*100.5*	*125.5*	*150.5*	*178*	*158.9*	*198.6*	*239*	*278*
Outside Diameter (mm)	*200*	*200*	*250*	*250*	*250*	*250*	*315*	*315*
Friction (m)	*2.974*	*4.475*	*2.107*	*2.869*	*2.328*	*3.511*	*1.316*	*1.738*
Friction percentage (%)	*0,4*	*0,6*	*0,28*	*0,38*	*0,31*	*0,47*	*0,18*	*0,23*
Total pressure (m)	*36*	*39*	*38*	*38*	*37*	*41*	*41*	*45*
Kilowatt (kW)	*13*	*18*	*20*	*23*	*21*	*28*	*33*	*42*
Kilowatt hours (kWh)	*39 610*	*42 234*	*40 436*	*40 039*	*62 197*	*66 395*	*65 975*	*71 335*
	INVESTMENT AND ELECTRICITY COSTS							
Pipe Investment (R)	*112 853*	*112 853*	*179 895*	*179 895*	*179 895*	*179 895*	*276 158*	*276 158*
Pivot Investment (R)	*638 483*	*669 000*	*723 186*	*739 654*	*815 452*	*835 239*	*842 405*	*930 818*
Pump Investment (R)	*14 368*	*21 655*	*20 661*	*20 661*	*20 661*	*22 216*	*22 216*	*22 216*
Total Investment Costs (R)	*765 704*	*803 518*	*923 742*	*940 210*	*1 016 008*	*1 037 350*	*1 122 779*	*1 229 192*
Total Variable Electricity Costs (R)	*541 411*	*549 204*	*508 959*	*494 362*	*849 125*	*865 063*	*832 717*	*883 347*
Total Fixed Electricity Costs	*307 099*	*307 099*	*307 099*	*307 099*	*307 099*	*307 099*	*394 056*	*394 056*
Total Electricity Costs (R)	*848 510*	*856 303*	*816 058*	*801 461*	*1 156 224*	*1 172 162*	*1 226 773*	*1 277 404*
Net Present Value (R)	*4 858 514*	*4 857 930*	*4 852 137*	*4 905 564*	*8 304 887*	*8 356 438*	*8 330 847*	*8 198 284*
Net Present Value (R/ha)	*161 412*	*161 393*	*161 201*	*160 838*	*174 107*	*175 187*	*174 651*	*171 872*

when increasing center pivot size. These changes in pipe diameters are a direct result of the higher flow rates associated with larger pivots.

Changes in pipe diameter and flow rate (delivery capacity) have a direct impact on the kilowatt requirement to drive the water through the system and therefore operating costs. If the pipe diameter stays the same friction increases as the flow rates increase, resulting in an increase in the kilowatt requirement. Friction increases from 2.974m to 4.475m if the flow rates increase from 100.5m^3/h to 125.5m^3/h resulting in an increase in the kilowatt requirement of 5kW. The optimal pipe diameter increases when flow rate increased from 125.5m^3/h to 150.5m^3/h which resulted in a decrease in friction even though the flow rates increase. Larger pipe diameters reduce friction loss and therefore total pressure with lower kilowatt requirements while increases in flow rate will cause an increase in kilowatt requirement. The direction of change in kilowatt requirement is therefore not self-evident if pipe diameter is increased in conjunction with an increase in flow rate. The results show that the kilowatt requirement will increase, but less proportional. For example, if the flow rate is increased from 125.5m^3/h to 150.5m^3/h for the small center pivot the friction decreases from 4.475m to 2.107m resulting in an increase in kilowatt requirement of 2kW. The same observation is made for the large center pivot. The percentage friction followed the same trend as the friction loss since the length of the main pipeline is constant. Important to note is that the percentage friction loss is much less than the norm of 1.5%. The results show that friction loss as a percentage of the length of the pipe never exceeds 0.6%. The implication of using the 1.5% norm is that thinner pipe diameters would be used which decrease investment cost but at the same time operating cost (electricity costs) is increased. Thus, increasing electricity costs will have a significant effect on profitability of irrigation systems if thinner pipes are used.

The results show that variable electricity costs increase as flow rate increases if the optimal pipe diameter stays the same. However, variable electricity costs decrease if the optimal pipe diameter increases in conjunction with flow rate increases. For example, if the flow rate increases from 158.9m^3/h to 198.6m^3/h, variable electricity costs increase from R 849 125 to R 865 063 when pipe diameter is constant and decrease from R 865 063 to R 832 717 if the flow rate increases to 239m^3/h and the optimal pipe diameter increases. Generalisations are, however, not possible since variable electricity costs decreased between the 12mm/day and 14mm/day irrigation system delivery capacities for the small center pivot even though pipe diameter stayed the same. The reason for the decrease in variable electricity costs is that the increase in kilowatt requirement is less than the decrease in irrigation pumping hours associated with irrigating with higher system delivery capacities which resulted in a decrease in kilowatt hours (kWh). The kilowatt hours decreased with 397kWh (40 436kWh – 40 039kWh) which caused a decrease in variable electricity costs of R 14 597 (R 508 959 – R 494 362) between the 12mm/day and 14mm/day irrigation system delivery capacities for the small center pivot. The interaction between kilowatt requirement and the pumping hours emphasises the importance of appropriately modelling the interaction between irrigation system design and management. Fixed electricity costs are the same (R 307 099) for all the irrigation systems except for the high irrigation system delivery capacities (12mm/day and 14mm/day) for the large center pivot due to a higher kilovolt-ampere point. The fixed electricity cost for the high system delivery capacity for the large center pivot is R 394 056 due to a 75KVA point. Total electricity costs for the large center pivot increase as flow rates increase due to the increase in fixed electricity costs.

Net present value (NPV) decreases as flow rate increases for the small center pivot with an exception for an increase between the 12mm/day and 14mm/day delivery capacities. The increase is due to a slightly larger irrigated area (ha) which causes total NPV to increase. However, NPV per hectare decreases as flow rate increases for the small center pivot. Increasing investment costs resulted in a decrease in NPV per hectare. The 8mm/day delivery capacity resulted in the most profitable irrigation system delivery capacity for the small center pivot. The NPV of the large center pivot increased between the 8mm/day and 10mm/day irrigation system delivery capacities and decreases for delivery capacities above 10mm/day. The 10mm/day delivery capacity resulted in the highest NPV for the large center pivot. Even though electricity costs and investment costs increased between the 8mm/day and 10mm/day delivery capacity, the NPV is highest for the 10mm/day delivery capacity because the crop yield for wheat was slightly higher resulting in higher gross margins. Again the increase in total investment costs is responsible for the decreasing trend in NPVs for irrigation system delivery capacities above 10mm/day for the large center pivot.

4.2.2 Landrate

Table 4.2 shows the design parameters, investment and electricity costs for Landrate for the eight different irrigation systems included in the analyses for a low water holding capacity of 100mm/m. The smallest irrigation system delivery capacity (8mm/day) resulted in a thinner optimal pipe diameter as compared to higher irrigation system delivery capacities (10, 12, 14mm/day) for both the center pivot sizes. Increasing the irrigation system delivery capacity above 8mm/day increased the optimal pipe diameter with 50mm and 65mm respectively for the small and large center pivot. The larger center pivot resulted in a larger optimised pipe diameter compared to a smaller center pivot with the same delivery capacity. The larger pipe diameters of the large center pivot directly contributed to the result of higher flow rates associated with larger center pivots. For example, the optimal pipe diameter for the 8mm/day irrigation system delivery capacity is 200mm while the optimal pipe diameter for the larger center pivot with the same irrigation system delivery capacity is 250mm.

The impact of pipe diameter and flow rate on the kilowatt requirement of an irrigation system is discussed next. If an increase in the pipe diameter occurs, friction decreases even though flow rate increases irrespective of center pivot size. However, a less than proportional increase in kilowatt requirement occurs due to a decrease in friction. For example, the friction loss decreased from 2.974m to 1.51m even though flow rate increased from 100.5m^3/h to 125.5m^3/h. The reduction in friction is because of the increase in pipe diameter. The net effect of the reduction in friction and the increase in flow rate causes kilowatt to increase with only 3kW for the small center pivot. Notwithstanding, the size of the center pivot friction in the main pipeline increases if flow rate increases when the pipe diameter is kept constant which causes an increase in the kilowatt requirement of an irrigation system. Increasing the flow rate from 125.5m^3/h to 150.5m^3/h increases the friction to 2.869m which increased the kilowatt requirement to 20kW. The percentage friction in all the cases considered is more than one percentage point lower than the norm of 1.5%.

The results for the large center pivot show that the variable electricity costs are constant for an increase in irrigation system delivery capacity between 8mm/day and 10mm/day whereas variable electricity costs show an increasing trend for irrigation system deliveries above 10mm/day. Changes in variable electricity costs are the direct result of the interaction between kilowatt requirement and pumping hours as measured by kilowatt hours (kWh). Increasing delivery capacity will reduce pumping hours but at the same time increase kilowatt requirement due to higher friction given the pipe diameter is not changed. The increasing trend in variable electricity cost is observed because kilowatt changes are the dominant factor affecting variable electricity costs for the large center pivot. Contradictory to the results of the large pivot the variable electricity costs of the small pivot decrease if the optimal pipe diameter increases when irrigation system delivery capacity increases to 10mm/day. Furthermore, no trend is observable if irrigation delivery capacities are increased above 10mm/day and the optimal pipe diameter is 250mm. The changes in kilowatt due to changes in flow rate are much smaller for the small pivot due to the relatively lower flow rates of the smaller pivots. As a result, the interaction between reduced pumping hours and increasing kilowatts associated with increasing irrigation system delivery capacities is much more important in determining the impact thereof on variable electricity costs. Fixed electricity costs stayed the same between the irrigation systems included in the analyses because the fixed electricity costs are independent of the size of an irrigation system.

The results of the NPVs indicate that the larger center pivot is more profitable than the smaller center pivot. The pivot with the 8mm/day delivery capacity is, however, the most profitable of the alternative delivery capacities considered. The net present value decreases if irrigation system delivery capacity increases above 8mm/day for both center pivot sizes with an exception for an increase between the 12mm/day and 14mm/day delivery capacity for the small center pivot. The increase in net present value is due to 0.4ha larger irrigated area for the 14mm/day irrigation system delivery capacity. Increasing investment costs are the major factor affecting the decrease in profitability of the irrigation system with higher delivery capacities.

Table 4.2: Optimised design parameters, investment and electricity costs for different irrigation systems using Landrate for a 100mm/m water holding capacity, 2014

	Center Pivot Size (ha)							
	Small (30.1)				**Large (47.7)**			
	Irrigation System Delivery Capacity (mm/day)				**Irrigation System Delivery Capacity (mm/day)**			
	8	**10**	**12**	**14**	**8**	**10**	**12**	**14**
	DESIGN PARAMETERS							
Flow Rate (m^3/h)	*100.5*	*125.5*	*150.5*	*178*	*158.9*	*198.6*	*239*	*278*
Outside Diameter (mm)	*200*	*250*	*250*	*250*	*250*	*315*	*315*	*315*
Friction (m)	*2.974*	*1.510*	*2.107*	*2.869*	*2.328*	*0.937*	*1.316*	*1.738*
Friction percentage (%)	*0.4*	*0.2*	*0.28*	*0.38*	*0.31*	*0.12*	*0.18*	*0.323*
Total pressure (m)	*36*	*36*	*38*	*38*	*37*	*38*	*41*	*45*
Kilowatt (kW)	*13*	*16*	*20*	*23*	*21*	*26*	*33*	*42*
Kilowatt hours (kWh)	*39 610*	*39 012*	*40 436*	*40 039*	*62 197*	*62 197*	*65 975*	*71 335*
	INVESTMENT AND ELECTRICITY COSTS							
Pipe Investment (R)	*112 853*	*179 895*	*179 895*	*179 895*	*179 895*	*276 158*	*276 158*	*276 158*
Pivot Investment (R)	*638 483*	*669 000*	*723 186*	*739 654*	*815 452*	*835 239*	*842 405*	*930 818*
Pump Investment (R)	*14 368*	*21 655*	*20 661*	*20 661*	*20 661*	*22 216*	*22 216*	*22 216*
Total Investment Costs (R)	*765 704*	*870 550*	*923 742*	*940 210*	*1 016 008*	*1 133 613*	*1 122 779*	*1 229 192*
Total Variable Electricity Costs (R)	*652 227*	*642 380*	*665 826*	*659 281*	*1 024 147*	*1 024 146*	*1 086 340*	*1 174 613*
Total Fixed Electricity Costs	*379 993*	*379 993*	*379 993*	*379 993*	*379 993*	*379 993*	*379 993*	*379 993*
Total Electricity Costs (R)	*1 032 220*	*1 022 373*	*1 045 819*	*1 039 275*	*1 404 140*	*1 404 139*	*1 466 334*	*1 554 607*
Net Present Value (R)	*4 796 388*	*4 724 886*	*4 643 845*	*4 730 731*	*8 141 881*	*8 055 133*	*7 973 632*	*7 769 924*
Net Present Value (R/ha)	*159 348*	*156 973*	*154 281*	*155 106*	*170 689*	*168 871*	*167 162*	*162 891*

4.2.3 Comparison, Discussion and Conclusion

Electricity tariffs increase between Ruraflex and Landrate. Ruraflex is a time-of-use tariff which provides lower tariffs when the demand for electricity is low whereas Landrate has a flat rate which is relatively high. The results show that the higher electricity tariff of Landrate causes optimal pipe diameters to increase more rapidly when increasing irrigation system delivery capacity. For both the center pivot sizes the increase in optimal pipe diameters occurred when increasing delivery capacities to 10mm/day for Landrate while the change occurred at 12mm/day for Ruraflex. The larger pipe diameters of the 10mm/day systems cause friction loss to decrease resulting in a decrease in kilowatt requirement of 2kW for both center pivot sizes when comparing Landrate to Ruraflex. The conclusion is that failure to consider electricity tariffs when designing irrigation mainlines may result in suboptimal designs which will increase electricity costs.

SABI accredited designers are allowed to design irrigation systems such that the friction as a percentage of the length of the pipeline does not exceed 1.5%. In order to test the norm, the friction percentages were calculated while assuming that it is not optimal to increase pipe diameter between the 10mm/day and 12mm/day systems for Ruraflex and 8mm/day and 10mm/day systems for Landrate. The results of the calculations are shown in Table 4.3. The percentage friction increased from 0.6% to 0.83% and from 0.47% to 0.66% respectively for the small and large center pivot if the flow rates were increased while the pipe diameter remained constant for Ruraflex. The breakeven percentage friction that will cause pipe diameter to increase is therefore between 0.6% and 0.66%. With Landrate the percentage friction increased from 0.4% to 0.6% and from 0.31% to 0.47% respectively for the small and large center pivot if the flow rates were increased from 8mm/day to 10mm/day. The range in which the breakeven percentage friction will be is 0.4% to 0.6% which is lower when compared to Ruraflex. Such a result is expected because Landrate electricity charges are relatively higher than Ruraflex and therefore it is optimal to increase pipe diameters more quickly. The conclusion is that electricity tariffs have a significant impact on breakeven percentage friction. The breakeven point is furthermore much lower than the norm of 1.5%.

Table 4.3: Friction losses from not using optimal pipe diameters for a small and large center pivot

	Center Pivot Size (ha)			
	30.1		**47.7**	
	Ruraflex			
Flow Rate (m^3/h)	125.5	150.5	198.6	239
Outside Diameter (mm)	200	200	250	250
Friction (m)	4.475	6.259	3.511	4.946
Friction percentage (%)	0.6	0.83	0.47	0.66
	Landrate			
Flow Rate (m^3/h)	100.5	125.5	158.9	198.6
Outside Diameter (mm)	200	200	250	250
Friction (m)	2.974	4.475	2.328	3.511
Friction percentage (%)	0.4	0.6	0.31	0.47

An important factor that determines total variable electricity costs is the product of kilowatt and pumping hours. Pumping hours are reduced if the irrigation system delivery capacity is increased. The degree of reduction is almost the same between the small and large center pivots. However, significant differences exist between the small and large center pivot in terms of increasing kilowatt requirements associated with increasing delivery capacities. Kilowatt requirements increase with 10kW and 21kW respectively for the small and large center pivot. The magnitude of the increase in kilowatt requirement for the large pivot causes the kilowatt hours to increase even though pumping hours are reduced with increasing delivery capacities. The relatively small change in kilowatt requirements necessary to increase delivery capacity for the small pivot causes kilowatt hours not to increase significantly with increasing delivery capacity. The direction of change in the kilowatt hours for the small center pivot depends more on the interaction between increasing kilowatt requirement and decreasing pumping hours resulting from increasing delivery capacities. Thus, the conclusion is that the interaction between kilowatt requirement and irrigation management (hours) becomes more significant for smaller irrigated areas in determining variable electricity costs.

The total variable electricity costs of Landrate are higher for all the alternatives when compared to Ruraflex even though the kilowatt requirement of the 10mm/day irrigation systems is 2kW less with Landrate. Higher total variable electricity costs are a direct result of the higher electricity tariff rate associated with Landrate. However, it is important to include fixed electricity costs since the fixed electricity costs differ between electricity tariff structures. Fixed electricity costs for Landrate are higher compared to Ruraflex, except for the 12mm/day and 14mm/day delivery capacity for the large center pivot. Landrate's fixed electricity tariffs are greater than Ruraflex's tariff. However, Ruraflex's network access tariff depends on the size of kilovolt-ampere (KVA), thus, higher kilovolt-amperes will result in higher fixed electricity costs. The fixed electricity costs for the

8mm/day delivery capacity for the large center pivot using Landrate is R 379 993 and R 307 099 for Ruraflex, while the fixed electricity costs for Ruraflex increase to R 394 056 for the 12mm/day and 14mm/day delivery capacity for the large center pivot. The increase is due to a kilovolt-ampere increase of 25KVA between the 10mm/day and 12mm/day delivery capacity for the large center pivot using Ruraflex.

The conclusion is that Ruraflex is more profitable than Landrate irrespective of pivot size and irrigation system delivery capacity since all the irrigation systems included in the analyses resulted in higher net present values using Ruraflex which is a direct result of lower electricity costs associated with Ruraflex. Furthermore, the larger center pivot resulted in higher NPVs per hectare compared to the small center pivot because as the center pivot size increases the total investment costs per hectare decrease since the total investment costs are divided by a larger number (hectares). Smaller delivery capacities (8mm/day) are the most profitable for both of the center pivot sizes and electricity tariff structures, except for the large center pivot using Ruraflex where the 10mm/day delivery capacity had the highest NPV.

4.3 Management Implications

Table 4.3 shows the optimised pumping hours for the alternative irrigation system designs using either Ruraflex or Landrate electricity tariffs. Total optimal pumping hours decrease as flow rate increases between irrigation system delivery capacities for both the center pivot sizes. Higher flow rates can apply more water in one hour, thus, less irrigation hours are necessary to apply the same amount of irrigation water.

Small variations in total irrigation hours are present between the center pivot sizes for a given irrigation system delivery capacity. Total irrigation hours for the 8mm/day delivery capacity using Ruraflex is 2 995hours for the small center pivot and 3 002hours for the large center pivot. The total irrigation hours for a given irrigation system delivery capacity and pivot size is exactly the same for the two electricity tariffs because the full water allocation was used for irrigation. However, the distribution of total pumping hours between maize and wheat is different between the two electricity tariffs for irrigation system delivery capacities smaller than 12mm/day. With Ruraflex the total pumping hours for maize is more while the pumping hours for wheat are less when compared to the pumping hours of these two crops under Landrate. The shift in irrigation hours towards maize is to reduce pumping of water during the portion of wheat's growing season that falls in the high energy demand season when the Ruraflex electricity tariff is very high. The results further show that the pumping hours in each of the time-of-use timeslots are less than the available pumping hours in a specific timeslot. The last mentioned is because the timing and magnitude of water applications are dictated by the status of the crop which is related to the soil water availability. The distribution of pumping hours within each of the time-of-use timeslots shows that maize is mostly irrigated during off-peak and standard time, while wheat needs to be irrigated during peak times when considering irrigation system delivery capacities below 12mm/day. The value of the marginal product is much higher than the marginal factor cost of applying irrigation water, therefore it is profitable to irrigate during peak timeslots. For irrigation system deliveries above 10mm/day the capacities are such that enough water could generally be applied to minimise irrigation during peak timeslots.

The conclusion is that careful consideration of the economics is necessary since smaller delivery capacities require much more intensive management, because longer irrigation hours are needed in order to avoid a decrease in crop yield. The timing of irrigation is of utmost importance since it has a direct effect on electricity costs and crop yield. The assumption made by various researchers and irrigation designers that all available off-peak hours will be used first before irrigation will take place in more expensive time-of-use timeslots is void by the fact that the water budget and the status of the crop will determine irrigation timing and amounts.

Table 4.4: Optimised irrigation hours for different irrigation systems using a 100mm/m water holding capacity for Ruraflex and Landrate

			Center Pivot Size (ha)							
			Small (30.1)				**Large (47.7)**			
			Irrigation System Delivery Capacity (mm/day)							
			8	**10**	**12**	**14**	**8**	**10**	**12**	**14**
Irrigation Hours	***Maize***	***OP***	*880*	*880*	*827*	*749*	*880*	*880*	*827*	*749*
		ST	*599*	*285*	*140*	*81*	*608*	*287*	*138*	*82*
		PE	*5*	*9*	*2*	*0*	*0*	*9*	*2*	*0*
	Wheat	***OP***	*855*	*783*	*728*	*677*	*855*	*784*	*727*	*678*
		ST	*510*	*419*	*301*	*206*	*510*	*420*	*299*	*207*
		PE	*146*	*22*	*3*	*0*	*149*	*22*	*3*	*0*
Total Irrigation Hours (Ruraflex)	***Maize***		*1 484*	*1 174*	*969*	*830*	*1 488*	*1 176*	*967*	*831*
	Wheat		*1 511*	*1 224*	*1 032*	*883*	*1 514*	*1 226*	*1 029*	*885*
	Total (Season)		*2 995*	*2 398*	*2 001*	*1 713*	*3 002*	*2 402*	*1 996*	*1 716*
Total Irrigation Hours (Landrate)	***Maize***		*1 449*	*1 159*	*969*	*829*	*1 453*	*1 162*	*966*	*831*
	Wheat		*1 546*	*1 239*	*1 032*	*884*	*1 549*	*1 240*	*1 030*	*885*
	Total (Season)		*2 995*	*2 398*	*2 001*	*1 713*	*3 002*	*2 402*	*1 996*	*1 716*

*OP: Off-Peak

*ST: Standard

*PE: Peak

CHAPTER 5

SUMMARY AND RECOMMENDATIONS

5.1 Summary

Ever increasing electricity costs are a serious threat to the sustainability of irrigation farmers. Operating practises and irrigation system designs create opportunities for irrigation farmers to lower the effect of increasing electricity costs. However, the complex interrelated relationships between irrigation management, irrigation system design and choice of electricity tariffs make it difficult to provide decision support to manage electricity costs. An inverse relationship exists between lowering investment costs by using smaller pipe diameters and increasing operating costs due to increasing kilowatt requirements to overcome the addition friction of using smaller pipe diameters. In the past irrigation main pipelines were designed to minimise investment costs because electricity costs were relative cheap and irrigators did not mind the higher electricity costs. Recent increases in electricity costs have renewed the importance of managing electricity costs which requires careful consideration of the trade-off between irrigation main pipeline investments and the total operating costs resulting from irrigation mainline design and management practices.

The unavailability of an integrated model that is able to model the interaction between irrigation management, irrigation system design and the choice of electricity tariffs further hampers decision support for improved energy and water management in irrigated agriculture. Consequently, irrigators are currently unsure about the trade-off between irrigation system investment costs and the resulting energy costs as well as the optimal management requirements of irrigation system investments. The main objective of this research was to develop an integrated non-linear programming model that unifies the interrelated linkages between mainline pipe diameter choice and the timing of irrigation events in conjunction with electricity tariff choice to facilitate better evaluation of the economic trade-offs of irrigation pipe investments for improved energy management.

The Soil Water Irrigation Planning and Energy Management (SWIP-E) programming model was developed to address the main objective of the research. A unique characteristic of the model is that irrigation pumping hours are determined through a daily soil water budget while simultaneously considering the time-of-use electricity tariff structure and changes in kilowatt requirements resulting from mainline design changes. SWIP-E was applied in Douglas, Northern Cape to evaluate the impact of electricity tariff structure choice, center pivot size and irrigation system delivery capacity on economically optimal pipe diameters, associated electricity costs and overall profitability.

The results showed that Ruraflex is more profitable than Landrate irrespective of the center pivot size and irrigation system delivery capacities. The average net present value for the small center pivot is R 4 868 536 for Ruraflex and R 4 723 962 for Landrate while the average NPV for the large center pivot was R 8 297 614 and R 7 985 143 for Ruraflex and Landrate, respectively. The larger center pivot resulted in higher NPVs compared to the small center pivot. The average NPV per hectare using Ruraflex was R 173 954 and R 161 211 for the large and small center pivot, respectively. Smaller delivery capacities (8mm/day) resulted in the highest NPV for both of the center pivot sizes and electricity tariff structures, except for the large center pivot using Ruraflex where the 10mm/day delivery capacity had the highest NPV. The conclusion is that Ruraflex and larger center pivot sizes are more profitable than Landrate and smaller center pivot sizes respectively. Another conclusion is that smaller irrigation system delivery capacities are more profitable compared to larger delivery capacities which is in contrast to the observation in the field where larger system delivery capacities are more commonly found. However, careful consideration of the management implications of smaller delivery capacities is necessary before recommending low delivery capacities.

The results of the management implications showed that small variation in total irrigation hours between center pivot sizes was observed for a given irrigation system delivery capacity. Furthermore, the results showed that total irrigation hours were exactly the same between electricity tariff structures. However, variation in total pumping hours between maize and wheat were observed. Irrigation of maize was mostly in off-peak and standard hours while irrigation of wheat was in off-peak, standard and peak timeslots when considering small irrigation system delivery capacities. The conclusion is that smaller irrigation system delivery capacities require much more intensive management and information to balance the cost of applying water with the possibility of crop yield reductions. Another conclusion is that irrigation designers cannot assume that all the available off-peak hours will be used first because the status of the soil water budget and crop will determine when and how much to irrigate.

The interaction between mainline design (kW) and management (pumping hours) are very important in explaining total variable electricity costs because a large portion of the electricity tariff is paid for the kilowatt hour consumed. The magnitude of the increased kilowatt requirement and decrease in pumping hours will determine the impact on kilowatt hours when increasing delivery capacity. The results show that the decrease in irrigation hours resulting from increasing delivery capacity is almost the same between the center pivot sizes. On the other hand, the increase in kilowatt requirement for larger center pivots is much more significant compared to the small center pivot when increasing delivery capacity from 8mm/day to 14mm/day. As a result, the impact of increasing delivery capacity on kilowatt hours is mixed for the small pivot whereas the kilowatt hours will increase for the large center pivot. The conclusion is that the importance of the interaction between kilowatt requirement and irrigation management is much more profound for small center pivots.

The optimal irrigation mainline design results showed that the higher electricity tariff associated with Landrate causes the optimal pipe diameter to change at lower delivery capacities. The optimal pipe diameter changed if the delivery capacity increased to 10mm/day for Landrate and to 12mm/day for Ruraflex. The breakeven percentage friction that will cause the pipe diameter to increase is between 0.6% and 0.66% for Ruraflex and between 0.4% and 0.6% for Landrate which is much lower than the design norm of 1.5%. The conclusion is that the electricity tariff structure should be considered when an irrigation mainline is designed since the electricity tariff structure may increase electricity costs which has an effect on the optimal pipe diameter. Furthermore, the conclusion is that the design norm of 1.5% friction is too high which will result in non-optimal pipe diameters with low investment costs and high electricity costs.

5.2 Recommendations

5.2.1 Irrigation System Design

- It is recommended that the SABI design norm must be lowered to ensure that there is a better balance between investment and operating costs. Lowering the norm will decrease operating costs while increasing the investment costs. However, applying a stricter norm will ensure that pipe diameter is closer to the optimal pipe diameter.

- Irrigation designers should apply economic principles when designing irrigation mainline designs since it will increase the overall profitability of the investment compared to applying the friction percentage design norm. Applying economic principles will automatically differentiate between electricity tariff structures (Ruraflex and Landrate) when designing an irrigation system.

- Irrigation designers should include both the investment costs and an estimate of the operating costs of the irrigation system design in order to allow farmers to make informed decisions.

- It is further recommended that SABI should oversee the development of software to support irrigation designers to apply economic principles when designing irrigation mainlines.

5.2.2 Further Research

- It is recommended that risk is included in the SWIP-E model in order to evaluate the risk associated with smaller irrigation system delivery capacities in combination with load shedding.

- The SWIP-E model can be further expanded to include a combination of irrigation systems, which imply that more than one operating point will exist. Multiple operating points will have an effect on the kilowatt requirement at the pumping station, electricity costs and irrigation water management.

- The model furthermore provides a powerful basis to evaluate the profitability of new technology such as variable speed drives, energy efficient pumps and motors as well as modification of existing irrigation system designs.

- The SWIP-E model provides a powerful basis for crop water use optimisation for a given irrigation system design. The model may prove invaluable in determining the impact of compulsory licensing of agricultural water use on irrigation farming profitability.

- The model could be expanded to include intra-seasonal competing crops, such as maize and groundnuts, which implies that crops will compete for water during a growing season.

- Lastly, it is recommended that the global optimality of the solutions of the model be tested with a genetic algorithm.

REFERENCES

ALLEN RG and BROCKWAY CE. 1984. Optimizing irrigation system design – Summary report. *Summary report to Department of Agriculture. Agriculture research service cooperative agreement No. 58-OAHZ-9-384.*

ALLEN RG, PEREIRA LS, RAES D and SMITH M. 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. *Irrigation and Drainage Paper No 56. FAO. Rome.*

ARMITAGE RM, LECLER NL, JUMMAN A and DOWE K. 2008. Implementation of the IRRIECON V2 decision support tool to assess net returns to irrigation systems. *Sugarcane Technology Association, 81: 454-465.*

ASCOUGH GW and KIKER GA. 2002. The effect of irrigation uniformity on irrigation water requirements. *Water SA, Vol 28, No. 2.*

BAZILIAN M, ROGNER H, HOWELLS M, HERMANN S, ARENT D, GIELEN D, STEDUTO P, MUELLER A, KOMOR P, TOL RSJ and YUMKELLA KK. 2011. Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy Policy 39: 7896-7906.*

BERNARDO DJ. 1985*. Optimal irrigation management under conditions of limited water supply.* Ph.D. dissertation. Washington State University.

BERNARDO DJ, WHITTLESEY NK, SAXTON KE and BASSET DL. 1987. An irrigation model for managing limited water supplies. *Western Journal and Agricultural Economics, 12: 164 -173.*

BEZUIDENHOUT N. 2012. Verbal communication with the author. University of the Free State. Bloemfontein. South Africa.

BOEHLJE MD and EIDMAN VR. 1984. *Farm Management.* New York: John Wiley and Sons.

BOTES JHF, BOSCH DJ and OOSTHUIZEN LK. 1996. A Simulation and optimization Approach for Evaluating Irrigation Information. *Agricultural Systems, 51: 165-183.*

BOTES JHF and OOSTHUIZEN LK. 1994. The effects of pumping restrictions on irrigation efficiency: implications for Eskom's time-of-use electricity supply to rural areas. *Agrekon 33(4): 248-251.*

BREYTENBACH P. 1994. *‘n Ekonomiese Evaluering van Energiegebruik by Besproeiing in die Wintertongebied met inagneming van Risiko. (Afrikaans).* M.Com Dissertation. Department of Agricultural Economics, University of the Free State. Bloemfontein. South Africa.

BREYTENBACH P, MEIRING JA and OOSTHUIZEN LK. 1996. Die belangrikheid van elektrisiteitskoste by besproeiingsboerdery. (Afrikaans). *Water SA, 22: 333-338.*

BROOKE A, KENDRICK D, MEERAUS A and RAMAN R. 1998. *Gams A user’s guide.* Gams Development Corporation.

BROWN PD, COCHRANE TA and KROM TD. 2010. Optimal on-farm irrigation scheduling with a seasonal water limit using simulated annealing. *Agricultural Water Management. 97: 892-900.*

BUREAU FOR FOOD AND AGRICULTURAL POLICY (BFAP). 2010. The effect of electricity costs on irrigation farming. *National Agricultural Marketing Council, RSA.*

BURGER JH, HEYNS PJ, HOFFMAN E, KLEYNHANS EPJ, KOEGELENBERG FH, LATEGAN MT, MULDER, SMAL HS, STIMIE CM, UYS WJ, VAN DER MERWE FPJ, VAN DER STOEP I and VILJOEN PD. 2003. *Irrigation Design Manual.* ARC-Institute for Agricultural Engineering.

CROSBY CT and CROSBY CP. (1999). SAPWAT: *A Computer Program for Establishing Irrigation Requirements and Scheduling Strategies in South Africa.* WRC Report No. 624/1/99. Water Research Commission, Pretoria, South Africa.

DARSHANA, PANDEY A, OSTROWSKI M and PANDEY RP. 2012. Simulation and optimization for irrigation and crop planning. *Irrigation and Drainage, 61: 178-188.*

DE JAGER JM. 1994. Accuracy of vegetation evaporation ration formulae for estimating final wheat yield. *Water SA, Vol. 20.*

DEPARTMENT OF LABOUR (DOL). 2014. Minimum wage for Farm Worker Sector with effect from 1 March 2014. South Africa.

DERCAS N and VALIANTZAS JD. 2012. Two explicit optimum design methods for a simple irrigation delivery system: Comparative application. *Irrigation and Drainage, 61:10-19.*

DOMINGUEZ A, DE JUAN JA, TARJUELO JM, MARTINEZ RS and MARTINEZ-ROMERO A. 2012. Determination of optimal regulated deficit irrigation strategies for maize in a semi-arid environment. *Agricultural Water Management, 110: 67-77.*

DOORENBOS J and KASSAM AH. 1979. *Yield response to water.* Food and Agriculture Organization of the United States.

DRUD A. 1998. Large scale NLP solver from AKRI Consulting and Development*. AKRI Consulting and Development A/S, Bagsvaerd, Denmark.*

ENGLISH MJ, SOLOMON KH and HOFFMAN GJ. 2002. A paradigm shift in irrigation management. *Journal of Irrigation and Drainage Engineering, 128(5): 267-277.*

ESKOM. 2013/14. Tariffs and Charges Booklet. Available online at: http://www.eskom.co.za/content/2013_14DraftTariffBookver3.pdf

ESKOM. 2014/15. Tariffs and Charges Booklet. Available online at: http://www.eskom.co.za/content/2014_15DraftTariffBookver3.pdf

GARCIA-VILA M and FERERES. 2012. Combining the simulation crop model AquaCrop with an economic model for the optimization of irrigation management at farm level. *European Journal of Agronomy, 36: 21-31.*

GHAHRAMAN B and SEPASKHAH AR. 2004. Linear and non-linear optimization models for allocation of a limited water supply. *Irrigation and drainage, 53: 39-54.*

GONZALEZ-CEBOLLADA C and MACARULLA B. 2012. Comparative analysis of design methods of pressurized irrigation networks. *Irrigation and Drainage, 61: 1-9.*

GRAINSA. 2012. Crop Estimated. Available online at: http://www.grainsa.co.za/pages/industry-reports/crop-estimates

GRIEKWALAND-WES KORPORATIEF (GWK). 2013. Input Costs Guide. November 2013.

GROVÉ B. 1997. *Modellering van die ekonomiese effekte van wisselvallige waterbeskikbaarheid vir besproeiingsboere in die Wintertongebied met inagneming van minimum binnestroomvloeivoorsiening.* (Afrikaans). M.Sc. Agric Dissertation. Department of Agricultural Economics, University of the Free State. Bloemfontein. South Africa.

GROVÉ B. 2006. Stochastic efficiency optimisation of alternative agricultural water use strategies. *Agrekon, 45(4): 406 - 420.*

GROVÉ B. 2008. *Stochastic efficiency optimisation analysis of alternative agricultural water use strategies in Vaalharts over the long- and short-run.* Ph.D. Thesis. Department of Agricultural Economics, University of the Free State. Bloemfontein. South Africa.

GROVÉ B and OOSTHUIZEN LK. 2010. Stochastic efficiency analysis of deficit irrigation with standard risk aversion. *Agricultural Water Management. 97: 792 – 800.*

GROVÉ B, VAN HEERDEN P and VENTER M. 2012. Crop water use optimisation: development and application of SAPWAT-OPT. 5th *South African National Commission on Irrigation and Drainage Symposium, Alpine Heath Resort, 21-23 November 2012***.**

GROVÉ B, VENTER M, VAN DER STOEP I and VAN HEERDEN P. 2013. Deliverable 1: Literature review. *WRC Research Project: The optimisation of electricity and water use for sustainable management of irrigation farming systems. K5/2279//4.*

HAARHOFF D. 2014. Verbal communication with author. GWK, Department van Landbou ontwikkeling (Afrikaans), Douglas, Northern Cape, South Africa.

HAILE BO, GROVÉ B, BARNARD J and VAN RENSBURG LD. 2014. Exploring genetic algorithms for improved salinity management using SWAMP. *6th South African National Commission on Irrigation and Drainage Symposium, Glenburn Lodge, 18-20 November 2014.*

HAMILTON JR, GREEN GP and HOLLAND D. 1999. Modelling the reallocation of snake river water for endangered salmon. *Agricultural and Applied Economics Association, Vol 81, No. 5, 1252-1256.*

HANCKE HP and GROENWALD JA. 1972. The effect of resource availability on optimum organization in irrigation farming. *Agrekon, 11(3): 9 – 16.*

JOHANNESBURG STOCK EXCHANGE. 2014. Historical price data. Available online at: https://www.jse.co.za/downloadable-files?RequestNode=/Safex/PriceHistory/Spot%20Months%20on%20all%20Grain%20Products

JUMMAN, A. 2009. *A framework to improve irrigation design and operating strategies in the South African sugarcane industry*. Unpublished M.Sc thesis. School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

KANOONI A and MONEM MJ. 2014. Integrated stepwise approach for optimal water allocation in irrigation canals. *Irrigation and Drainage, 63: 12-21.*

LABEY Y. 1981. Iterative discontinuous method for networks with one or more flow regimes. *Proceedings of the International Workshop on Systems Analysis of Problems in Irrigation, Drainage and Flood Control. New Delhi; 30 Nov – 4 Dec. 31–40 pp.*

LAMADDALENA N and KHILA S. 2011. Energy saving with variable speed pumps in on-demand irrigation systems. *Irrigation Science, 30: 157-166.*

LECLER NL. 2004. *Performance of irrigation and water management systems in the Lowveld of Zimbabwe.* Ph.D. thesis. School of Bioresources Engineering and Environmental Hydrology. University of Natal, Pietermaritzburg.

LETEY J, DINAR A, WOODRING C and OSTER JD. 1990. An economic analysis of irrigation systems. *Irrigation Science, 11: 37-43.*

LOPEZ-MATA E, TARJUELO JM, DE JUAN JA, BALLESTEROS R and DOMINGUEZ A. 2010. Effect of irrigation uniformity on the profitability of crops. *Agricultural Water Management, 98: 190-198.*

MEIRING JA. 1989. *'n Ekonomiese evaluering van alternatiewe spilpuntbeleggingstrategieë in die Suid-Vrystaat substree met inagneming van risiko*. (Afrikaans). M.Sc. Agric. Dissertation. Department of Agricultural Economics. University of the Orange Free State. Bloemfontien. South Africa.

MEIRING JA, OOSTHUIZEN LK, BOTHA PW and CROUS CI. 2002. *The implementation of the FARMS system for managing decision-making in irrigation farming summary report and user guides.* WRC Report No: 894/1/02. Water Research Commission, Pretoria, South Africa.

MONTERO J, MARTINEZ A, VALIENTE M, MORENO MA and TARJUELO JM. 2013. Analysis of water application costs with a center pivot system for irrigation of crops in Spain. *Irrigation Science, 31: 507-521.*

MORENO MA, MEDINA D, ORTEGA JF and TARJUELO JM. 2012. Optimal design of center pivot systems with water supplied wells. *Agricultural Water Management, 107: 112-121.*

MURALIDHARAN D and KNAPP KC. 2009. Spatial dynamics of water management in irrigated agriculture. *Water Resource Research, Vol.45.*

MYBURGH C. 2014. Verbal communication with the author. Valley, Douglas, South Africa.

NELDER JA and MEAD R. 1965. A simplex method for function minimization. *Comp. Journal, 7: 308-13.*

OOSTHUIZEN LK. 1985. A procedure for estimating sprinkler irrigation costs. *Department of Agricultural Economics. University of the Orange Free State. Bloemfontein. South Africa.*

OOSTHUIZEN LK, BOTES JHF, BOSCH DJ and BREYTENBACH P. 1996. *Increasing Economic Efficiency of Water and Energy Use for Irrigation at Whole Farm Level in the Winterton Area.* WRC Report No: 347/2/96. Water Research Commission, Pretoria, South Africa.

OOSTHUIZEN LK, BOTHA PW, GROVÉ B and MEIRING JA. 2005. Cost-estimating procedures for drip-, micro-, and furrow-irrigation systems. *Water SA, 31: 403-406.*

ORTEGA JF, DE JUAN JA and TARJUEOLO JM. 2005. Improving water management: The irrigation advisory service of Castilla-La Mancha (Spain). *Agricultural Water Management, 77: 37-58.*

OTTERMAN AB. 1988. *Optimizing irrigation systems.* Master of Engineering (Civil). Dissertation. Department of Engineering. University of Stellenbosch. South Africa.

PEDRAS CMG, PEREIRA LS and GONCALVES JM. 2009. MIRRIG: a decision support system for design and evaluation of microirrigation systems. *Agricultural Water Management, 96(4): 691-701.*

PEREZ R, VIDAL R and IZQUIRERDO J. 1993. Main network pipe sizing. Hydraulic design of irrigation networks. *Fluids Mechanics Department., Polytechnic University of Valencia, Spain.*

PLANNELS P, ORTEGA JF and TARJUELO JM. 2007. Optimization of irrigation water distribution networks, layout included. *Agricultural Water Management, 88: 110-118.*

PRASAD AS, UMAMAHESH NV and VISWANATH GK. 2006. Optimal irrigation planning under water scarcity. *Journal of Irrigation and Drainage, Vol. 132, No. 3.*

RADLEY R. 2000. Sagteware vir die ontwerp van besproeiingstelsels – ‘n ondersoek na geskikte pakkette. (Afrikaans). *ARC-Institute for Agricultural Engineering.*

RANA T, KHAN S and RAHIMI M. 2008. Spatio-temporal optimization of agricultural drainage using groundwater models and genetic algorithms: an example from the Murray Irrigation Area, Australia. *Hydrogeology Journal, 16: 1145-1157.*

RECA J, ROLDAN J, ALCAIDE M, LOPEZ R and CAMACHO E. 2001. Optimisation model for water allocation in deficit irrigation systems I. Description of the model. *Agricultural Water Management, 48: 103-116.*

SCHEIERLING SM, YOUNG RA and CARDON GE. 2004. Determining the price responsiveness of demands for irrigation water deliveries versus consumptive use. *Journal of Agricultural and Resource Economics, 29(2): 328-345.*

SCHÜTZE N, DE PALY M, and SHAMIR U. 2012. Novel simulation-based algorithms for optimal open-loop and closed-loop scheduling of deficit irrigation system. *Journal of Hydroinformatics, 14 (1): 136-151.*

SCHÜTZE N and SCHMITZ GH. 2010. New planning tool for optimal climate change adaptation strategies in irrigation. *Journal of Irrigation and Drainage engineering, 136 (12): 836-846.*

SENGUPTA JK and FOX FA. 1975. Economic analysis operations research: Optimization techniques in quantitative economic models. *Studies in mathematical and management economics, no. 10. Amsterdam: North Holland.*

SEPASKHAH AR and GHAHRAMAN B. 2004. The effects of irrigation efficiency and uniformity coefficient on relative yield and profit for deficit irrigation. *Biosystems Engineering, 87(4): 495-507.*

SHANGGUAN Z, SHAO M, HORTON R, LEI T, QIN L and MA J. 2002. A model for regional optimal allocation of irrigation water resources under deficit irrigation and its applications. *Agricultural Water Management, 52: 139-154.*

SPALL J. C. 2003. Introduction to stochastic search and optimization: Estimation, Simulation, and Control. *New Jersey: John Wiley and Sons, Inc.*

SYMINGTON HM and VILJOEN MF. 1997. Optimum management strategies for typical farmers in the Vaalharts irrigation area during conditions of variable water supply. *Agrekon, 36(2): 157-182.*

THEOCHARIS ME, TZIMOPOULOS CD, SAKELLARIOU-MAKRANTONAKI MA, YANNOPOULOS SI and MELETIOU IK. 2010. Comparative calculation of irrigation networks using Labye’s method, the linear programming method and a simplified nonlinear method. *Mathematical and Computer Modelling, 51: 286-299.*

TROSKIE CG. 2012. *The economic impact of electricity price increases on the potato industry in South Africa.* M.Com. Agric. Dissertation. Department of Agricultural Economics, Extension and Rural Development. University of Pretoria. South Africa.

VALIN MI, CAMEIRA MR, TEODORO PR and PEREIRA LS. 2012. DEPIVOT: A model for center-pivot design and evaluation. *Computers and Electronics in Agriculture, 87: 159-170.*

VAN DIJK M, VAN VUUREN SJ and VAN ZYL JE. 2008. Optimizing water distribution systems using a weighted penalty in genetic algorithms. *Water South Africa, 34(5): 273-280.*

VAN HEERDEN PS, CROSBY CT, GROVÉ B, BENADE N, SCHULZE RE and TEWOLDE MH. 2009. *Integrating and updating of SAPWAT and PLANWAT to create a powerful and user-friendly irrigation planning tool.* WRC Report No: TT391/08. Water Research Commission, Pretoria, South Africa.

VAN HEERDEN PS. 2012. PICKWAT. Verbal communication with the author. Bloemfontein, South Africa.

VAN ROOYEN CJ. 1979. The availability of water and labour as variable resources in planning for optimum organisation in irrigation farming*. Agrekon, 18(1): 9-17.*

VINK N and KIRSTEN JF. 2000. Deregulation of agriculture marketing in South Africa: Lessons learned. *Free Market Foundation Monograph, 25.*

APPENDIX A: ENTERPRISE BUDGETS

Table A.1: Yield and area dependent costs for maize with a target yield of 13ton/ha, 2013

Inputs	Product	Unit	Amount	Price/unit	Costs/ha
Yield Dependent Costs					
Hedging	Safex	ton	*13*	*150,00*	***1950,00***
Fertilization	N	kg	*286*	*14,47*	***4138,42***
	P	kg	*52*	*23,49*	***1221,48***
	K	kg	*80*	*12,32*	***985,60***
	Ca	kg	*10*	*25,64*	***256,40***
	Mg	kg	*10*	*38,79*	***387,90***
	S	kg	*25*	*5,00*	***125,00***
Insurance	GWK	ton	*13*	*2,6%*	***0,34***
Harvesting	Transport	ton	*1*	*58,00*	***58***
Area Dependent Costs					
Fuel	Diesel	litre	*52*	*11,57*	***601,64***
Micro Elements	Sidi Seed	kg	*0,125*	*151,35*	***18,92***
	Sidi Zn	kg	*2*	*56,57*	***113,14***
	Sidi Maize	kg	*2*	*58,70*	***117,40***
	Sidi Boost	kg	*2*	*55,86*	***111,72***
	Speedfol	kg	*1*	*25,50*	***25,50***
	Sidi Moly	litre	*1*	*81,42*	***81,42***
	Marinure	litre	*1*	*110,85*	***110,85***
	Comcat	kg	*0,2*	*600,14*	***120,03***
	Anngro	litre	*0,12*	*320,14*	***38,42***
Seed	Seed	kernels	*90000*	*0,028*	***2520,00***
Weed Control	Atrazine	litre	*1,5*	*53,35*	***80,03***
	Wenner	litre	*1*	*73,60*	***73,60***
Pest Control	Curaterr	kg	*20*	*49,75*	***995,00***
	Dursban	litre	*2*	*99,60*	***199,20***
	Karate	litre	*0,2*	*218,57*	***43,71***
	Abacus	litre	*1,6*	*308,67*	***493,87***
	Duett	litre	*1*	*209,00*	***209,00***
	Abactien	litre	*1*	*93,83*	***93,83***
	Airplane	ha	*2*	*115,00*	***230,00***
Harvesting	Combine	ha	*1*	*675,00*	***675,00***
Mechanization	M & R	ha	*1*	*363,54*	***363,54***

Source: GRIEKWALAND-WES KORPORATIEF (2013)

Table A.2: Yield and area dependent costs for maize with a target yield of 17ton/ha, 2013

Inputs	**Product**	**Unit**	**Amount**	**Price/unit**	**Costs/ha**
Yield Dependent Costs					
Hedging	Safex	ton	*17*	*150,00*	***2250,00***
Fertilization	N	kg	*386*	*14,47*	***5585.42***
	P	kg	*70*	*23,49*	***1644.30***
	K	kg	*160*	*12,32*	***1971.20***
	Ca	kg	*10*	*25,64*	***256,40***
	Mg	kg	*10*	*38,79*	***387,90***
	S	kg	*25*	*5,00*	***125,00***
Insurance	GWK	ton	*17*	*2,6%*	***0,442***
Harvesting	Transport	ton	*1*	*58,00*	***58***
Area Dependent Costs					
Fuel	Diesel	litre	*52*	*11,57*	***601,64***
Micro Elements	Sidi Seed	kg	*0,125*	*151,35*	***18,92***
	Sidi Zn	kg	*2*	*56,57*	***113,14***
	Sidi Maize	kg	*2*	*58,70*	***117,40***
	Sidi Boost	kg	*2*	*55,86*	***111,72***
	Speedfol	kg	*1*	*25,50*	***25,50***
	Sidi Moly	litre	*1*	*81,42*	***81,42***
	Marinure	litre	*1*	*110,85*	***110,85***
	Comcat	kg	*0,2*	*600,14*	***120,03***
	Anngro	litre	*0,12*	*320,14*	***38,42***
Seed	Seed	kernels	*90000*	*0,028*	***2520,00***
Weed Control	Atrazine	litre	*1,5*	*53,35*	***80,03***
	Wenner	litre	*1*	*73,60*	***73,60***
Pest Control	Curaterr	kg	*20*	*49,75*	***995,00***
	Dursban	litre	*2*	*99,60*	***199,20***
	Karate	litre	*0,2*	*218,57*	***43,71***
	Abacus	litre	*1,6*	*308,67*	***493,87***
	Duett	litre	*1*	*209,00*	***209,00***
	Abactien	litre	*1*	*93,83*	***93,83***
	Airplane	ha	*2*	*115,00*	***230,00***
Harvesting	Combine	ha	*1*	*675,00*	***675,00***
Mechanization	M & R	ha	*1*	*363,54*	***363,54***

Source: GRIEKWALAND-WES KORPORATIEF (2013)

Table A.3: Yield and area dependent costs for wheat with a target yield of 7.5ton/ha, 2013

Inputs	Product	Unit	Amount	Price/unit	Costs/ha
Yield Dependent Costs					
Hedging	Safex	ton	*7,5*	*150,00*	***1125,00***
Fertilization	N	kg	*250*	*14,47*	***3617,50***
	P	kg	*48*	*23,49*	***1127,52***
	K	kg	*78*	*12,32*	***960,96***
	Ca	kg	*15*	*25,64*	***384,60***
	Mg	kg	*10*	*38,79*	***387,90***
	S	kg	*16*	*5,00*	***80,00***
Insurance	GWK	ton	*7,5*	*5,50%*	***0,41***
Harvesting	Transport	ton	*1*	*58,00*	***58***
Area Dependent Costs					
Fuel	Diesel	litre	*54*	*11,57*	***624,78***
Micro Elements	Sidi Seed	kg	*0,125*	*151,35*	***18,92***
	Sidi Zn	kg	*2*	*56,57*	***113,14***
	Sidi Wheat	kg	*2*	*58,70*	***117,40***
	Sidi Boost	kg	*3*	*55,86*	***167,58***
	Speedfol	kg	*1*	*45,21*	***45,21***
	Marinure	litre	*1*	*110,85*	***110,85***
	Comcat	kg	*0,4*	*600,14*	***240,06***
	Anngro	litre	*0,12*	*320,14*	***38,42***
Seed	Seed	kg	*100*	*11,60*	***1160,00***
Weed Control	Broxonil	litre	*1,5*	*81,10*	***121,65***
	MCPA	litre	*0,5*	*49,75*	***24,88***
Pest Control	Bumper	litre	*1,2*	*112,50*	***135,00***
	Methomidaphos	litre	*1*	*75,00*	***75,00***
	Karate EC	litre	*0,65*	*218,57*	***142,07***
	Wetsit	litre	*1,2*	*96,20*	***115,44***
	CECECE 750	litre	*0,8*	*128,40*	***102,72***
	Ethaphon	litre	*1*	*79,20*	***79,20***
	Abamectien	litre	*0,5*	*93,83*	***46,92***
	Airplane	ha	*3*	*115,00*	***345,00***
Harvesting	Combine	ha	*1*	*625,00*	***625,00***
Mechanization	M & R	ha	*1*	*449,41*	***449,41***

Source: GRIEKWALAND-WES KORPORATIEF (2013)

Table A.4: Yield and area dependent costs for wheat with a target yield of 8.5ton/ha, 2013

Inputs	Product	Unit	Amount	Price/unit	Costs/ha
Yield Dependent Costs					
Hedging	Safex	ton	8,5	150,00	**1275,00**
Fertilization	N	kg	275	14,47	**3979,25**
	P	kg	52.5	23,49	**1233.23**
	K	kg	98	12,32	**1207.36**
	Ca	kg	15	25,64	**384,60**
	Mg	kg	10	38,79	**387,90**
	S	kg	16	5,00	**80,00**
Insurance	GWK	ton	8,5	5,50%	**0,47**
Harvesting	Transport	ton	1	58,00	**58**
Area Dependent Costs					
Fuel	Diesel	litre	54	11,57	**624,78**
Micro Elements	Sidi Seed	kg	0,125	151,35	**18,92**
	Sidi Zn	kg	2	56,57	**113,14**
	Sidi Wheat	kg	2	58,70	**117,40**
	Sidi Boost	kg	3	55,86	**167,58**
	Speedfol	kg	1	45,21	**45,21**
	Marinure	litre	1	110,85	**110,85**
	Comcat	kg	0,4	600,14	**240,06**
	Anngro	litre	0,12	320,14	**38,42**
Seed	Seed	kg	100	11,60	**1160,00**
Weed Control	Broxonil	litre	1,5	81,10	**121,65**
	MCPA	litre	0,5	49,75	**24,88**
Pest Control	Bumper	litre	1,2	112,50	**135,00**
	Methomidaphos	litre	1	75,00	**75,00**
	Karate EC	litre	0,65	218,57	**142,07**
	Wetsit	litre	1,2	96,20	**115,44**
	CECECE 750	litre	0,8	128,40	**102,72**
	Ethaphon	litre	1	79,20	**79,20**
	Abamectien	litre	0,5	93,83	**46,92**
	Airplane	ha	3	115,00	**345,00**
Harvesting	Combine	ha	1	625,00	**625,00**
Mechanization	M & R	ha	1	449,41	**449,41**

Source: GRIEKWALAND-WES KORPORATIEF (2013)

APPENDIX B: ADDITIONAL TABLES

Table B.1: Optimised design parameters, investment and electricity costs for different irrigation systems using Ruraflex for a 130mm/m water holding capacity, 2014

	Center Pivot Size (ha)							
	Small (30.1)				Large (47.7)			
	Irrigation System Delivery Capacity (mm/day)							
	8	10	12	14	8	10	12	14
	DESIGN PARAMETERS							
Flow Rate (m3/h)	100.5	125.5	150.5	178	158.9	198.6	239	278
Outside Diameter (mm)	200	200	250	250	250	250	315	315
Friction (m)	2.974	4.475	2.107	2.869	2.328	3.511	1.316	1.738
Friction percentage (%)	0.4	0.6	0.28	0.38	0.31	0.47	0.18	0.23
Total pressure (m)	36	39	38	38	37	41	41	45
Kilowatt (kW)	13	18	20	23	21	28	33	42
Kilowatt hours (kWh)	38 935	43 164	40 000	39 399	63 042	67 256	65 868	72 072
	INVESTMENT AND ELECTRICITY COSTS							
Pipe Investment (R)	112 853	112 853	179 895	179 895	179 895	179 895	276 158	276 158
Pivot Investment (R)	638 483	669 000	723 186	739 654	815 452	835 239	842 405	930 818
Pump Investment (R)	14 368	21 655	20 661	20 661	20 661	22 216	22 216	22 216
Total Investment Costs (R)	765 704	803 518	923 742	940 210	1 016 008	1 037 350	1 122 779	1 229 192
Total Variable Electricity Costs (R)	546 947	555 206	515 578	493 310	847 878	876 999	841 032	881 569
Total Fixed Electricity Costs	307 099	307 099	307 099	307 099	307 099	307 099	394 056	394 056
Total Electricity Costs (R)	854 046	862 305	822 677	800 409	1 154 977	1 184 099	1 235 088	1 275 625
NPV (R)	4 941 043	4 935 360	4 885 848	4 976 826	8 385 348	8 457 372	8 431 543	8 310 628
NPV (R/ha)	164 154	163 965	162 321	163 174	175 793	177 303	176 762	174 227

Table B.2: Optimised design parameters, investment and electricity costs for different irrigation systems using Landrate for a 130mm/m water holding capacity, 2014

	Center Pivot Size (ha)							
	30.1				47.7			
	Irrigation System Delivery Capacity (mm/day)							
	8	**10**	**12**	**14**	**8**	**10**	**12**	**14**
	DESIGN PARAMETERS							
Flow Rate (m3/h)	100.5	125.5	150.5	178	158.9	198.6	239	278
Outside Diameter (mm)	200	250	250	250	250	315	315	315
Friction (m)	2.974	1.510	2.107	2.869	2.328	0.937	1.316	1.738
Friction percentage (%)	0.4	0.2	0.28	0.38	0.31	0.12	0.18	0.23
Total pressure (m)	36	36	38	38	37	38	41	45
Kilowatt (kW)	13	16	20	23	21	26	33	42
Kilowatt hours (kWh)	38 948	38 368	40 000	39 422	63 042	62 452	65 868	72 072
	INVESTMENT AND ELECTRICITY COSTS							
Pipe Investment (R)	112 853	179 895	179 895	179 895	179 895	276 158	276 158	276 158
Pivot Investment (R)	638 483	669 000	723 186	739 654	815 452	835 239	842 405	930 818
Pump Investment (R)	14 368	21 655	20 661	20 661	20 661	22 216	22 216	22 216
Total Investment Costs (R)	765 704	870 550	923 742	940 210	1 016 008	1 133 613	1 122 779	1 229 192
Total Variable Electricity Costs (R)	817 644	805 301	834 693	826 489	1 283 891	1 283 890	1 361 858	1 472 519
Total Fixed Electricity Costs	379 993	379 993	379 993	379 993	379 993	379 993	379 993	379 993
Total Electricity Costs (R)	1 197 638	1 185 294	1 214 686	1 206 482	1 663 884	1 663 883	1 741 852	1 852 512
NPV (R)	4 878 898	4 809 178	4 727 109	4 817 754	8 241 049	8 184 078	8 102 631	7 906 019
NPV (R/ha)	162 090	159 773	157 047	157 959	172 768	171 574	169 866	165 745

Table B.3: Optimised irrigation hours for different irrigation systems using a 130mm/m water holding capacity for Ruraflex and Landrate

			Center Pivot Size (ha)							
			30.1				47.7			
			Irrigation System Delivery Capacity (mm/day)							
			8	10	12	14	8	10	12	14
Irrigation Hours	***Maize***	***OP***	*816*	*815*	*768*	*777*	*816*	*800*	*789*	*778*
		ST	*645*	*339*	*196*	*61*	*522*	*367*	*185*	*61*
		PE	*0*	*0*	*2*	*0*	*56*	*0*	*0*	*0*
	Wheat	***OP***	*859*	*775*	*716*	*659*	*1 056*	*763*	*703*	*660*
		ST	*525*	*436*	*313*	*217*	*551*	*436*	*313*	*216*
		PE	*150*	*35*	*6*	*0*	*1*	*36*	*6*	*0*
Total Irrigation Hours (Ruraflex)	***Maize***		*1 461*	*1 153*	*965*	*837*	*1 394*	*1 167*	*974*	*840*
	Wheat		*1 534*	*1 245*	*1 035*	*876*	*1 608*	*1 235*	*1 022*	*876*
Total Irrigation Hours (Landrate)	***Maize***		*1 454*	*1 153*	*970*	*824*	*1 457*	*1 155*	*960*	*825*
	Wheat		*1 542*	*1 245*	*1 030*	*890*	*1 545*	*1 247*	*1 036*	*891*

*OP: Off-Peak

*ST: Standard

*PE: Peak