A FRAMEWORK TO IMPROVE IRRIGATION DESIGN AND OPERATING STRATEGIES IN THE SOUTH AFRICAN SUGARCANE INDUSTRY

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Ashiel Jumman

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ABSTRACT

The purpose of this study was to develop a framework to assess irrigation design and operating strategies. This objective was achieved successfully and the framework was applied to formulate guidelines to increase farm profitability whilst using scarce resources, such as water and electricity, effectively. The study was targeted at sugarcane irrigated with semi-permanent irrigation systems.

"*ZIMsched 2.0", a* water balance and crop yield prediction model and the "*Irriecon V2*" economic assessment model were available at the start of the study. The missing link, however, was a relatively cost effective and efficient method to design and cost irrigation hardware alternatives. Irrigation hardware impacts on both the agronomic and economic performance of systems, for example, through different peak design capacities and associated operating limitations. Thus, a novel, spreadsheet-based irrigation design tool, with an automated costing component, was developed to complete the framework.

The framework was used to investigate the costs and benefits of potential design and operating solutions to a selection of irrigation issues, including: over-irrigation on shallow soils, the opportunity to shift electricity use out of expensive peak periods and, the opportunity to demonstrate the benefits of deficit irrigation strategies.

For shallow soils, the increase in system hardware costs, needed to better match water application to soils, increased margins due to more effective water use. Innovative deficit designs and operating strategies allowed for reductions in water and electricity costs. The reduced costs, however, did not always offset yield penalties and revenue loss resulting from water stress. The financial benefits of deficit irrigation strategies were shown when water savings were used to convert dry land cane into irrigated cane. This highlighted the differences between the direct and opportunity costs of water.

Finally, a field work component, relating to the precise monitoring of irrigation strategies and corresponding crop responses was included in this study. Systems which enabled soil water potential and stalk extension to be monitored remotely via the internet were considered useful for the successful implementation of an optimum irrigation strategy. The easily accessible data allows for effective decision making and more importantly, reassures famers of the current state of their crop.

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1. INTRODUCTION

Wallace (2000) reported that the world population is projected to increase by 65 % over the next 50 years. Wallace (2000) further reported that almost all of the world's population increase will occur in developing countries, with a 50 % increase occurring in the next 25 to 30 years. A major consequence of the projected increase in population is the increased demand for food and an associated increased demand on the limited water resource for food production (Fisher *et al.*, 2007). Furthermore, the increasing world population is projected to exacerbate adverse climate changes, especially in Africa, highlighting the vulnerability of agricultural production and increasing pressure on water resources (Benhin, 2006).

South Africa is a water scarce country with a low average annual precipitation and a comparatively high evaporation rate. The mean annual precipitation in South Africa is 450 mm, well below the world's average of 860 mm (NWRS, 2004). The rainfall in South Africa is unevenly distributed and irregular in occurrence (Perret, 2002). Irrigated agriculture is reported to utilise 62 % of the country's stored water resources (NWRS, 2004) while generating less than 4 % of the Gross Domestic Product and employing 14 % of the labour force (Perret, 2002). Schmidt (1998) reported that approximately 412 000 hectares of land in South Africa was under sugarcane production, of which approximately 21 % (87 000 hectares) was irrigated. In the Northern areas such as Pongola and Mpumalanga, where irrigation is a necessity, sugarcane production was linked to the generation of R0,6 billion in revenues as well as the creation of 32 000 employment opportunities. In these areas, as a result of increased competition for water resources from other economic sectors, the pressure on the sugar industry to justify its use of irrigation water was escalating (Schmidt, 1998).

Recognising that water is a finite resource and to mitigate the imbalance between availability and demand, the then Department of Water Affairs and Forestry (DWAF) launched several campaigns to ensure water use was lawful, equitable, efficient and sustainable. These campaigns included Compulsory Registration and Licensing, the Water Allocation and Reform (WAR) Program and the Water Conservation and Water Demand Management (WCWDM) Program (DWAF, 2008). As a consequence of the above, irrigation water use has come under scrutiny. The focus has been to produce more agricultural goods with less water input (Playan and Mateos, 2005).

From a grower's perspective, using less water to produce more agricultural goods may be in alignment with maximising profitability because decreasing water input will reduce water and electricity overheads (English, 2002). Electricity contributes largely to the operating costs of an irrigation system. In the South African context, the start of the electricity crisis in 2008 has adversely impacted on farmers. The imbalance between electricity demand and supply has resulted in power outages and load shedding. Hence irrigation systems may have been unable to operate during critical periods resulting in yield and profit losses. Furthermore, in order to fund remedial programmes, a 34 % increase in electricity tariffs was enforced in 2008 (NERSA, 2007) and a further 34 % in 2009 (Eskom, 2009), thus contributing to the pressure on irrigation farmers to utilise resources more sparingly and efficiently.

Increasing water and electricity tariffs coupled with increasing inflation, interest rates, diesel prices and chemical (fertiliser and herbicide) costs, impacts on the financial viability of farmers and their ability to remain profitable. In addition, farmers irrigating by means of sprinkler irrigation, constituting 60 % of the area under irrigation in South Africa (Van der Stoep, 2008), are faced with issues such as theft and operational difficulties relating to labour and correct and timely movement of sprinklers. Sprinklers are often not moved, moved to the incorrect position or moved at the wrong time. These issues have resulted in increased maintenance costs, inefficient use of water and declining yields whilst increasing operating costs (Lecler *et al.*, 2008).

The above discussion summarizes the context in which growers struggle to remain profitable. The question then posed was what options or alternatives can be developed to help overcome the many challenges faced in these economic times? What solutions can irrigation consultants and experts offer a grower? The intentions for this work was to identify some of the major challenges or opportunities facing irrigation designers, consultants and farmers in the sugar industry and to investigate various solutions in order to provide acceptable or better guidelines for alternative irrigation practices. A review of profit optimising strategies and tools are presented in Chapter 2. This review assisted in highlighting the current status of irrigation strategies and the availability of irrigation analytical tools. This information was used in the development of the project objectives. The objectives of this study were as follows:

Objective 1: To develop a framework with the appropriate tools to, holistically, assess alternative irrigation design and operating practices.

The literature review in Chapter 2 revealed an absence of a relatively efficient and holistic approach to assess alternative irrigation design and operating practices. Individual tools were available but often used in isolation. In addition, means to quickly design and cost irrigation hardware were lacking. For this reason, existing tools as identified in Chapter 2, were integrated into a proposed “irrigation assessment framework”. This is described in Chapter 3. Furthermore, the development of a novel, spreadsheet-based irrigation design and costing tool, in order to complete the “irrigation assessment framework” is also presented in Chapter 3. Development of such a framework provided the ideal platform to rapidly assess alternative solutions. Objective 2, as explained below, therefore provides the opportunity to apply and test the framework while researching potential solutions to current industry problems.

Objective 2: To investigate potential solutions for: over irrigation on shallow soils and increasing electricity tariffs, and to assess the potential benefit of deficit irrigation strategies, by applying the decision support framework.

Sixty percent of the sugar plantations in South Africa are on grey soils. Grey soils have a rating of moderate to poor suitability for irrigation, largely attributed to the shallow nature of the soil (SASEX, 1999). To compound matters, shallow soils are often irrigated, inappropriately, with dragline sprinkler systems due to the low costs of the system (ARC-ILI, 2004 and Hoffman *et al.*, 2007). It is often difficult to apply small amounts of water frequently with dragline systems as required for shallow soils. The framework was used to develop and assess innovative designs to irrigate shallow soils with sprinkler irrigation. This was reported in Section 4.1.

As pointed out above, significant increase in electricity tariffs has adversely impacted on farmers. The electricity service provider in South Africa, Eskom, provides many tariff structure options to consumers. Examples of these options are Landrate, which represents a fixed tariff, and Ruraflex, which rewards for use during low demand period with lower tariffs while penalises for consumption during high demand periods with relatively higher tariffs. Very little research investigating the cost implications of different tariff options has been conducted in South Africa in the context of irrigation. Complex tariff structures with differing incentives and opportunities create uncertainty as to which tariff option a grower should select. Hence the opportunity was taken to use the framework to assess alternative electricity tariff options and is presented in Section 4.2. The aim in Section 4.2 was to provide a better understanding of complex tariff structures, before attempting to develop deficit irrigation strategies to optimise use of water and electricity in Section 4.3.

Deficit irrigation is an optimising strategy that targets maximum profits as opposed to maximum yields. In agricultural production in South Africa, water is generally the limiting resource and the benefits of a deficit irrigation strategy are attributed to realising the opportunity cost of water. Water savings from under irrigation can be used to irrigate additional area thereby increasing water use efficiency. In addition, reducing irrigation in deficit irrigation strategies provides the opportunity to keep irrigation out of expensive electricity peak periods. An increasing amount of work has been conducted for deficit strategies on various crops around the world, but less on sugarcane and for sugarcane in the South African context. In Section 4.3, the framework was used to assess deficit irrigation strategies, specifically for the South African Context.

Objective 3: To field test and refine a prototype continuous monitoring system in order to assess the potential value as a decision support mechanism for irrigation farmers.

Finally, one of the big challenges facing the irrigation industry at present was the lack of monitoring or evaluation at a field level to ensure that an irrigation system or strategy was performing well. The precise nature of deficit irrigation, coupled with small tolerances for error suggests that monitoring tools would be pivotal to successful implementation. The challenge was, on completion of research such as this, how would one assess the performance of any recommended irrigation strategies at a field level? Hence the objective of Chapter 5 was to research the continuously changing face of infield irrigation monitoring tools in order to compile and field test a continuous monitoring system to assess the field performance of irrigation strategies on sugarcane.

At this stage it must be noted that the work reported in this document was specific to the sugarcane industry. In addition, the irrigation scenarios assessed in the study were limited to a semi-permanent irrigation system. Many experts, at the time, perceived that the large areas irrigated by dragline were not performing well and semi-permanent systems were deemed to be an appropriate replacement/upgrade (Lecler *et al.*, 2008). The structure of the dissertation is summarized in Figure 1.1 below, clearly illustrating the link between development of the framework in Chapter 3, application of the framework in Chapter 4 and the development of monitoring strategies for field assessment in Chapter 5.

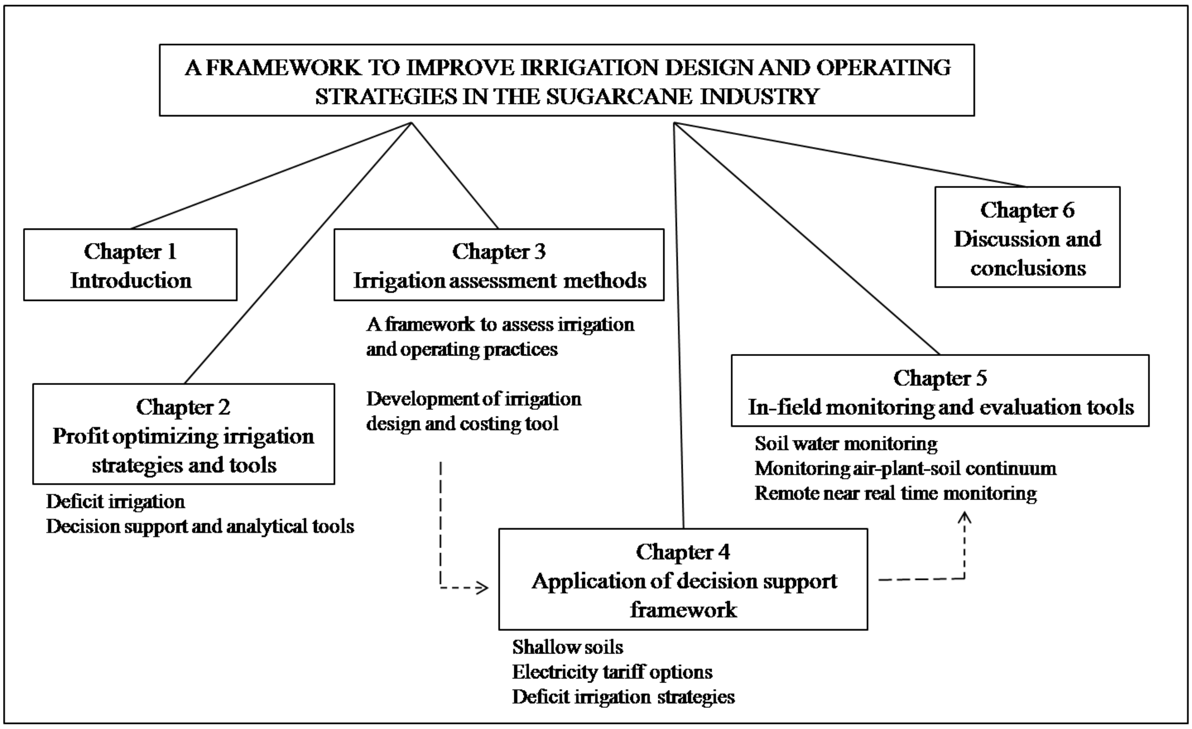

Figure 1.1 Dissertation layout

2. PROFIT OPTIMISING IRRIGATION STRATEGIES AND TOOLS

Worldwide, standard procedures for determining irrigation design capacity, and scheduling to a certain degree, have focused on meeting the peak crop water demands to maximise crop yields or limit crop stress (English and Raja, 1996). English (2002) suggested that a profit maximising strategy, namely deficit irrigation, as opposed to a yield maximising strategy, derives more benefits in terms of water savings, food security and reduced environmental degradation. This chapter explores the potential to implement deficit irrigation strategies on a sugarcane crop to increase profitability. As pointed out many times before, farm profitability was pertinent in the current economic climate. Also included in this Chapter is a review of irrigation analytical tools that were available in the sugar industry. These tools were considered vital for the further research into deficit irrigation strategies.

2.1 Deficit Irrigation

This section is broken down into two sub-sections. The first is a review of fundamental deficit irrigation concepts and the second sub-section deals with the sugarcane crop in the context of deficit irrigation

2.1.1 Review of deficit irrigation concepts

This section was included to help the reader understand the dynamics and mechanisms of deficit irrigation. These include the interactions between irrigation, crop yield and the economics. The relationship between crop yield and applied water and crop yield and transpiration is illustrated in Figure 2.1.

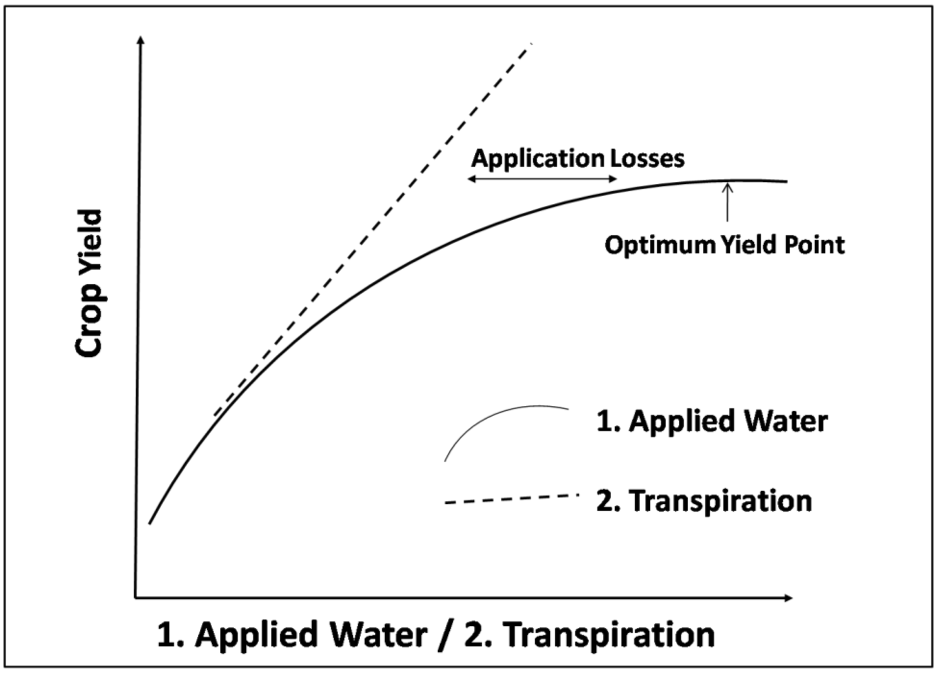

Figure 2.1 Schematic of the general form of crop production (Lecler 2004a, adopted from English, 1990)

As shown in Figure 2.1, the yield benefit from increasing water applications is linear up to a point. Increasing the water application further, however, still increases yield but at a reduced rate, as shown by the curvilinear slope, until the optimum yield point is reached. The optimum yield point represents the peak crop water required, and is the capacity figure traditionally designed for, as discussed above. At this stage the efficiency of water use is reduced as the increased application often contributes to increased losses from surface evaporation, runoff and deep percolation. Applying water beyond the optimum yield point often reduces yield due to leaching of nutrients, diseases and anaerobic soil conditions associated with excessive irrigation. As a result of increased water losses and higher capital and operating costs to apply more water, maximum profitability is seldom attained when applying water sufficient to achieve maximising yields (English, 1990; English and Raja, 1996; Lecler, 2004a; Fereres and Soriano, 2007).

English (1990) reported that profits could be maximised by employing a deficit irrigation strategy. Deficit irrigation aims to increase water use efficiency by applying reduced amounts of irrigation water. Crop stress and reduced yields due to the smaller amounts of irrigation can be offset by reduced capital and operating costs (Lecler, 2001). This is illustrated in Figure 2.2 and is explained further, below.

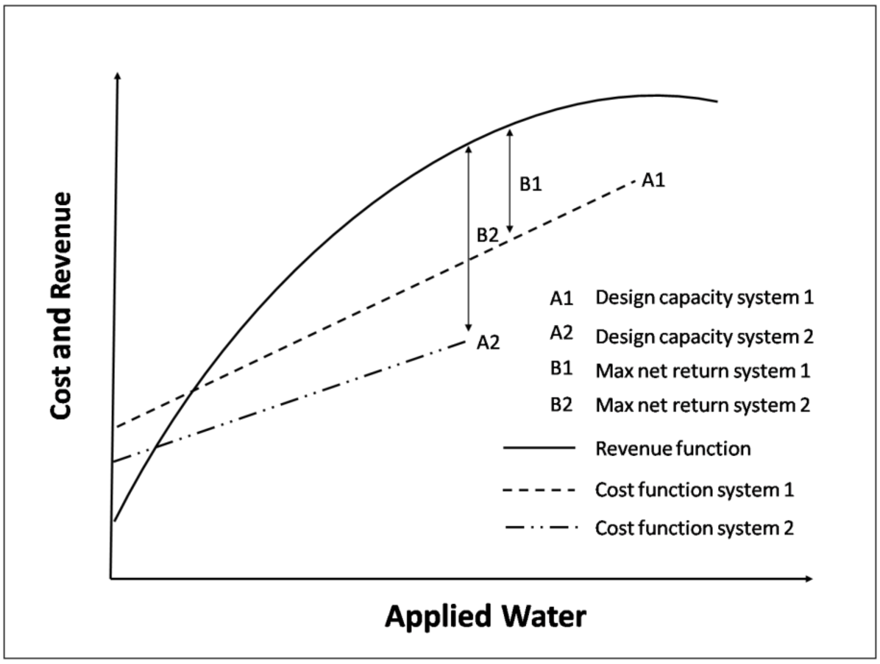

Figure 2.2 Schematic of cost and revenue functions (Lecler 2004a after English 1990)

In the cost and revenue functions shown in Figure 2.2, revenue is determined as the product of the crop yield and a constant crop price, and therefore takes the same shape as the crop yield function for applied water shown in Figure 2.1. The cost function is shown as a straight line where the intercept and the slope represent capital and operating costs, respectively. Profitability is determined as the difference between the revenue and cost functions and is shown by distances B1 or B2 in Figure 2.2. For the cost and revenue functions shown in Figure 2.2, the maximum net return occurs at reduced levels of applied water, to the left of the optimum yield point. Furthermore, the system with the lower design capacity is probably less able to meet peak crop water requirements but, due to lower capital and operating costs has the ability to attain almost double the net returns compared to the system with a larger system capacity (English 1990, English and Raja, 1996, cited by Lecler 2004a). English and Nuss (1982) reported that designing an irrigation system explicitly for deficit strategies allows for the departure from design norms and standards and may result in substantially reduced capital costs, more so than the cost of water and energy. Furthermore, if water is the limiting resource and not land, water savings from a deficit strategy could be used to irrigate a larger area and contribute further to profit margins. This is referred to as the opportunity cost of water (English, 1990).

Risks associated with deficit irrigation include the possibility of equipment failure and the consequent financial implications due to excessive crop stress (English and Raja, 1996). Furthermore, the theory discussed above is subject to accurately predicted crop yields for given levels of applied water. This may prove difficult considering the dependency on unpredictable climate and the complex interaction with soil fertility and threat of pests and diseases (English, 1990). Other concerns include increased salinity levels in the soil due to reduced irrigation volumes which do not meet the leaching requirements (English 1990).

The risks and concerns associated with deficit irrigation can be mitigated to a certain degree through management practices and highlight the need for skilled management and supportive advisory and extension services (English 2002). Nevertheless, deficit irrigation appears to be an attractive strategy for the South African context. In the next section, the target crop, sugarcane is reviewed to assess its suitability to a deficit irrigation strategy.

2.1.2 Sugarcane in the context of deficit irrigation

A sugarcane crop responds differently to water deficits during different crop growth stages. In a situation where water is limited, knowledge of critical crop growth stages and associated responses to water stress will aid management decisions regarding the timing of irrigation and help identify potential periods for deficit or reduced irrigation (Inman-Bamber and Smith, 2005). The aim of this section is to demonstrate the physiological characteristics of sugarcane and the related potential to implement deficit irrigation.

The ability to model and predict crop yield and growth responses is valuable for applications in planning, design and operation of irrigation schemes. Equation 2.1 was developed by Doorenbos and Kassam (1979) in order to quantify the impact of soil water stress on crop yields. During the course of this project, the FAO Aquacrop model (Raes *et al.*, 2009), with improvements to Doorenbos and Kassam's (1979) approach was released. To the best of the author's knowledge, however, crop parameters and model calibration, specifically for sugarcane, were not available at the time (Raes *et al.*, 2009). Hence the Doorenboss and Kassam (1979) approach as shown in Equation 2.1 was used. This will be discussed further in Section 2.2.1

$$1-Y_a/Y_m = K_y(1-ET_a/ET_m) \quad \text{Eq 2.1}$$

where

Y_a = yield under water deficit conditions (t/ha),

Y_m = maximum yield under full irrigation (t/ha),

ET_a = actual evapotranspiration under water deficit conditions (mm),

ET_m = maximum evapotranspiration under full irrigation (mm), and

K_y = yield response factor.

In Equation 2.1, the response of yield to water is quantified through the yield response factor, K_y, which relates the relative decrease in yield, $(1-Y_a/Y_m)$, to a relative deficit in total evaporation, $(1-ET_a/ET_m)$, (Doorenbos and Kassam, 1979).

The K_y values for sugarcane for different growth stages, as shown in Table 2-1, were determined from numerous experiments and trials. Sugarcane goes through four different growth stages, comprising of establishment, vegetative growth, yield formation and maturation or ripening (Doorenbos and Kassam, 1979). The yield response factors, in Table 2-1 illustrate that sugarcane is most sensitive to water stress during the vegetative growth stage immediately before and after crop canopy establishment and then during the grand growth or yield formation stage. Table 2-1 also illustrates that the yield response to water stress in the late maturation stage is insignificant.

Table 2-1 Yield response factors for sugarcane for a high producing variety well adapted to the growing conditions (Doorenbos and Kassam, 1979)

Crop	Establishment Phase	Vegetative Phase	Yield Formation Phase	Maturation and Ripening Phase	Total Growing Period
Sugarcane	-	0.75	0.5	0.1	1.2

In the following paragraphs, experiments and trials are presented to corroborate the yield response factors as presented in Table 2-1 by Doorenbos and Kassam (1979).

Inman-Bamber and Smith (2005) and Olivier *et al.* (2006) clearly indicated that water stress during the maturity and ripening phase beneficially resulted in water savings and an increase in sucrose content. In South Africa under various "drying off" treatments, Robertson and Donaldson (1998) demonstrated increases in sucrose content up to 18%. For this reason a common management practice is to stop irrigation and "dry off" the crop prior to harvest. Not only does "drying off" increase sucrose content and saves water but also results in reduced biomass and beneficially reduced transport and haulage costs (Inman-Bamber and Smith, 2005). In a rain shelter experiment, well watered cane yielded a sucrose content of 11.8 t/ha while cane denied water for 5 months yielded a sucrose content of 10.7 t/ha. In the latter treatment however, cane yield was reduced from 108 t/ha to 75 t/ha showing an increase in sucrose content from 10.9% to 14.3% (Inman-Bamber and De Jager, 1998). "Drying off" the sugarcane crop is a practice which provides opportunity for water savings, increased sucrose contents and reductions in harvesting and haulage costs.

Opportunities to save water also exist in the early stages of the crop growth cycle. Robertson *et a.l* (1999) reported on past experiments conducted by Roberts *et a.l* (1990) that illustrated an apparent compensatory growth and fairly good recovery after experiencing water stress in the early growth stages, provided crop water requirements were met thereafter. Robertson *et al.* (1999) conducted trials in order to analyse the physiological impact of early and mid season water deficits on sugarcane growth and yield. In the early season water deficit treatment, irrigation was withheld for almost five months after the crop received one establishment irrigation. No significant differences in the biomass and sucrose yield between the well watered control and early season water deficit treatment led Robertson *et al.* (1999) to conclude that sugarcane has the ability to recover from water deficit early in the season provided water requirements are met thereafter. In addition, evaporation from the soil surface prior to canopy cover was reported to be as high as 39% of the total evapotranspiration (Inman-Bamber and Smith, 2005). Water loss from the bare soil surface is non-beneficial and should be minimised. Resistance to water stress in the early crop growth stages allows for reduced irrigation and therefore reduced evaporation losses from the bare soil surface.

Contrary to the early season water deficit treatment, water stress during the canopy establishment and grand growth phases resulted in severe yield and sucrose reductions (Robertson *et al.*, 1999, Inman-Bamber, 2002, and Inman-Bamber and Smith, 2005). In a similar experiment, Pene and Edi (1999) also found that sugarcane was far more sensitive to water stress during stem elongation as compared to tillering and recommended the use of a deficit irrigation strategy during tillering rather than stem elongation. Chaudhry and Leme (1996) also found that percentage yield reduction due to water stress was highest (35%) after establishment of full canopy cover and second highest (30%) just before full canopy was established.

In summary, the schematic shown in Figure 2.3 below, illustrates the periods most sensitive to water stress in the sugarcane lifecycle. In this section, it has therefore been made clear that the potential existed to implement deficit irrigation on a sugarcane crop within specific growth stages.

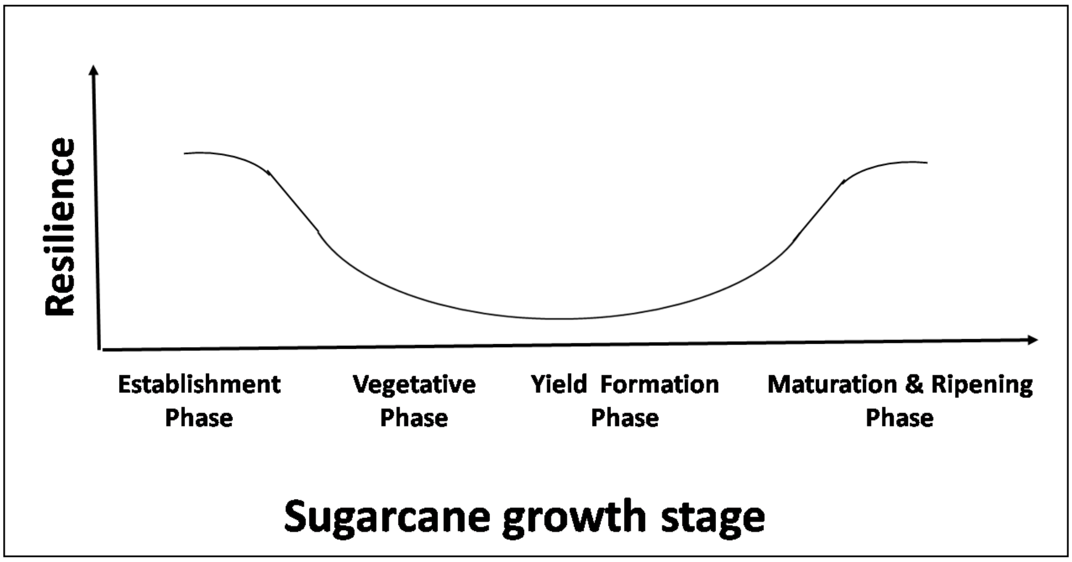

Figure 2.3 Schematic illustrating sugarcane resilience to water stress for different crop growth stages

2.2 Decision Support and Analytical Design Tools

In order to provide decision support to a farmer in moving from conventional to deficit irrigation, analytical tools to evaluate and demonstrate the potential benefits are required. Determining and optimising the benefits of deficit irrigation requires the ability to assess the tradeoffs and consequent impacts of various irrigation strategies and the associated limitations on yield, system costs and profitability. In this chapter, existing and required irrigation assessment tools are reviewed.

2.2.1 Water balance and crop yield prediction models

A detailed literature review by Greaves (2007) pointed out that a number of water balance and crop yield prediction models existed and were successfully used to assess the performance of sugarcane irrigation practices. These models included *ZIMsched 2.0* (Lecler, 2003 and Lecler, 2004a), SA*sched* (Lecler, 2004b), CANESIM (Singels *et al.*, 1998 and Singels and Smit, 2006) and *ACRU*cane (Moult *et al.*, 2006). Of these models, the *ZIMsched 2.0* model was found to be the most appropriate for this study.

The *ZIMsched 2.0* model forecasts the crop yield based on algorithms developed by Doorenbos and Kassam (1979). In *ZIMsched 2.0* the overall yield response factor (*Ky*) of 1.2, as shown in Table 2-1, is used, up until the maturation and ripening period (Lecler, 2004a). The yield response factor for the maturation and ripening phase, however, was changed from 0.1 to -0.01 in the model. This change allowed the model to better predict crop yield and was based on field trial data that showed that stress during the maturation and ripening phase does not inhibit sucrose yield (Lecler, 2004a).

During the course of this project the new AquaCrop model (Raes *et al.*, 2009), which improves on the work reported by Doorenbos and Kasam (1979) was released. The AquaCrop model differs from the Doorenbos and Kassam (1979) approach in two ways. Firstly, evapotranspiration is separated into evaporation from the soil and crop transpiration. “This separation was important to avoid the confounding effect of non-productive consumptive use of water” (Raes *et al.*, 2009). It is important to note that, prior to development of the AquaCrop model, this modification was also completed in the *ZIMSCHED 2.0* model by Lecler (2004a). The second difference was related to the final yield. The final yield was separated into a biomass component and a harvest index component. This separation was important to better model the functional relations between the crop and the environment (Raes *et al.*, 2009). In this regard, various parameters such as those shown for maize, in Appendix A are required to run the AquaCrop model. Even though AquaCrop appears to be a better and improved model, calibration of the model for the sugarcane crop is apparently outstanding. Crop parameters, such as those shown in Appendix A, were available for cotton, maize, soya beans and sugar beet. To the author's knowledge, these parameters were not yet available for sugarcane. Hence the *ZIMsched 2.0* model was used.

"The *ZIMsched 2.0* model was developed to predict how field derived indices of irrigation performance, such as the coefficient of uniformity (CU) impacted on yields and the water balance" (Lecler, 2003). The model was unique in that it possessed the ability to account for irrigation systems performing at different levels of uniformity. This was important when accounting for the impact of irrigation hardware and strategies on yield (Moult *et al*., 2006). In *ZIMsched 2.0*, "the complexities of water budgeting were integrated in the form of robust algorithms based on leading research by, *inter alia*, Schulze (1995) and Allen *et al.* (1998)". Processes such as:

- evaporation from the soil surface and transpiration (in relation to atmospheric evaporative demand, available soil water, crop and rooting characteristics and irrigation system type), and
- surface runoff and deep percolation (as impacted on by rainfall effectiveness and uniformity or non-uniformity of irrigation water applications)

are all accounted for (Lecler 2004a).

The inputs into the model are not exhaustive and include the following: agronomics details such as planting date and length of season, irrigation system constraints including irrigation frequency and depth, soil and climate characteristics such reference evaporation and rainfall, amongst others (Greaves, 2007). The outputs include the water use and corresponding yield or soil water deficit for irrigation scheduling purposes. The yields and water use simulated by *ZIMsched 2.0* can therefore be used to assess the performance of various irrigation strategies, including deficit strategies.

2.2.2 Economic assessment model

Irriecon v2 is a spreadsheet based tool used to assess different irrigation strategies through determining detailed capital, operating and marginal costs (Armitage *et al*., 2008). As shown in

Figure 2.4 below, the specific costs associated with sugarcane farming practices such as the application of fertilizer and herbicide, planting, harvesting and haulage together with irrigation systems, water and electricity costs are accounted for (Armitage *et al.*, 2008). The tool was developed based on cost estimation procedures for irrigation systems as presented by Oosthuizen *et al.* (2005).

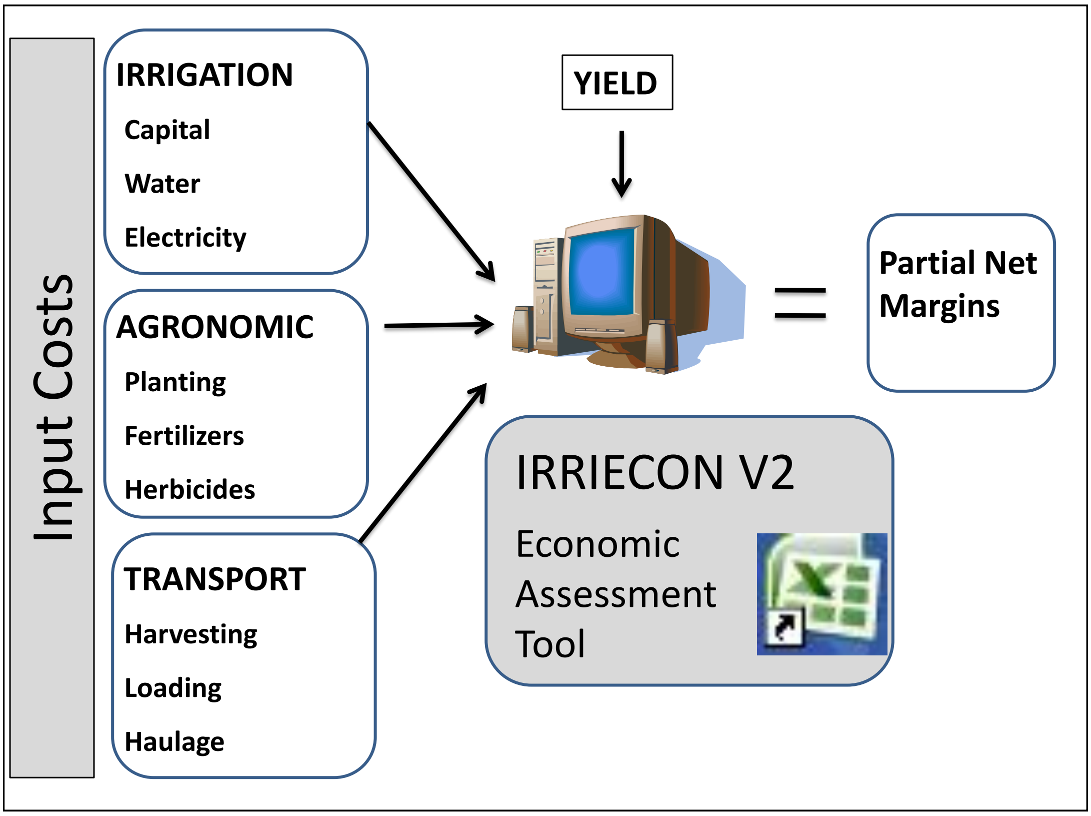

Figure 2.4 Schematic of the *Irriecon V2* model

An example of the application of the model is profitability assessment of irrigated versus dry land sugarcane farming (Armitage *et al.*, 2008). Other applications include comparison of systems (e.g. sprinkler versus drip) and different irrigating strategies such as more frequent smaller water applications versus less frequent larger applications, when used in conjunction with a model such as *ZIMsched 2.0* (Armitage *et al.*, 2008). The model was a suitable tool for determining optimum irrigation strategies for different systems and contexts which take into consideration economic aspects, including water costs, various electricity tariff options, irrigation design, irrigation constraints, agronomic practices and associated crop yield expectations. *Irriecon v2*, however, must be used in conjunction with yield and water use data, which may be simulated using water balance and crop prediction models such as *ZIMsched 2.0*.

2.2.3 Irrigation design evaluation and costing tool

The water balance and crop prediction model and the economic assessment tool existed and had already been used successfully as described above. The missing link, however, was a tool to quickly generate irrigation designs and associated costs of hardware that are representative of the constraints used in *ZIMsched 2.0*. For example, in *ZIMsched 2.*0, “system A” might represent a lower coefficient of uniformity due to sprinklers operating at a wider spacing and lower operating pressure, while “system B” may have higher coefficient of uniformity as a result of smaller spacing and correct operating pressure. When comparing, “system A” may require less pipes to cover the same area and therefore have lower capital costs. System “A”, however, may generate lower yields and revenue due to non uniform application of water (Benami and Ofen, 1984). Hence, in order to assess the tradeoffs between yield penalties and reduced system costs, a design and costing component was required to provide capital and operating costs of irrigation systems.

To the author’s knowledge, options to cost irrigation hardware for alternative designs are limited to outsourcing to irrigation consultants, an option used by Oosthuizen *et al.*(2005) or purchasing commercially available design tools, such as Model Maker (2009). Outsourcing was considered too expensive and inflexible. Although purchasing Model Maker was a potential option, it was decided to rather develop a spreadsheet-based design and costing tool for the following reasons:

- there were budget limitations – Model Maker was priced at R 16, 200 (Model Maker, 2009)
- developing a spreadsheet-based tool allowed for a high degree of flexibility
- and developing a tool ensured all design procedures and implications were well understood.

The design and costing tool will be further discussed in Chapter 3.

2.3 Conclusions

In a time of financial strain, deficit strategies appear to be the best bet profit optimising strategy for growers. In addition the sugarcane crop’s response to water stress, during different growth stages, provides opportunities to implement deficit strategies. In order to encourage the uptake of these strategies, further research demonstrating and quantifying the benefits were required.

This presented an opportunity to use simulation models and analytical tools to formulate and assess various deficit irrigation strategies specifically for the South African context. Appropriate tools and assessment methods, however, were vital for further research. Existing tools that were successfully used in the past were reviewed in order to gauge their appropriateness for this study. The *ZIMsched 2.0* and *Irriecon V2* models were found to be well suited. Irrigation design and costing tools, however, were not easily accessible or well suited. In the next chapter, the manner in which these tools will be used is illustrated via the development of an irrigation assessment framework. In addition, a detailed description of the spreadsheet-based irrigation design and costing tool is presented.

3. IRRIGATION ASSESSMENT METHODS

Irrigation can be broken down into two large components. Firstly the planning and design of an irrigation system and secondly the operation, management and maintenance of the irrigation system after it has been installed. Analytical tools are typically used in the planning and design phase to assess scenarios and optimise systems before implementation. Agricultural production, however, is a complex system and assessment of an irrigation system in the planning phase should include three components, namely engineering, agronomic and economic performance.

The first component is the engineering design and performance which to a large degree dictates the capital and operating costs of the system. More uniform, and therefore effective, systems involve a trade off between increased capital expenditure on equipment and the benefits of reduced water application associated with high uniformity (Brennan, 2008). For example, sprinkler “A” has to be operated at 12 x 12m spacing at 250 kPa in order to perform at the acceptable uniformity level. The sprinkler and lateral spacing will dictate the number of sprinklers and pipes required, while the pressure requirements will be used to determine the size of pipes and pumps. Hence, the design impacts on both the capital and electricity costs. A poorly designed system, for example sprinkler “A” operated at a wider 15 x 15m spacing and 200 kPa, may have lower costs but will result in non uniform application of water. Hence a direct relationship exists between system hardware costs and engineering performance.

The second component is the agronomic performance of the crop in terms of yield and is largely dependent on the capability of the irrigation system and management. Finally, the third component is the economic performance which is both a function of irrigation design to determine costs and crop yield to determine revenue generated by the irrigation system.

It is easy to see that these three components are inter-related and need to be accounted for concurrently to holistically asses an irrigation strategy. In practice, however, even though the analytical tools to assess the three components exist, it appears that they are not frequently used conjunctively. Irrigation designers often generate and implement irrigation designs that simply meet the recommended and widely accepted engineering standards and norms. Optimising and refining a design is considered too costly an exercise in terms of tools required and more importantly the perceived lack of benefit for the time consumed. This chapter, therefore, focuses on the development of an efficient and relatively quick method to generate and assess alternative irrigation strategies. It was envisaged that researchers would use the framework to assess alternatives and develop recommendations for practical and real problems faced by irrigation designers and practitioners.

3.1 A Framework to Assess Alternative Irrigation Design and Operating Practices

Optimising the use of water for irrigation will inevitably involve the use of tools to analyse and assess the performance of various strategies. These tools are often referred to as decision support tools. As described above, assessment of irrigation strategies should include the engineering, agronomic and economic performance. Shown in Figure 3.1 below is the framework proposed to holistically asses alternative irrigation strategies. Figure 3.1 graphically illustrates the tools used to assess each component and there interacting relationships.

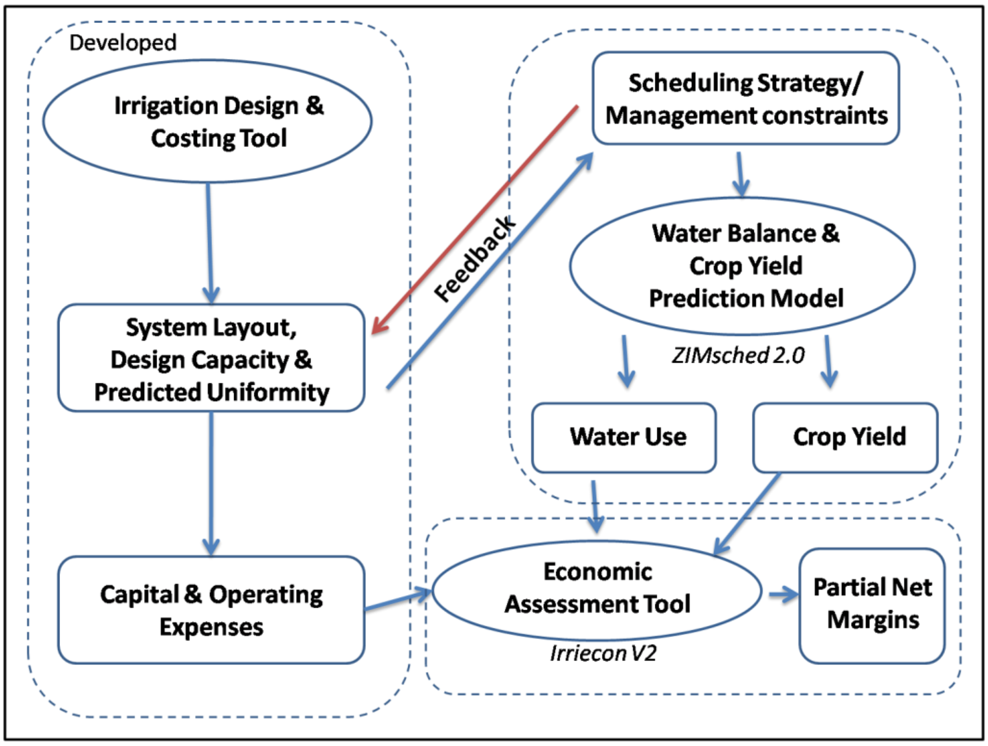

Figure 3.1 Framework for assessing alternative design and operating strategies

In Figure 3.1, the first tool on the top left hand corner is an irrigation design and costing tool. This tool would be used to generate a series of alternative irrigation designs and assess the cost implications of differing irrigation hardware. The engineering performance of the irrigation system, in terms of uniformity, would form part of the minimum design criteria. The second tool is the water balance and crop yield prediction model. This model would be used to assess the agronomic performance in terms of crop yield for a given irrigation regime and its constraints. And the final tool is the economic assessment tool. The effectiveness of this framework, however, is dependent on the availability, suitability, cost and ease of use of the individual models used to assess each component. In the context of the South African Sugarcane Industry, the *ZIMsched 2.0* and *Irriecon v2* models, reviewed in the previous chapter, appeared to be ideal for use within the framework. The missing link, however, was the design and costing tool.

3.2 Development of an Irrigation Design and Costing Tool for Semi-permanent Sprinkler Irrigation

The decision was taken to develop a spreadsheet-based tool which would allow for transparency regarding system design and selection processes. In addition, a spreadsheet based tool allows for a high degree of flexibility to modify and change design algorithms easily. It was assumed that this tool would be used predominantly by researchers who are knowledgeable with irrigation design procedures. Shown in Figure 3.2, is a schematic of the different components in the design and costing tool.

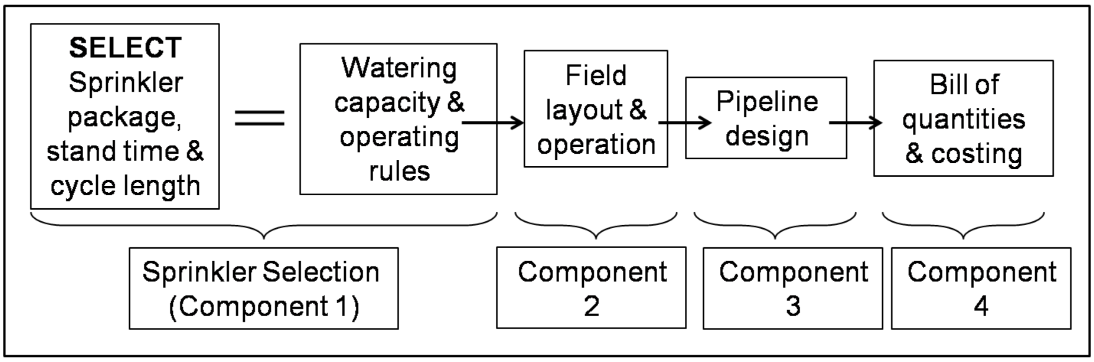

Figure 3.2 Components of the design and costing tool

The tool constitutes four components, namely, sprinkler selection, field layout & operation, pipe design and finally, the bill of quantities and costing. Figure 3.2 demonstrates the logical sequence with which the tool was designed. It should be noted that the development of the design and costing tool formed a pivotal role in this project. Without the design and costing tool, the analysis in Chapters 3, 4 and 5 would not have been a simple task. In this chapter, the reader will be led through the above sequence, in order to understand how the tool was developed. Due to the significant role of the tool, description of thought processes and justification of methods used during development are also presented.

3.2.1 Sprinkler selection for a target system capacity – component 1

The role of an irrigation designer is to identify, with the help of the end user, the desired result and then select and specify, taking into account existing resources, the equipment and operating rules required to meet the desired result. For sprinkler irrigation, this is illustrated in Figure 3.3.

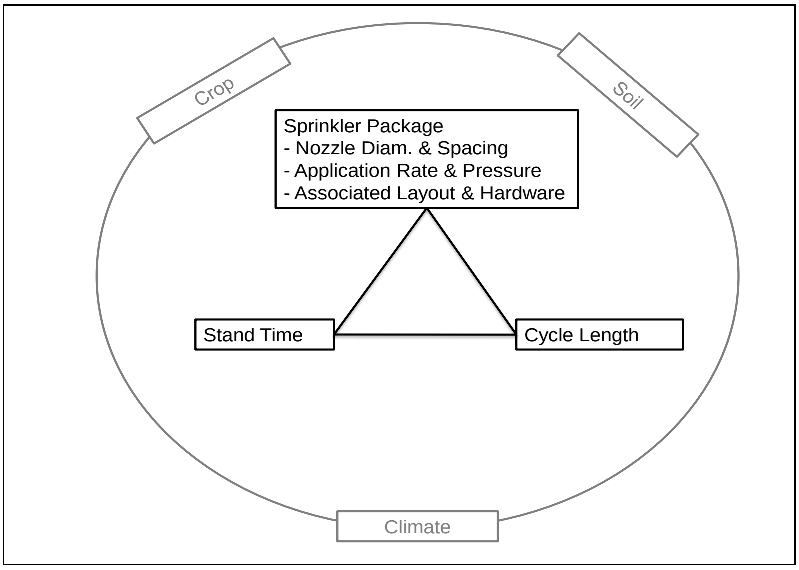

Figure 3.3 Illustration of irrigation parameters to be selected for sprinkler irrigation

In Figure 3.3, the crop, climate and soil, on the outer ring, represents existing or fixed parameters that would be used to determine the crop water requirements and accordingly the target depth. The irrigation designer would then select the sprinkler package, the cycle length and stand time in conjunction with one another to meet the target depth. This is best explained with an example. Say for instance the target depth of application is 4.4 mm/day. One would then select, say sprinkler X with a 4 mm nozzle operated at 350 kPa delivering 1.2 m^3/hr. If sprinkler X was laid out at 18 x 18 m spacing, the area covered by one sprinkler is 324m^2.

Hence application rate for this instance = $\frac{Q}{A}\left[\frac{m^3/hr}{m^2}\right]$

$$= \frac{1.2}{324}\left[\frac{m^3/hr}{m^2}\right] = 0.0037 \text{ m/hr} \times 1000$$

$$= 3.7 \text{ mm/hr.}$$

One now needs to select an appropriate stand time and cycle length. In this case, if the sprinkler was operated for 12 hours once every 10 days, i.e stand time = 12 hours and cycle length = 10 days, depth of application = 3.7 mm/hr × 12 hrs

= 44.4 mm every 10 days

= 4.4 mm/day

Referring back to Figure 3.3, it must be noted that the parameters in the triangle; i.e. sprinkler package, cycle length and stand time, are interdependent and can be determined or chosen in any order. For this reason, more than one combination may provide an acceptable solution. For instance, in the example above, for the same sprinkler package, a stand time of 7 hours and a cycle length of 6 days returns the application depth = 3.7 mm/hr × 7 hrs

= 25.9 mm every 6 days

= 4.32 mm/day

In this case, the farmer may have indicated that no irrigation would take place on Sundays and for this reason the cycle length of 6 days may have been selected first. Both sets of operating rules meet the targeted depth. The choice of either option has an implication on the agronomic performance and cost of the system. The user should ensure that only the most suitable option is selected. For example, the user should ensure that the water application is well matched to the soil.

As described above, Figure 3.3 adequately encapsulates the criteria for selecting the systems target peak capacity. For this reason, Figure 3.3 formed the basis of the first design component. In the next section Figure 3.3 was transformed into a spreadsheet-based tool were the necessary parameters were used to select the appropriate sprinkler package and operating rules.

3.2.1.1 Matching system application depth to target depth

In Table 3-1 below, the tool was set up were the target depth could be matched to the system application depth by selecting an appropriate combination of the sprinkler package, cycle length and stand time. The target depth represents the desired target in terms of mm water application per day, while the system application depth is the actual application capacity that a system can deliver for the selected sprinkler, stand time and cycle length. In Table 3-1, the user is required to enter, in any order, appropriate values into the shaded cells, which represent, either, the sprinkler package, the cycle length or the stand time. Non shaded cells are calculated automatically as specified in ARC-ILI (2004). The sprinkler information had to be obtained from sprinkler laboratory test data. This is discussed further, below.

Table 3-1 Demonstration of the first section of the design tool were sprinkler packages and operating rules are selected to achieve a desired target

Sprinkler Information[1]			**Target Depth**	mm/day	**5.00**
Brand/ type	VYRSA 35				
Nozzle diameter	4.4	mm	Area per sprinkler	m^2	378
Nozzle material	Brass		Gross Applic. Rate	mm/h	4.30
Operating pressure	300	kPa			
Sprinkler spacing	18	m			
Lateral spacing	21	m	**Cycle Length**[2]	days	10.00
Application rate	4.3	mm/hr	**Stand Time**[2]	h	12
Discharge rate	1.6254	m^3/h	**Sets per day**[2]	no	2
Coefficient of Uniformity	87	%			
Distribution Uniformity	83	%	**Application Depth**	mm/cycle	51.6
				mm/day	**5.16**

1 – Sprinkler data obtained from ARC sprinkler test data (ARC-ILI, 2008)

2 – Cycle length, stand time and sets per day adjusted to match target depth to application depth for a given sprinkler package.

One of the challenges faced by users was how does one select an appropriate sprinkler? This was because sprinkler manufacturers provide very little information regarding the performance, in terms of uniformity, for varying operating pressures and spacing. This implied that a user, if depending on sprinkler manufacturers catalogues, would often have trouble filling in the shaded cells under sprinkler information in Table 3-1. Sprinkler catalogues typically only provide the corresponding application rate for popular sprinkler spacing, such as 18 x 18m or 12 x 12m, and varying combinations of operating pressures and nozzles (HOI, 2008). Combinations of sprinkler and lateral spacing and corresponding uniformities are almost never available. Hence, sprinkler test data was sourced from ARC-ILI (2008) in order to develop a sprinkler database query utility.

3.2.1.2 Sprinkler database query utility

Mr. Adrian van Niekerk (ARC-ILI, 2008), over many years, had tested several sprinklers with an indoor single leg sprinkler testing facility. The test data allowed one to assess the performance of a specific sprinkler in terms of application rate and uniformity for varying combinations of spacing and operating pressures. An example of the sprinkler test data is provided in Appendix B. The test data for every sprinkler, however, was saved onto a different Microsoft Excel file in a format not suitable for selecting sprinklers. This implied that one would have to sift through a multitude of files and sprinkle spacing and operating pressure combinations in order to find a suitable sprinkler for a specific application. The author, for this reason, compiled a database query utility. The utility consisted of a database of all the sprinkler test data that was acquired from the ARC. It must be noted that the sprinkler database query utility is not comprehensive as it was limited to only the sprinklers and nozzles tested at the ARC facility. This data base is a work in progress and new sprinkler test data can be added at any given time. Furthermore, the tool was set up where an advanced filter function in Microsoft Excel allows a user to select sprinkler options according to pre determined criteria. For example, a user could specify criteria such as: an application rate greater than 3.8 but less than 4.2 mm/hr, sprinkler and lateral spacing greater the 15 x 15m, operating pressure less than 350 kPa and a coefficient of uniformity greater than 80%. The advanced filter function is then used to search through the database. Sprinkler options that match the criteria are copied and pasted into an output table where the user can analyse and determine which option is the most appropriate. Data for the selected sprinkler is then manually entered into the irrigation design and costing tool under the sprinkler information section as shown in Table 3-1.

Completing Table 3-1 appropriately, provides insight as to what sprinkler package and operating rules are required to meet the desired irrigation application depth. The next step in the design tool was to determine how the hardware would be laid out and operated in the field. How many sprinklers would be used? How would the sprinklers move across a field? What lengths of laterals are required? What area could be irrigated by the selected hardware? These types of questions are addressed in the next section of the design and costing tool.

3.2.2 Field layout and operation – component 2

This section consisted of three aspects, namely, sprinkler movement in the field, optimum mainline and sub mainline layout and finally quantifying field dimensions. These are discussed below.

3.2.2.1 Sprinkler movement in the field

One of the many challenges facing traditional dragline systems was the movement of sprinklers across the field. In many instances, if proper records were not kept, it was very difficult for a famer to tell if the sprinkler was moved to the correct position at the correct time. It was clear that the success of a well designed irrigation system, even for semi-permanent systems in this case, was dependent on how easy it was to operate and manage. For this reason, a systematic and logical method of moving the sprinklers in the field was selected for the irrigation design and costing tool. This is illustrated in Figure 3.4 below. Shown in Figure 3.4 is a mainline, running up the slope, with 4 laterals, parallel to the contours. All laterals and mainlines are permanent and buried. Only the sprinklers are mobile and dependent on labour. The numbers on the 2 top laterals represent hydromatic valves where a sprinkler can be placed. In this example, the sprinkler starts at position 1. The grey shade indicates that a sprinkler is located and operating at that point. The sprinkler would then move from position 1 to 2, 2 to 3, 3 to 4, all the way through in a loop to position 10.

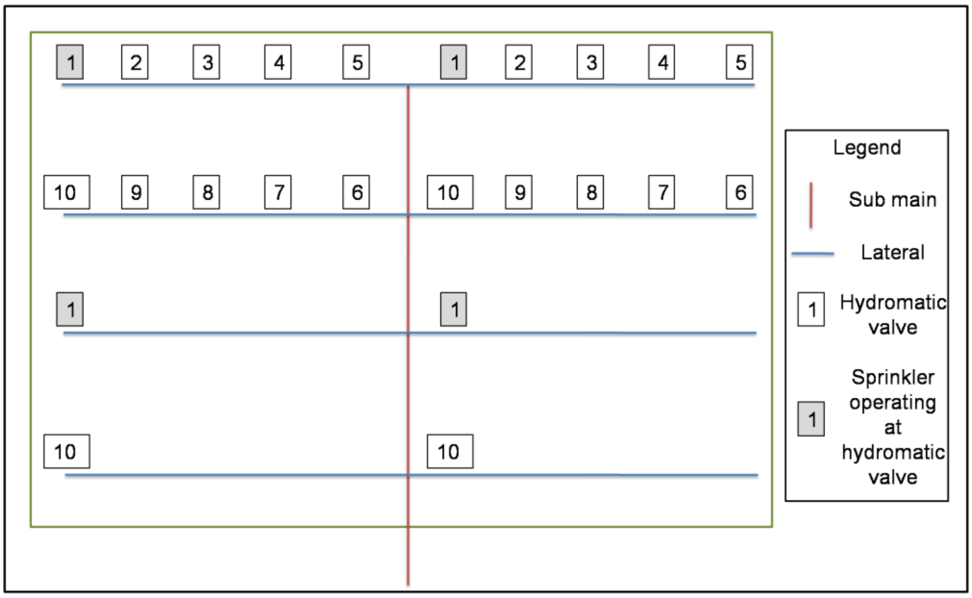

Figure 3.4 Layout and movement of sprinklers in the field

In this system, every alternative lateral is equipped with 2 sprinklers. The sprinklers are placed at position 1 on either side of the sub mainline. By operating the sprinklers on either side of the sub mainline, the flows are split. Hence, each lateral is designed for the flow of a single sprinkler. The major advantage of this was reduced capital costs since relatively small pipe diameters were required. In addition, since the flows were relatively small, water hammer would not be a concern and the sprinklers could be moved without having to switch off the pump. Furthermore, all active sprinklers would be well aligned. Hence, if the grower drove along the field edge, it will be easy to see if a sprinkler was not operating in the correct position. Finally, the looping movement also helps get the sprinkler back to the starting position. Hence, the design tool made use of this simple operating rule for sprinklers. All systems were designed to incorporate sprinkler movement as described above.

3.2.2.2 Optimum layout for mainline and sub mainlines

The second issue was related to field layout? The author wanted to ensure that the most cost effective layout was used as the template in the design and costing tool. Hence, alternative field layouts as shown in Figure 3.5 were investigated. In Figure 3.5, the assumptions were as follows. The field was located 20 m away from a river. The slope from the river up the field was consistent and fixed at 2%, in this instance. The option, however, to alter the slope does exist in the tool. The cross slope, parallel to the river was assumed to be 0. Hence any given lateral was assumed to be consistently on the same level, except in system B. The different layouts are described below.

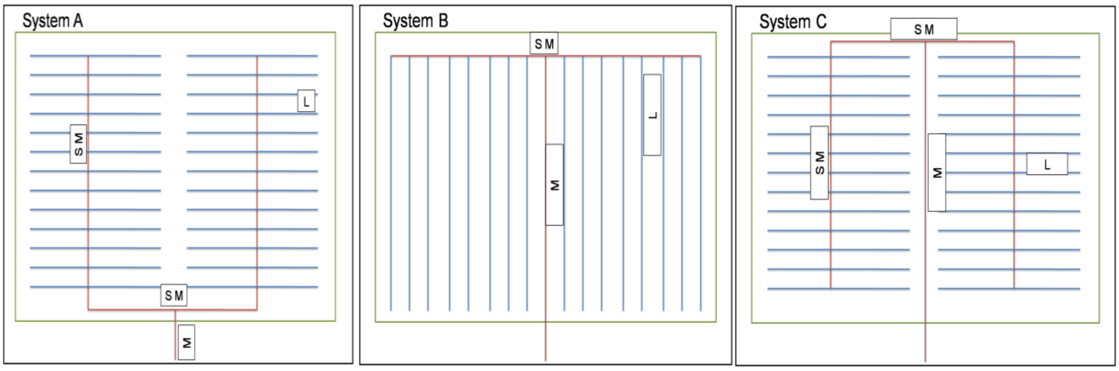

Figure 3.5 Alternative field layouts that were investigated. M = mainline, S M = Sub Mainline, L = Laterals

As shown, in system A, the mainline only runs for 20 m up to the field's edge before it splits into two sub mains which then feed into the laterals. When designing system A, the minimum sprinkler pressure requirements must be met for the laterals at the top of the field. Invariable this implies that too high pressures are supplied to sprinklers on the lower laterals resulting in non uniform applications. The alternatives were to either make use of pressure regulating valves or consider options shown in system B and C. Pressure regulator valves would have to be installed on every lateral since sprinklers will be operating on a number of laterals at any time. This may prove to be expensive. Systems B and C on the other hand have main lines that run all the way to the top of the hill and either laterals (system B) or sub mains (system C) that run down the hill. The theory was that by running the laterals or sub mainlines down the slope, the gain in pressure due the increasing gravity head could be balanced by friction. Hence in designing the pipe line, appropriate diameters are selected to maintain the pressure variation within the allowable standards. This eliminates the need for pressure regulator valves, except for when there are steep slopes. The main lines, however, will have significantly higher costs since the water volume for the entire system will have to be pumped to the highest point in the field. This implies larger diameter and higher class pipes will be required.

As an aside matter, the above discussion is a great demonstration of questions an irrigation designer might pose and not necessarily have the tools or time to answer. This illustrates the usefulness and potential value of the irrigation design and costing tool. Since the tool was spreadsheet based, modifications in the tool to assess each option were relatively easy. With that being said, the tool was used to assess the above alternative field layouts. Separate spreadsheets were configured for each of the above systems and the costs were determined. System A, made use of the Senniger pressure regulating valves and worked out to be cheaper than the alternatives. The cost breakdown and percentage increase of each system is shown in Table 3-2 below.

Table 3-2 Cost break down for the alternative field layouts that were investigated

Area = 53.49 ha	**System A**	**System B**	**System C**
Sprinkler package	R 73, 385	R 73, 385	R 73, 385
Laterals	R 303, 710	R 680, 126	R 303, 710
Sub Mains	R 84, 867	R 33, 783	R 109, 177
Main Line	R 4, 082	R 111, 914	R 108, 107
Valves	R 8, 845	--	R 800
Crosses / Tees / Hydrants	R 66, 310	R 31, 974	R 63, 848
Trenching	R 212, 592	R 228, 048	R 218, 016
Total	**R 753, 792**	**R 1, 159, 230**	**R 877, 043**
% increase in costs from System A	**0%**	**54%**	**16%**

As shown in Table 3-2, system A was the cheapest and for this reason system A was used as the template field layout for the design and costing tool.

3.2.2.3 Quantification of field dimensions

The next step was to quantify the details pertaining to the field layout. These included determining the number of laterals, lateral length, field area and number of sprinklers. Before getting into the detail, it is important to note that the tool was designed to provide representative irrigation hardware costs for easy comparison of various scenarios and irrigation systems.

Hence, the field layout was hypothetical and based on simplifying assumptions. The field was always assumed to be rectangular in shape. In addition, for reasons that will be discussed below, target design areas, for example 50 hectares, were not always achievable. Hence, when comparing irrigation systems that covered varying areas, the costs were reduced to Rand per hectare. This provided fairly representative system costs and allowed for easy comparison. In the following paragraphs, the rationale and calculations for determining the field dimensions and area are presented.

Only three bits of information were required for this section i.e. the length of the sub mainline, the number of sub mainlines and the number of sprinkler positions per lateral. These data were entered into the shaded cells in the Table in Figure 3.6. As shown in Figure 3.6, 700 m was selected for the first parameter, the sub mainline length. The criteria for selecting the sub mainline length, in this case, were related to achieving a realistic pumping head and obtaining a fairly square field. Take note, when preparing a number of designs for comparison purposes, the sub mainline length and therefore the pumping head should be kept constant to allow for sensible comparison. In this case, a 2% slope of 700 m equated to a 14 m pumping head. Furthermore, a 700 m sub mainline, when targeting 50 hectares, delivered a field length and width of 710 and 720 m, respectively. See below for the explanation of how these dimensions were calculated.

Length of Sub main	**m**	**700**
No. of laterals / sub main		**33**
No of sub mains	**no**	**2**
No. of sprinklers positions/lateral		**20**
Lateral Length	**m**	**342.00**
Field Width	**m**	**720.00**
Field Length	**m**	**710.50**
Area	**ha**	**51.16**
No of sprinklers		**66.00**
Flow rate	**m^3/hr**	**107.3**

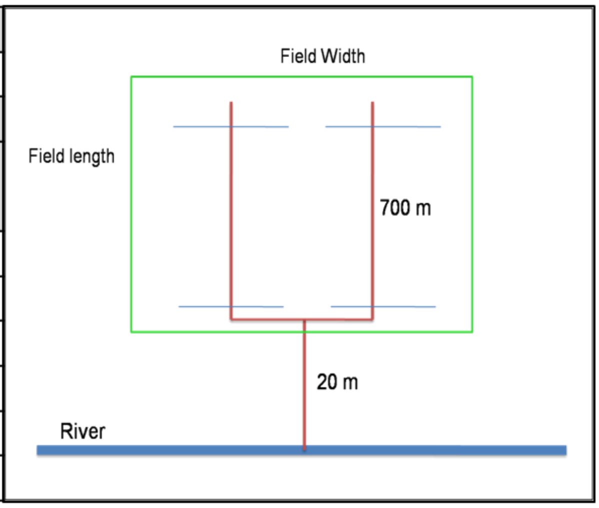

Figure 3.6 Illustration of field layout and table where data required for this component is entered

Having already selected the sprinkler package, the sprinkler and lateral spacing was already known and was used to determine the number of laterals. In Table 3-1, the lateral spacing was

21 m. Hence a 700 m sub mainline, shown in Figure 3.6, can be divided into thirty three 21 m segments. Hence the number of laterals per sub mainline for this example was 33.

Next, the user was required to enter the number of sub mainlines that were to be used. In this case, as shown in Figure 3.6, 2 sub mainlines were used. The number of sub mains “input” was used to prevent the system from having too long laterals. Longer laterals, with fewer sub mainlines would have higher mainline flows and frictions losses resulting in higher pumping costs. The other factor that was used to determine the length of laterals was the number of sprinkler positions per lateral. This input, however, required special attention. As explained in Figure 3.4, the system was designed so that the sprinklers could be moved in a looping manner. Hence, for this mechanism to work, the number of sprinkler positions on a lateral had to be a multiple of the cycle length. For example, in this case the cycle length was 10 days, therefore 20 sprinkler positions was entered into the shaded cell. Similarly if a 7 day cycle length was used, the values entered into the shaded cells would be limited to 7, 14, 21 or 28 sprinkler positions. If this rule was not adhered to, the sprinklers would either not complete the loop in time or complete the loop too early. This would disrupt the logical movement of the sprinklers.

In addition, adhering to this rule limited the flexibility with which lateral lengths and therefore design areas where selected. For this reason, as mentioned above, target areas such as 50 hectares were not always achieved. Nevertheless, this was overcome by optimally designing for areas that were still within the same scale and reducing the costs to Rand per hectare.

Having selected the number of sub mainlines and the number of sprinkler positions, the lateral length was then easily determined as a function of the sprinkler spacing. The lateral and sub mainline lengths were then used to determine the field width and length respectively. The distance from the edge of the field to the sub mainline or sprinkler was fixed at half the lateral or sprinkler spacing, respectively. The area was then simply determined as the product of the field length and width. Take note, if designing for a target area, say 50 hectares. One would have to enter the correct combination of sub mainline length, number of sub mains and number of sprinkler positions into the shaded cells to match the target area, as close as possible.

Next, the number of sprinklers was also determined as a function of the number of laterals and number of sub main lines. In this case, 1 sprinkler was operated per lateral. Therefore the number of sprinklers was equal to the number of laterals i.e. 33 laterals × 2 sub mainlines = 66 sprinklers required. Finally, the total system flow rate was the product of the number of sprinklers and the flow for a single sprinkler.

3.2.3 Pipeline design – component 3

The next step was the hydraulic design and sizing of the pipes. In this section all methods and design rules were according to the Irrigation Design Manual (ARC-ILI, 2004). It was assumed that the user would be fairly knowledgeable with regards to irrigation design and for this reason the basics are not described in great detail. Instead, the aim of this section was to describe how the tool was set up and to demonstrate the ease with which the necessary calculations can be completed.

A spreadsheet was set up as shown in Table 3-3. The table was set up for point to point design. In other words, the calculations would begin at a point and pressure or flow values, for example, would be carried over to the next point. In this case, as shown in Table 3-3, the calculations were started at point AB1. AB1 represented the sprinkler position at the end of a lateral in the field. This is shown as position 1 in Figure 3.4. The calculations would then proceed from the end of the lateral through to AB2 and AB3 and so on, working towards the sub main line. In this case, Table 3-3 shows the design of one half of the lateral, starting at the end sprinkler position, AB1, and moving in 18 m segments to the next sprinkler position for 10 segments/sprinkler positions. Since the other half of the lateral was a mirror image due to the splitting of flows, the design for the first half was exactly the same as the second half. Similarly, all laterals were identical, in terms of slope, number of sprinklers (flow rate) and length. Therefore only a single lateral was sized and applied to the others.

Table 3-3 Lateral design worksheet showing example of hydraulic pipe design

Position	**Flow rate**	**Length**	**Allowable H_f**	**Diameter**	**Pipe Class**	**Internal D**	**Velocity**	**H_f (Hazen Williams)**	**H_f (General exponential)**	**Pressure required to overcome friction**	**Height**	**Total pressure**
	m^3/s	m	m	m		m	m/s	m	m	kPa	m	kPa
		0								300	0	
AB1	0.00045	18	0.27	0.03	32&9	0.03	0.68	0.40	0.42	304.00	0	304
AB2	0.00045	18	0.27	0.03	32&9	0.03	0.68	0.40	0.42	308.01	0	308
AB3	0.00045	18	0.27	0.03	32&9	0.03	0.68	0.40	0.42	312.01	0	312
AB4	0.00045	18	0.27	0.03	32&9	0.03	0.68	0.40	0.42	316.01	0	316
AB5	0.00045	18	0.27	0.03	32&9	0.03	0.68	0.40	0.42	320.01	0	320
AB6	0.00045	18	0.27	0.03	32&9	0.03	0.68	0.40	0.42	324.01	0	324
AB7	0.00045	18	0.27	0.03	32&9	0.03	0.68	0.40	0.42	328.02	0	328
AB8	0.00045	18	0.27	0.03	32&9	0.03	0.68	0.40	0.42	332.02	0	332
AB9	0.00045	18	0.27	0.03	32&9	0.03	0.68	0.40	0.42	336.02	0	336
AB10	0.00045	18	0.27	0.03	32&9	0.03	0.68	0.40	0.42	340.03	0	340
	Sum	180	2.7			Allowable pressure variation						60

Hf = Friction loss in the pipe.

Two methods were made available for pipe sizing. The first was to restrict the friction loss to less than 1.5% of the length of the pipe. This value was shown in the column with the title "allowable H_f". The second option was to select pipe diameters to ensure that pressure variation in the pipeline was less than 20% of the sprinkler operating pressure. Both methods are in accordance with SABI norms (ARC-ILI, 2004). The second option was less conservative and therefore used to design the lateral. Essentially, in most cases, this allowed for the same pipe diameter to be used for the entire length of the lateral, making implementation much easier. This is demonstrated in Table 3-3 above. As before, a user was only required to input values in the grey shaded cells, i.e. pipe diameter and class of pipe. All other values are either determined or carried forward from previous tables in the tool. For example, since only one sprinkler operated per lateral, the flow rate for all segments in the lateral was equal to that of a single sprinkler and was carried forward from the sprinkler information in Table 3-1. Similarly, the sprinkler spacing of 18 m was carried forward from Table 3-1 to the length column in Table 3-3. In the case of the internal diameter, the pipe diameter and class was used in conjunction with a lookup table to bring forward the corresponding values.

In the tool, the Hazen Williams formula (ARC-ILI, 2004) was used to calculate the pipe friction loss. In addition the General Exponential Equation (ARC-ILI, 2004) was also presented as a check. In Table 3-3, the first value in the "pressure required to overcome friction" column was 300 kPa, representing the operating pressure of the sprinkler. Hence the allowable pressure variation was 20% of 300 kPa which was equal to 60 kPa. In designing the lateral, as is the case in Table 3-3, the pipe diameters and classes were selected to ensure that the pressure variation did not exceed 60 kPa. In this case, 32 mm class 9 pipes incurred a pressure increase from 300 kPa up to 340 kPa. The resultant 40 kPa pressure variation was below the allowable 60 kPa and therefore acceptable. Take note, only class 9 pipes were available in the 32mm diameter range and 32 mm class 9 pipes were cheaper than 40 mm pipes. See Table 3-5. Hence 32 mm pipes were used for all laterals. The next step was to design the sub main lines. As shown in Table 3-4, a similar approach was used. The design started at lateral 1 on the top of the hill and worked its way down the sub mainline in 21 m segments. Table 3-4 is only an extract, showing 5 segments, of the complete sub main line design.

Table 3-4 Sub main line design worksheet showing an example of hydraulic design

Position	Flow rate	Length	Allowable H_f	Diameter	Pipe Class	Internal D	Velocity	H_f (Hazen Williams)	H_f (General exponential)	Pressure required to overcome friction	Height	Total pressure
	m^3/s	m	m	m		m	m/s	m	m	kPa	m	kPa
										340.03	14.40	
1	0.0009	21	0.315	0.05	50&4	0.05	0.52	0.16	0.16	341.64	14.40	341
2	0.0009	21	0.315	0.05	50&4	0.05	0.52	0.16	0.16	343.24	13.98	347
3	0.001806	21	0.315	0.063	63&4	0.06	0.63	0.18	0.18	345.00	13.56	349
4	0.001806	21	0.315	0.063	63&4	0.06	0.63	0.18	0.18	346.77	13.14	350
5	0.002709	21	0.315	0.063	63&4	0.06	0.96	0.37	0.36	350.50	12.72	354

Hf = Friction loss in the pipe.

Once again, the user only needs to select appropriate pipe diameters and classes. Values, such as the pressure were brought forward from the lateral design sheet. Unlike the lateral design, however, the pressure variation rule was not used to design the sub mainlines. Instead the allowable friction loss was determined as 1.5% of the pipe length for each segment. This more conservative approach was used for the sub main line and main lines since higher flows were encountered. Higher flows can result in increased velocities and water hammer problems if not designed carefully. Hence pipe sizes and classes were selected to ensure that the friction as determine by the Hazen Williams formula (ARC-ILI, 2004) was less than the allowable friction. For example, in position one in Table 3-4, the allowable friction was 0.315 m and the Hazen Williams friction was 0.1649 m for the 21m length of pipe and specified flows and diameter. This was acceptable. In position 5, however, the Hazen Williams friction, 0.3596 m was greater than the allowable 0.315 m. Hence the selected 63 mm pipe was too small and must be changed to the next bigger diameter. As before, on completion of the sub mainline design, relevant information was then carried forward in to another table for the main line design. The process in terms of sizing pipes and minimising friction within allowable limits was the same as for the sub mainline and is therefore not shown here.

3.2.4 Bill of quantities and costing – component 4

The final component in the design tool was to prepare a bill of quantities and the associated costs. As reported previously, this design tool was required to provide systems costs. System costs which would be used as inputs in the *Irriecon V2* model for economic assessment of a pre-designed strategy. The objective was to have the costing portion automated in the tool, so that no input or effort was required from the user. This would allow for quick and easy generation of adequately designed systems and the associated system costs. This objective was achieved as follows.

A template with costs for all pipe sizes and classes was set up on a different worksheet. Shown in Table 3-5 is an extract of the template with only three pipe diameters, namely 32, 40, and 50 mm. As explained previously, three separate worksheets within the same Excel file were used to design the lateral, sub main and main lines. This was done purposefully. A separate bill of quantities table was then set up for the lateral, sub main and mainline so that the cost for each component can be determined individually. The unit costs for the irrigation hardware were sourced from Incledon (2009), Agrinet (2009) and Irrigation Unlimted (2009). It must be noted that in practice, discounts, pending on the volume purchased, are usually applied to these prices. Hence the prices, as they appear in Table 3-5, may be higher than those typically obtained. Nevertheless, all designs will be priced from the same database and will therefore be adequate for comparison purposes. In addition, the unit prices in Table 3-5 should be updated periodically.

Table 3-5 Extract of bill of quantities with unit cost for pipes

Laterals						Sub main lines						Main line					
			[1]Quantity	[2]Unit Price/m	Total				Quantity	Unit Price/m	Total				Quantity	Unit Price/m	Total
32mm Diam.						32mm Diam.						32mm Diam.					
	Class 9	m	23760	R 9.17	R 217,879		Class 9	m	0	R 9.17	R 0.00		Class 9	m	0	R 9.17	R 0
	Class 12	m	0	R 10.73	R 0		Class 12	m	0	R 10.73	R 0.00		Class 12	m	0	R 10.73	R 0
	Class 16	m	0	R 13.19	R 0		Class 16	m	0	R 13.19	R 0.00		Class 16	m	0	R 13.19	R 0
40mm Diam.						40mm Diam.						40mm Diam.					
	Class 6	m	0	R 11.88	R 0		Class 6	m	0	R 11.88	R 0.00		Class 6	m	0	R 11.88	R 0
	Class 9	m	0	R 13.35	R 0		Class 9	m	0	R 13.35	R 0.00		Class 9	m	0	R 13.35	R 0
	Class 12	m	0	R 16.81	R 0		Class 12	m	0	R 16.81	R 0.00		Class 12	m	0	R 16.81	R 0
	Class 16	m	0	R 20.86	R 0		Class 16	m	0	R 20.86	R 0.00		Class 16	m	0	R 20.86	R 0
50mm Diam.						50mm Diam.						50mm Diam.					
	Class 4	m	0	R 16.35	R 0		Class 4	m	84	R 16.35	R 1,373		Class 4	m	0	R 16.35	R 0
	Class 6	m	0	R 18.40	R 0		Class 6	m	0	R 18.40	R 0.00		Class 6	m	0	R 18.40	R 0
	Class 9	m	0	R 21.34	R 0		Class 9	m	0	R 21.34	R 0.00		Class 9	m	0	R 21.34	R 0
	Class 12	m	0	R 25.95	R 0		Class 12	m	0	R 25.95	R 0.00		Class 12	m	0	R 25.95	R 0
	Class 16	m	0	R 34.10	R 0		Class 16	m	0	R 34.10	R 0.00		class 16	m	0	R 34.10	R 0

1 Counter function programmed into this column to search through the lateral design worksheet and count the number of lengths, if pipe diameter and pressure/class of pipe correspond.

2 Unit costs sourced from Incledon (2009), in this case.

All the calculations were programmed into the quantity column of Table 3-5. The tool essentially needed to quantify what length of pipes, in their respective diameters and classes, were required. The mechanism used was a "countif" function in Microsoft Excel. The "countif" function has the ability to count the number of times specific criteria are met within a range of cells. In this application the criteria were the pipe diameter and the total pressure, which was used to determine the class of pipe required.

For example, consider the 50 mm, class 4 pipe in the "sub main lines" section of Table 3-5. Pipe class is a function of pressure and in this case if the pressure was less than 400 kPa, it was matched to a class 4 pipe. Hence, in the quantity cell in Table 3-5, the countif function was programmed to search through two columns in the "sub main line" worksheet. The two columns were the pipe diameter and total pressure columns, as shown in Table 3-4. The countif function counted the number of times the selected columns matched the criteria. In this example the "countif" function was used to count how many times a 50 mm class 4 pipe was required. The answer in this example was two. Hence two 21 m segments (42 m) of 50 mm class 4 pipes were used per sub mainline. Since in this design there were two sub mainlines, the total length of 50 mm class 4 pipes required was 84 m. This was reflected correctly in Table 3-5. Also shown is the cost of these pipes amounting to R 1, 373.

It should be noted that the criteria for each countif function differed and had to match the pipe diameter and class for which the count was being completed. In the above example, the criteria were a 50 mm pipe diameter and pressure less than 400 kPa. If the next class, class 6, was considered, the "countif criteria" would change and the pressure range searched for would now be between 400 and 600 kPa. The result was that a unique set of criteria had to be programmed for each quantity cell in the lateral, sub main line and main line components. Hence setting up the template for each pipe diameter and class required a bit of effort. Nevertheless, once set up, the database and counting mechanism proved extremely valuable. Similar to the pipes, determining the number of sprinklers, pressure reducing valves and cross pieces were all automatic. These results were then carried forward to a summary table reflected in Table 3-6 below.

Table 3-6 Summary of irrigation system costs

No	Description		Costs	Costs/ha
	Area (ha)	50.65		
1	Sprinkler Package[1]		R 52, 645.56	R 1, 039.36
2	Underground pipes		R 356, 956.61	R 7, 047.24
2.1	Laterals	R 217, 879.20		R 4, 301.49
2.2	Sub Mains	R 90, 376.09		R 1, 784.26
2.3	Mainline	R 4, 082.08		R 80.59
2.4	Pressure regulating valves	R 6, 345.24		R 25.27
2.5	Cross pieces at lateral junction	R 38, 274.00		R 755.63
3	Trenching costs		R 157, 536.00	R 3, 110.16
	Laterals @ R6 per meter	R 142, 560.00		R 2, 814.50
	Mains and Sub mains @ R8 per meter	R 14, 976.00		R 295.66
		Total	R 567, 138.17	R 11, 196.76

1 sprinkler package consists of 3m tripod, sprinkler, nozzle and connecting components that plug into hydromatic valve.

Table 3-6 is broken into three components, the sprinkler package, underground pipes and trenching. For the trenching costs, the sub main and mainline trenches were assumed to costs R8 per meter while the smaller lateral trenches were assumed to cost R6 per meter (Lecler *et al.*, 2008). The table also shows the costs of the full system and the cost break down per hectare. In this case, the capital investments for the 50.65 hectares amounted to R 567, 138.17 or R 11, 196.76 per hectare. R11, 196.76 per hectare appears to be low for a semi-permanent irrigation system but it was also important to note that this did not include pumping costs. The design and costing tool, does not size and cost the required pumping system. This was completed manually and the associated pumping costs were entered directly into *Irriecon V2*. The design and costing tool, however, did determine the total flow and pumping head required, which in turn informed the pump selection process. At this stage, it must be reported that there is room for refinement in the design tool. Components such as local friction losses, air and other control valves and pump selection are not addressed. The design and costing tool, however, was still adequate and extremely valuable for the work required in this project.

3.2.5 Summary and conclusions

The development of the design and costing tool now implied that the framework, as represented in Figure 3.1, was in place allowing for relatively quick and efficient assessment for varying irrigations scenarios and strategies. The next three chapters demonstrate how the framework can be applied to assess potential solutions to challenges facing the sugarcane and irrigation industry.

Prior to writing up this work, Armitage *et al.* (2008) made use of part of this framework to assess dry land production versus irrigation, as well as sprinkler versus drip versus travelling big gun irrigation systems. In addition, different system capacities were also evaluated. Refer to Appendix C. In that case, however, irrigation consultants were used to generate the designs and costs for the different systems. This proved a costly and relatively inflexible exercise, but nevertheless, illustrated the potential of a complete framework which included the hardware design and costing component. The design and costing tool and therefore, the framework in this project were applied specifically to semi-permanent irrigation systems. It must be noted, however, that the design and costing tool is spreadsheet based and therefore can quite easily be modified for other systems.

Summarizing: the design and costing tool was developed for a knowledgeable person to quickly generate alternative irrigation designs and associated system costs. This tool completed the missing link in a holistic irrigation assessment framework. The assessment framework now provides the platform for easy analysis of alternative solutions for various irrigation challenges facing the industry. In the next three chapters, some of the major problems facing the industry were explored and analysed using the irrigation assessment framework.

4. APPLICATION OF DECISION SUPPORT FRAMEWORK

In this chapter, the irrigation assessment framework was used to assess three current and major issues facing the irrigated sugarcane industry in South Africa. These included over irrigation on shallow soils, the electricity crisis and increasing tariffs, and efficient use of water through deficit irrigation. The first issue, over irrigation on shallow soils, is addressed in Section 4.1 below, followed by the background to electricity tariff options and deficit irrigation strategies in Section 4.2 and 4.3, respectively.

4.1 Irrigation Design and Operating Strategies for Shallow Soils

As pointed out in the introduction, sixty percent of the sugarcane farming in South Africa is practised on grey soils. Grey soils have a rating of moderate to poor suitability for irrigation, largely attributed to the shallow nature of the soil (SASEX, 1999). Irrigating shallow soils efficiently generally requires small applications on a frequent basis. This is because the shallow depth limits the volume of water that maybe stored in the soil profile and application of too much water is lost through runoff and deep percolation. Hence, effective irrigation of shallow soils requires application of smaller amounts of water more frequently. The concern is that a large portion of this area is irrigated by overhead sprinkler dragline systems which are not suited to apply small amounts frequently.

The reasoning is as follows: Draglines systems are cheap and therefore very popular. Draglines systems are cheap because, typically, a limited amount of hardware is used to irrigate a large area. This is achieved by using sprinklers and dragline hoses to irrigate an area over a selected stand time and then moving the hardware to irrigate the next area. Hardware selection and use of time is critical. If, for example, the same sprinklers and draglines can be used thrice within the same day, three times the area can be irrigated for the costs of one set of sprinklers and draglines. For this reason, systems are designed to make use of the 24 hours available in a day.

The limitation, however, is that labour is used to move sprinklers and it is impractical to move sprinklers at night. A common dragline strategy, therefore, is to irrigate for 12 hours during the day, then move the sprinklers while still bright and irrigate again for the next 12 hours during the night. The sprinklers can then be moved to the next position in the morning when there is enough light again (Zadrazil, 1990 and Reinders, 2001). A 12 hour application, however, applies too much water for most shallow soils. The trade off for most growers was a cheaper irrigation system but poor use of water.

For this reason, a lot of dragline sprinkler systems are operating inefficiently resulting in over irrigation on a large portion of the sugar industry (Lecler *et al*., 2008). Automating the irrigation system so that sprinkler applications could be better matched to the soil and operated on, say, an 8 hour stand time would help solve this problem. Automation of draglines is practically impossible. For this reason, an alternative semi-permanent (hop along) system was considered. In this chapter a typical “12 hour stand time system” was compared to an innovative, better matched, semi automated “8 hour system”. The framework, as described in Chapter 3.1 was used to cost and assess the performance of these two systems. The hypothesis was that the yield improvement from more effective use of water will offset the additional costs for partially automating the 8 hour system.

4.1.1 Engineering design, operation and costing of alternative irrigation systems

Before designing the systems, the following important criteria were selected. The targeted irrigation depth was set at 5 mm/day, in this instance representative of the Komatipoort area. The soil was assumed to be a 0.6 m deep Sandy Clay Loam with a “Total Available Water” content (TAW) of 57 mm as shown in Figure 4.1. Again, this was fairly representative of a shallow soil. It was assumed that 60 % of the TAW would be allowed to deplete before an irrigation event was triggered. Hence the depth of water required from irrigation to refill the depleted amount was 34 mm (60% of 57 mm).

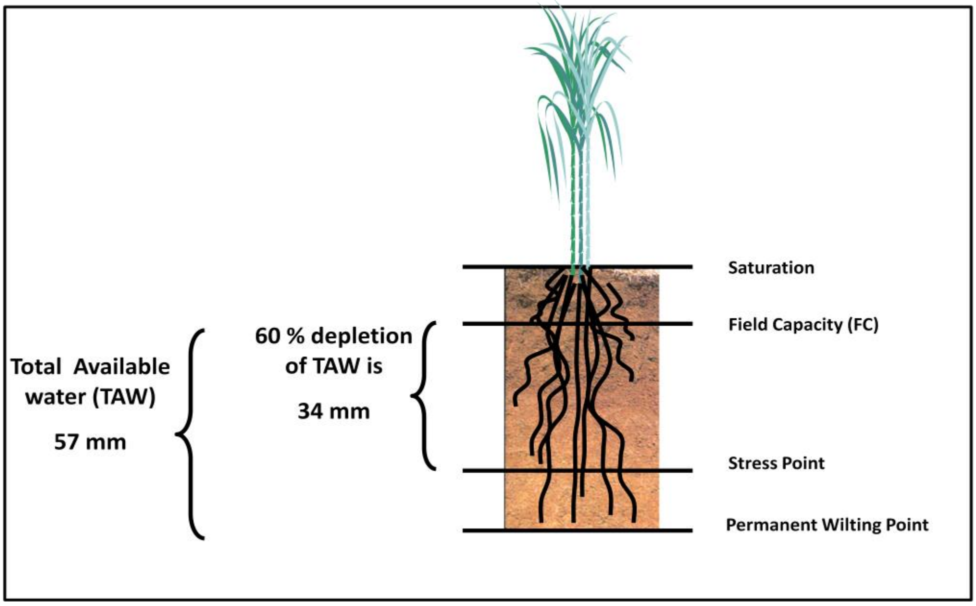

Figure 4.1 Illustration of soil criteria selected for irrigation design

Using the sprinkle database query utility and irrigation design tool, two irrigation designs were generated. In the 1st system, a stand time of 12 hours, similar to current practices, was used. The details of this system are as follows. A VYRSA 35 sprinkler with 4 mm brass nozzle was selected. This sprinkler was capable of delivering 4.3 mm/hour with a coefficient of uniformity of 87 % if operated at 300 kPa and sprinkler and lateral spacing of 18 × 21 m. Running the sprinkler on a 12 hour stand time will deliver 51.6 mm (4.3mm/hr × 12hrs) every 10 days. This translates into an equivalent of 5.16 mm/day, which is well matched to the target depth of 5 mm/day. Applying 51.6 mm per irrigation event, however, exceeds the 34 mm refill depth. This is illustrated in part A of Figure 4.2. In this figure it is easy to see how application of excess water is lost.

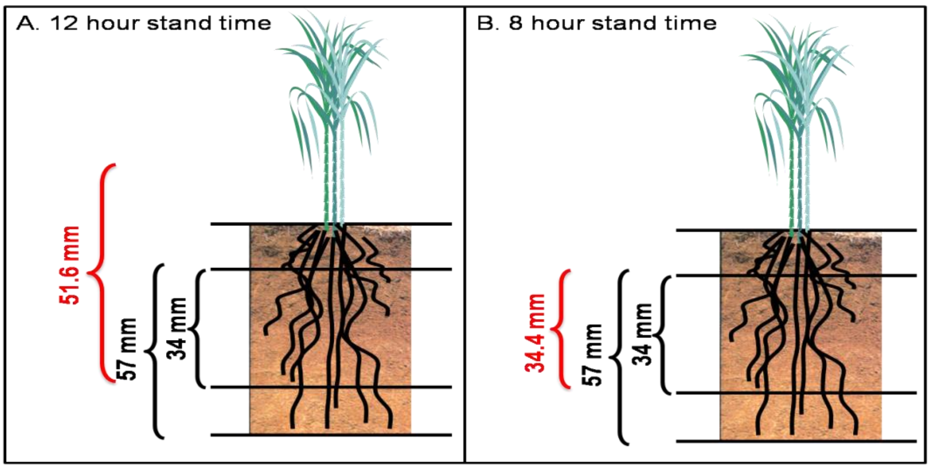

Figure 4.2 Illustration of poorly matched irrigation application to the soil

For the 2nd system, however, the same sprinkler package, spacing and operating pressure was now operated on an 8 hour stand time and a 6 day cycle. Hence, 34.4 mm (4.3mm/hr × 8hrs) was applied every 6 days, translating into 5.73 mm/day. The 8 hour system, demonstrated in part B of Figure 4.2, was better matched to the soil and still met the target depth of 5 mm/day. The challenge, however, was how does one automate and operate a sprinkler system so that labour was not required to move the sprinklers at night? Before describing the innovative 8 hour design, the commonly occurring 12 hour system (Reinders, 2001) is first described in Figure 4.3 below.

In Figure 4.3, the numbers along the two laterals in the figure represent sprinkler positions, where the 1st digit represents the day in the cycle. A cycle length of 10 days represents 10 sprinkler positions. The 2nd digit represents the number of moves for that day. In other words, 6.2 refers to the 2nd move on day 6. Also, as indicated in Figure 4.3, the numbers in black indicate sprinkler moves that occur in the morning for irrigation during the day and the numbers in grey indicate sprinkler moves that occur in the afternoon for irrigation during the night. Furthermore, in Figure 4.3, only the left portion of lateral A and B are shown. The right portion was a mirror image but designed to operate independently. The system would operate as follows. The sprinkler would begin in position 1.1 and operate for the day in that position. At the end of the day, labour would then move the sprinkler to position 1.2, where it will operate for the evening. The cycle would continue, similarly, on day 2 and over the next 10 days.

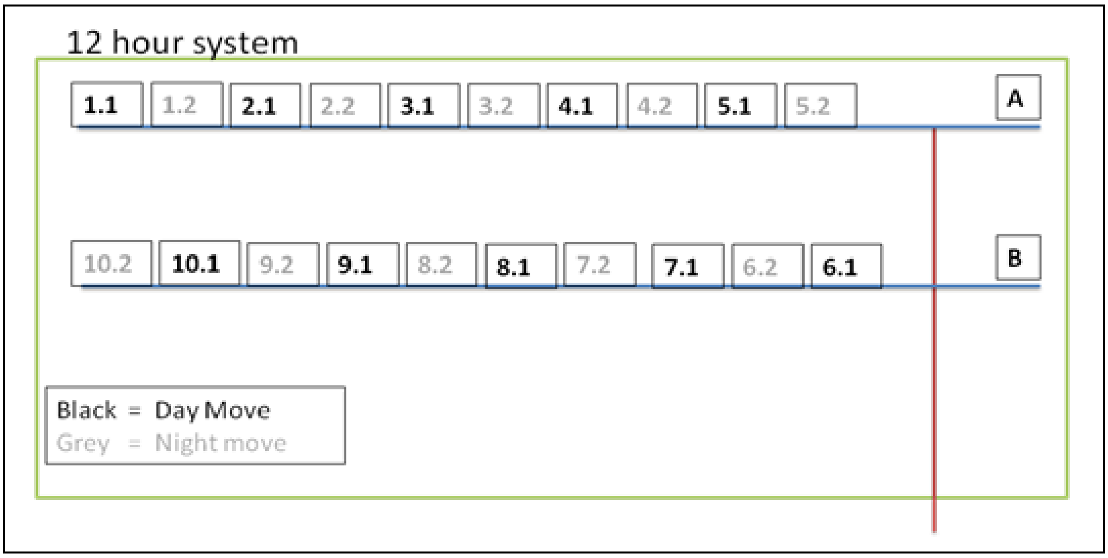

Figure 4.3 Field operation of sprinkler for the 12 hour system

Figure 4.3 above illustrates the layout and sprinkler operation of 2 laterals with 2 sprinklers in a 12 hour system. The 12 hour system was designed to use 66 sprinklers and 66 laterals to irrigate an area of 50.65 hectares. The 8 hour system, however, required some modification. This system required for a sprinkler to be operated in three different positions within 24 hours. This implied that labour would have to work in the dark, if operated traditionally. Instead, an additional set of sprinklers was introduced to the system. The additional sprinkler would be placed on a lateral which is then isolated during traditional operation in the day. Hence, when the time for operation at night arrived, the isolated sprinkler could be switched on via a valve and the lateral that was working during the day would now be switched off. Hence, instead of having to move sprinklers at night, an irrigation supervisor would simply walk or drive along the sub main and switch the appropriate laterals on and off. This is demonstrated in Figure 4.4 below.

As in Figure 4.3, the 1st digit was the day in the cycle; the 2nd digit was the number of moves in the day and the black equals day moves whilst grey equals night moves. In this case, for the 2nd digit, 1 represent a move in the morning, 2 represents a move in the afternoon and 3 represents a move in the evening. Each lateral, both on the left and right was equipped with a simple gate valve on a hydrant type set up. Unlike the 12 hour system, each lateral was also equipped with a sprinkler. Hence, for 66 laterals, 132 sprinklers were used. The system was designed to operate as follows. A sprinkler would be placed at position 1.1 and 1.3, on lateral A and B respectively. In the morning, lateral A would be switched on and lateral B switched off. The sprinkler at 1.1 would operate here for 8 hours, after which labour would move the sprinkler to position 1.2. The sprinkler at 1.2 on lateral A would then operate for 8 hours into the evening. At the end of the 8 hours, the irrigation supervisor would venture out in the dark to simply switch lateral A off and Switch on lateral B, activating the sprinkler at 1.3. The sprinkler at 1.3 would then irrigate until the next morning.

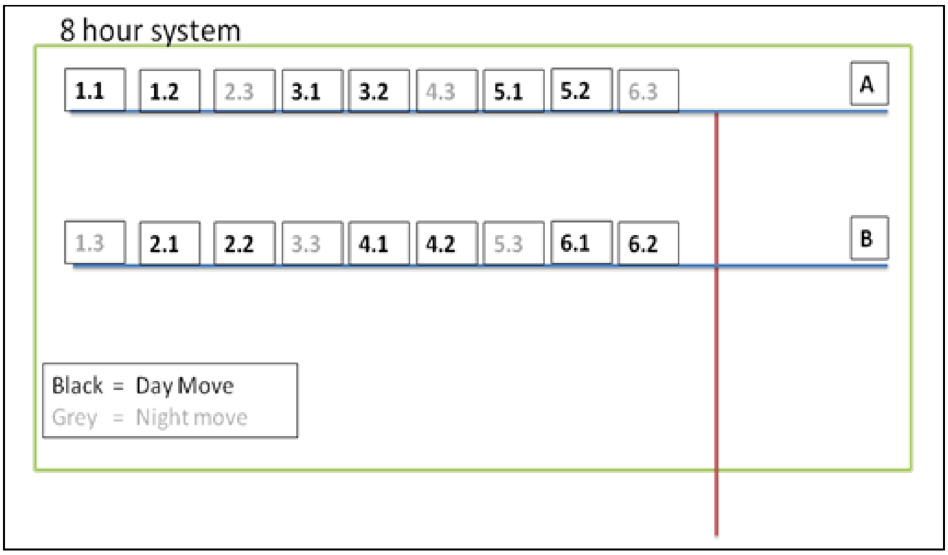

Figure 4.4 Field operation of sprinkler for the 8 hour system

The next morning, labour would move the both the sprinklers on lateral A and B from 1.2 to 2.3 and 1.3 to 2.1 respectively. Lateral B would remain open and irrigation would proceed at 2.1, while lateral A remains closed but ready for the next night move. The operation of the system would continue in this manner to the end of the cycle on day 6. At the end of day 6, all sprinklers would be returned to the original starting positions. Take note that this system was only semi-automated since labour was still required to move sprinklers. The innovation, however, allows for easy irrigation at night at an increased cost. The first task was to quantify what the costs differences were for each system. The newly developed irrigation design and costing tool was used to optimally size the pipes and cost both systems. The summary of costs is provided in Table 4-1.

Table 4-1 Summary of system costs per hectare for 12 and 8 hour stand time designs

Description	**12 Hour (R/ha)**	**8 Hour (R/ha)**
Sprinkler package	R 1, 039	R 2, 309
Laterals	R 4, 301	R 4, 301
Sub Mains	R 1, 779	R 1, 967
Mainline	R 81	R 90
Senniger Valves	R 125	R 139
Crosses/Tees/Hydrants	R 758	R 2, 407
Trenching	R 3, 110	R 3, 143
Total	**R 11, 193**	**R 14, 356**
% increase in costs	**100%**	**128%**

Table 4-1 illustrates that the 8 hour system costs 28% more than the 12 hour system. This translates into an additional R 3, 163 per hectare. The difference, as expected, was largely due to the additional set of sprinklers and the components required for the hydrants and valves at each lateral for the 8 hour system. Marginal differences were also accounted for in the cost of sub mains and mainlines. These were due to varying pipe diameters and classes to balance and optimise friction losses. At this stage it should also be noted that the pumping requirements of both systems were very similar. The 12 hour system required an 18.43 KW pump to pump 107.28 m^3/hr at a head of 44.54m while the 8 hour system required an 18.60 KW pump to 107.28 m^3/hr at a head of 44.13m. Hence for all intents and purposes, the capital and operating costs for both pumping systems were assumed to be the same. This will be discussed further in the economic analysis section. The next task was to assess the agronomic performance of the different irrigation regimes.

4.1.2 Agronomic assessment

Looking back to the hypothesis, it was anticipated that the 8 hour system would deliver a better yield. The *ZIMsched* 2.0, water balance and crop prediction, model was configured to simulate the performance of both systems over 12 seasons from 1988 until 1999. The following parameters were selected or assumed in the model:

- 0.6 m deep Sandy Clay Loam with a "Total Available Water" content (TAW) of 57 mm
- poor drainage conditions
- 10 % of total applied water was assumed to be lost by wind drift and spray evaporation (after McNaughton (1981), Tolk *et al*. (1995) and Thompson *et al*. (1997)
- planting date on 30 March
- coefficient of uniformity of 87 % as per ARC sprinkler test
- weather data for Komatipoort was obtained from the South African Sugarcane Research Institute's (SASRI's) meteorological database to drive the model. These include maximum and minimum daily temperatures, daily FAO evapotranspiration and rainfall
- irrigation scheduling rules were as follows:
    - No irrigation was to take place during the crop maturation and ripening phase. i.e. during the "dry off period". The start of the "dry off" period was calculated as the amount of time required to deplete 85.5 mm of soil water (1.5 × TAW) from the end of the cropping cycle.
    - Successive irrigation events could only take place provided the minimum cycle time had passed.
    - Using the soil water budget, irrigation was applied when 34 mm of soil water was depleted (60% × TAW). Hence if rainfall refilled the soil water levels, irrigation was delayed until the soil water was depleted to the specified level.
- system operation rules: 12 hour system
    - Gross application = 51.6 mm
    - Cycle length = 10 days
    - Peak application depth = 5.16 mm/day
- system operation rules: 8 hour system
    - Gross application = 34.4 mm
    - Cycle length = 6 days
    - Peak application depth = 5.73 mm/day

The results obtained are represented in Figures 4.5, 4.6 and 4.7, below. Figure 4.5 illustrates the seasonal water applications for both systems. Due to similar system capacities, both systems applied very similar amounts of water over the 12 year period. The slightly higher capacity "8 hour system" was able to apply marginally more water in the drier years of 1995, 1996 and 1997. On average both systems applied in the region of 1400 mm of water per a season. These systems were not optimized in terms of water use, as shown by Lecler and Jumman (2009) in Appendix D, but were fairly representative of high yielding systems for Komatipoort. At this stage, an 8 hour system which costs more but applies similar amounts of water appears less attractive.

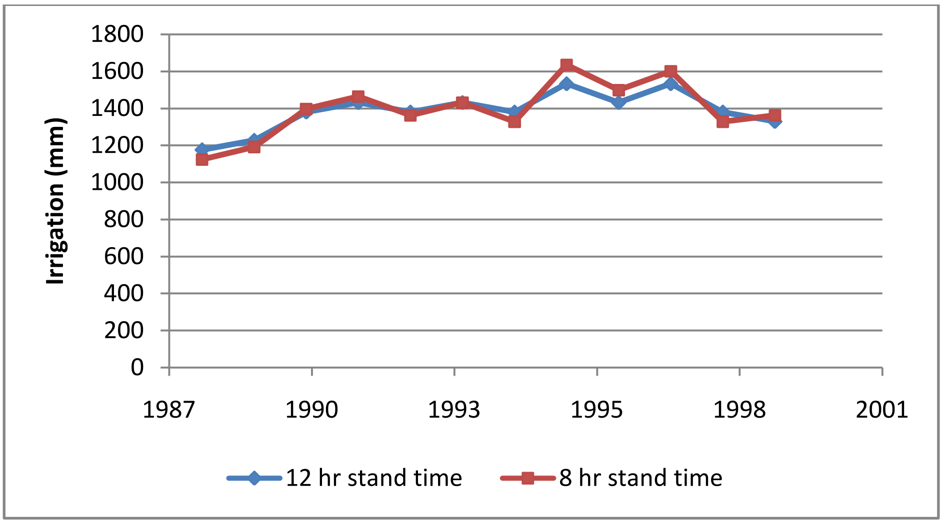

Figure 4.5 Time series of seasonal water application for 12 and 8 hour systems

Interestingly, Figure 4.6 below shows that the 8 hour system performs significantly better in terms of yield compared to the 12 hour system for similar water applications. The average yield for the 12 hour system was 128 tons/ha with a maximum of 139 tons/ha in the 1992 season. The 8 hour system, however, for the same rainfall and similar water applications on average yielded 138 tons/ha with a maximum of 148 tons/ha in 1992.

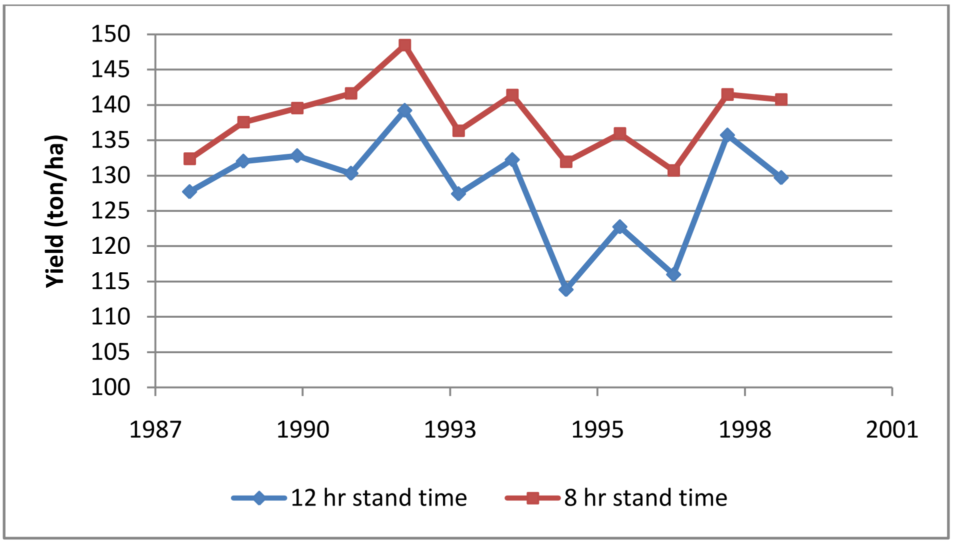

Figure 4.6 Time series of seasonal yield for 12 and 8 hour systems

To better understand why the 8 hour system yields so much higher one needs to consider Figure 4.2 again. In Figure 4.2, the application of water by the 12 hour system beyond the soils water holding capacity is demonstrated. This implies that excess water applied cannot be stored in the soil and was therefore not available to the crop. The excess water was lost through runoff and deep percolation. This is shown in Figure 4.7. The 8 hour system, however, was better matched to the soil. Hence a larger portion of the applied water can be stored in the soil and is therefore available to the crop. So even though similar amounts of water are applied, the 8 hour system delivers better yields because it allows for more effective use of water.

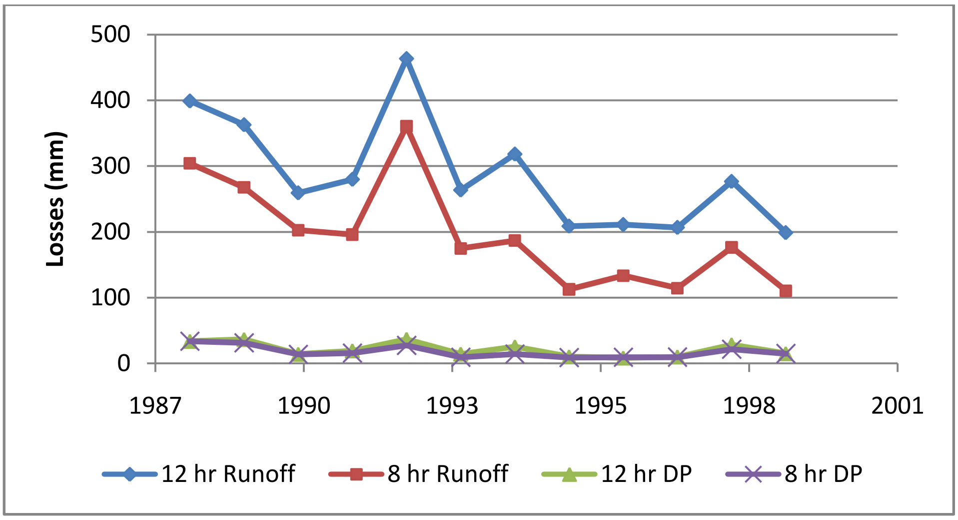

Figure 4.7 Time series of deep percolation and runoff losses for the 12 and 8 hour systems

In Figure 4.7, the deep percolation losses, abbreviated as DP in the legend, are similar for both systems and considerably smaller when compared to the runoff losses. This was attributed to the assumption of poor drainage conditions in the model and was also representative of sprinkler irrigation. Over irrigation by an overhead sprinkler system was more likely to result in increased runoff then deep percolation. On average, the 12 hour system lost an additional 100 mm of water to runoff, annually, compared to the 8 hour system. With the help of the *ZIMsched* 2.0 model, the agronomic assessment revealed that the 8 hour system outperformed the 12 hour system in terms of yield. The next task was to assess if the revenue gained from the increase in yield was enough to balance the additional costs of the 8 hour system.

4.1.3 Economic assessment

The *Irriecon v2* model was used to conduct the economic assessment. The model was configured with the necessary input information: Presentation and discussion of all model inputs are not relevant to this study and therefore not included. Examples of relevant information used include:

- Seasonal water use and cane yield as predicted by the *ZIMsched* 2.0 model,
- Irrigation system and pumping costs determined by the design and costing tool. These costs were important to represent the 28% increase in capital investment for the 8 hour system,
- 2007/2008 cost of electricity on the land rate tariff option (ESKOM, 2007),
- Water tariffs, obtained from DWAF (2008), were 4.06 c/m^3,
- Following Hoffman *et al.* (2007), labour requirements for sprinkler systems were set at 1.65 hrs/ 1000 m^3, where cost of labour was R 6.88/hour. The labour cost for switching valves in the 8 hour systems was considered negligible.
- RV Price of cane at the time was R 1583.12/ton,
- And finally, an annual inflation of 7 % and interest rate of 13.5 % was assumed to calculate the interest and depreciation costs of the equipment.

In certain instances, the costs for both systems were fairly similar if not identical. These included the mainline operating costs largely consisting of electricity and the planting and ratooning costs as shown in Table 4-2. The mainline operating costs were similar as a result of identical pumping systems and similar water applications per season for both systems, as pointed out previously. The agronomic, harvesting and transport costs for both systems, shown in Table 4-2, were represented but are not discussed in great detail here due to the lack of direct relevance to this work. It should be noted, however, that costs associated to harvesting and transport are dependent on yield and yield in turn dependent on irrigation. Hence, consideration of these costs was important for holistic assessment of the systems. The major differences between the two systems were the revenue generated for cane yields and the mainline and system fixed costs.

Table 4-2 *Irriecon* V2 results presented as the average over 12 years in units Rand per hectare

REVENUE		**12 hour (average)**	**8 hour (average)**
	Cane sales	23,618.17	25,427.88
IRRIGATION COSTS			
	Mainline costs		
	Mainline fixed costs	1,065.33	1,241.63
	Mainline operating costs	1,310.94	1,323.11
	Total mainline costs	2,376.27	2,564.74
	System costs		
	System fixed costs	141.45	314.31
	System variable costs	869.64	1,012.58
	Total system costs	1,011.09	1,326.89
	Total irrigation costs	3,387.35	3,891.63
OTHER DIRECT COSTS			
	Planting costs	942.93	942.93
	Ratooning costs	3,289.92	3,289.92
	Harvesting costs	1,493.95	1,608.42
	Haulage costs	4,065.36	4,376.86
	Total other direct costs	9,792.15	10,218.13
NET MARGIN		**10,438.66**	**11,318.12**

Systems variable costs also differed significantly. This was due to the cost of repairs and maintenance, which was calculated as 2% of the systems fixed cost (Oosthuizen *et al.,* 2005). Hence, the 8 hour system, having an additional set of sprinklers, was likely to cost more in terms of repairs and maintenance. The information most sort after from this assessment was the net margins above allocated cost. The economic assessment revealed that the 8 hour system generated better net margins on average when compared to the 12 hours system. In Table 4-2, the average net margins for the 12 and 8 hour systems were R 10, 438.66 and R 11, 318.12 per hectare, respectively. This implies an average gain of R 879.46 per hectare, amounting to an 8% improvement in returns, for the 8 hour system. The annual net margins for both systems are shown in Figure 4.8 below. Figure 4.8 reflects the seasonal variation for both weather and yields for both systems

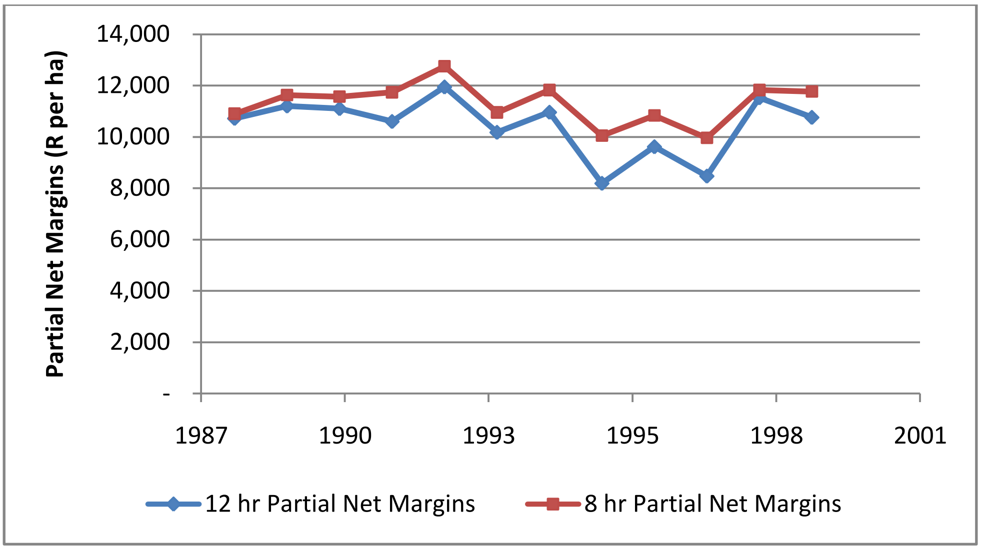

Figure 4.8 Partial net margins in Rand per hectare for the 12 and 8 hour systems

Figure 4.8 clearly reflects the better performance of the 8 hour system in all years, irrespective of the seasonal variation. In addition the degree of performance, for the 8 hour system, improves in 1995, 1996 and 1997 were rainfall was less than 230 mm. This confirms the hypothesis that the additional costs of the 8 hour system was offset by the increase in yields due to more effective use of water.

4.1.4 Conclusions

In this chapter, strategies to better irrigate shallow soils with semi-permanent sprinkler systems were investigated. Traditionally, normal practices made use of a 12 hour stand time to prevent the use of labour during the evening and to make use of the full 24 hours in a day. 12 hour stand times, however, often applied more water than what could be stored in the soil profile. This resulted in losses through runoff and deep percolation. A new and innovative method to irrigate in shorter intervals was developed and assessed. In this case, the new system applied water over an 8 hour stand time and was compared to the traditional 12 hour stand time. As a result of the modifications, the 8 hour systems cost 28 % more in fixed costs. The 8 hour system, however, performed better than the 12 hour system, both in terms of yield and profit generation. In addition, the 8 hour system used similar amounts in terms of water and electricity resources.

This was significant in the context of this study. The increased investment to modify and partially automate an irrigation system, to match the application of water to the soil profile, proved to be beneficial economically. On average the 8 hour system returned an 8% improvement in profits compared to the 12 hour system.

In addition, the 12 hour system resulted in more runoff. Not only does this result in ineffective use of water but also has serious environmental impacts (Perry, 2007). Runoff often carries with it, valuable top soil and nutrients. Over a period of time, the loss of soil and nutrients can have significant impacts on crop yield. The economic impact of this was not determined but such environmental impacts add to the motivation for farmers to invest in systems that are better matched to the soil. Farmers and irrigation designers are therefore recommended to ensure that irrigation systems are well matched to soils. The economic and environmental benefits of well designed and operated systems appear to outweigh the additional investments for such systems. Moreover, this highlights the importance of considering the water budget during the design phase. The fate of the various fractions of water applied should be considered (Burt *et al.*, 1997)

Furthermore, the use of the "Irrigation Assessment Framework" was demonstrated. If this assessment was stopped at the 1st stage where the alternative systems were only designed and priced, it would have appeared that the 12 hour system was the better option since it was cheaper. However, looking beyond into the agronomic assessment, the 8 hour system proved to deliver better yields for similar water use. The economic assessment then confirms that the 8 hour system is indeed a better system. Firstly, this emphasizes the importance of assessing alternate strategies holistically and secondly, highlights the role of the framework and tools described in Chapter 3. In the next chapter, the frame work is used to explore the more current and burning topic of electricity tariffs in the context of irrigation.

4.2 Electricity Tariff Assessment

In previous years, the cost of electricity in South Africa was rated amongst the cheapest in the world (FIN24, 2007). This has changed in recent times. Due to the increase in population, the increase in costs for fossil fuels and difficulties with infrastructure, the countries energy supplier, Eskom, has struggled to meet the electricity demands (ESKOM, 2007). As a result, a number of increases in the electricity tariffs have been affected to mitigate the situation. Increases included: 14.2% effective from 1st April 2008, 34.4% effective from 1st July 2008 and finally a further 33.6% increase on 1st July 2009 (ESKOM, 2007, 2008 & 2009). The increase in 2009 also included an environmental levy of 2c per Kilo Watt hour (ESKOM, 2009). In light of the economic climate, largely attributed to the cost of fuel and agrochemicals, the increase in electricity tariffs has significantly impacted the profitability of farmers. For this reason this chapter aims to explore how irrigators can reduce their electricity costs. This section focuses largely on a better understanding of the electricity tariff structure, while the next section will focus on strategies to reduce electricity consumption and therefore costs.

4.2.1 South African tariff options available to farmers

ESKOM, guided by the National Electricity Regulator of South Africa (NERSA), have designed a number of tariff options for electricity users. In this work, only the rural tariff options applicable to farmers were considered. These consisted of the Landrate, Ruraflex and Nightsave options.

All tariff options included a fixed cost, for the use of infrastructure irrespective of whether electricity was used or not, and variable costs for the actual consumption of electricity. The Landrate option consists of a flat rate, dependant on the size of supply, for both fixed and variable costs. The Ruraflex and Nightsave options, however, were designed to promote the use of electricity during low demand season and off peak hours. For this reason the variable costs for energy consumption are differentiated according to the time of use. In other words use of electricity during low demand and off-peak periods were rewarded with lower tariffs and charges. The various tariffs for each option, for the 2008/2009 season, are displayed below in Table 4-3. Table 4-3 only represents a summary of the cost breakdown and is presented to demonstrate the tariff structure for a pre-selected supply size. The full list of tariffs and charges can be obtained from Eskom (2008).

Table 4-3 Break down of electricity tariffs for the Landrate, Ruraflex and Nightsave options for 2008/2009 (Eskom, 2008)

Options	**Supply**	**Fixed Charges**				**Variable Charges**					
Landrate		Network Access	Service				Active Energy				
	25 KVA	R 9.04/day	R8.60/day				40.63 c/kWh				
Ruraflex	**Supply**	Administration	Service	Network Access		Reactive Energy	Active Energy			Voltage Surcharge	Transmission Surcharge
	<100 KVA	R8.11/day	R5.54/day	R5.56/KVA		2.82 c/Kvarh	Peak c/kWh	Standard c/kWh	Off-Peak c/kWh	10.07%	1%
							139.84	39.16	19.22	High Demand	
							38.74	23.63	16.45	Low Demand	
Nightsave	**Supply**	**Fixed Charges**				**Variable Charges**					
		Administration	Service	Network Access	Energy Demand	Reactive Energy	Active Energy			Voltage Surcharge	Transmission Surcharge
	<100 KVA	R7.92/day	R5.54/day	R4.22/KVA		-				10.07%	1%
				High Demand	R85.79/KVA	-	19.60c/kWh				
				Low Demand	R56.50/KVA	-	13.50c/kWh				

Notes: Voltage Surcharge – Determined as a percentage of network access and active energy charges dependent on supply voltage.
Transmission Surcharge – Determined as percentage of network access, active and reactive energy charges dependent on the distance from a central point in Johannesburg
High Demand Season – June to August
Low Demand Season – September to May

In addition to low and high demand periods, Eskom have also designated peak, standard and off-peak periods. These periods are illustrated, for the Ruralflex and Nightsave options in Figure 4.9 below.

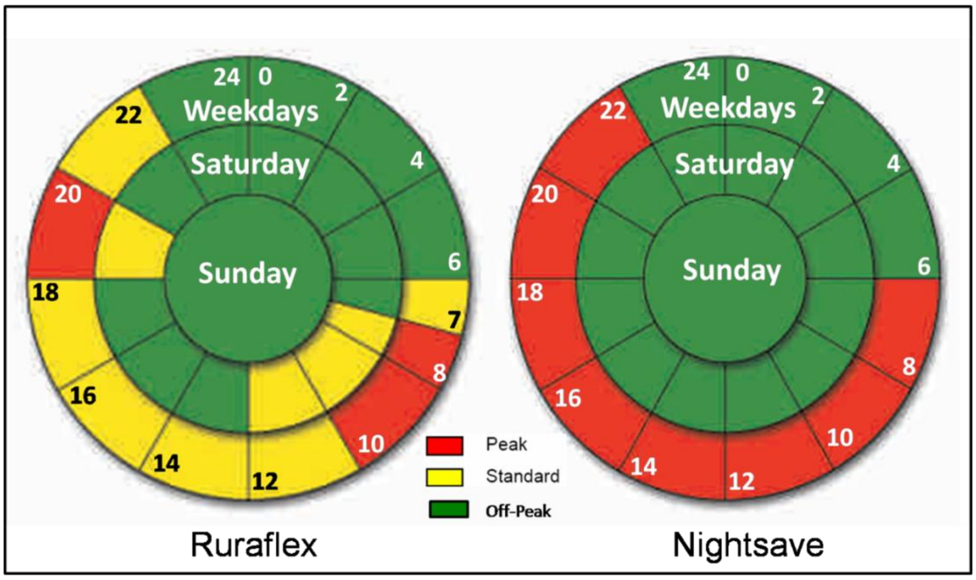

Figure 4.9 Designated periods for peak, standard and off-peak consumption of electricity (ESKOM, 2008)

Table 4-3 and Figure 4.9 both provide insight into the complexity facing irrigation farmers and designers. How does one decide which electricity tariff option to register on, in order to minimise costs? Manually determining the electricity costs for a given irrigation system with specific constraints is time consuming and tedious. Hence assessing a number of options and alternative scenarios is not always practical. The recently developed *Irriecon V2* model, however, allows one to quickly calculate and assess the electricity costs for various designs and strategies.

For this reason, the irrigation assessment framework was used to assess the cost of electricity for a given system. At this stage, it must be pointed out that *Irriecon V2*, was developed following Oosthuizen *et al*. (1998), and did not include the algorithms to calculate electricity tariffs on the Nightsave option. This implied that the framework could only be used to compare the Landrate and Ruraflex options. This proved to be a short fall. Nonetheless, value could still be obtained from comparing the Landrate and Ruraflex options. The remainder of the chapter investigates the cost implications of using the Landrate tariff option versus the Ruraflex tariff option[1].

[1] Subsequent to the writing of this dissertation, the author built into *Irriecon V2* algorithms for the Nightsave option. The analysis for the Nightsave option was completed and reported on by Jumman and Lecler 2010. See Appendix F

4.2.2 Landrate versus Ruraflex

The aim of this section was to better understand and demonstrate the differences between the Landrate and Ruraflex electricity tariff structure. The procedure to achieve this was as follows. A hypothetical irrigation system was assessed, using *Irriecon V2*, as if it was operated on the Landrate option first, and then on the Ruraflex option. The irrigation design and costing tool and *ZIMsched 2.0* was used to provide the costing and agronomic input for the economic assessment in *Irriecon V2*. In this way: the capital costs of the irrigation system, the seasonal water applications and crop yields are all identical for both scenarios. The only variation therefore will be in the operating costs due to the different electricity tariff options.

4.2.2.1 Methodology and model configuration

The irrigation system was designed to apply 48 mm in 10 days on a 12 hour stand time. This translated into the equivalent application of 4.8 mm/day, which was a pre-selected capacity appropriate for a 1.2 m deep sandy clay loam in the Heatonville area. The total available water (TAW) for the soil was calculated as 114 mm. A VYRSA 35 sprinkler with a 4.4 mm brass nozzle was selected. The sprinklers were spaced at 21 × 21 m and operated at 352 kPa at a coefficient of uniformity of 88%. For the designed 60 hectares, the pumping system was required to pump a flow of 116.42 m^3/hr at a head of 50.39 m, and a power rating of 25.38 KW. The total capital investment required was R 687 750 which equated to R 11 638/ha.

The *ZIMsched 2.0* model was configured with the system constraints as described above and 15 years of weather data for Heatonville, ranging from 1985 to 1999. As in the previous chapter, 10% of total applied water was assumed to be lost by wind drift and spray evaporation. Irrigation scheduling rules as described on page 42 in the previous Chapter were applied. Running the *ZIMsched 2.0* model for the 15 year period returned the following results.

The average crop yield over the 15 years was 125.25 tons/ha with an average annual rainfall of 918.6 mm and an average seasonal irrigation application of 734.98 mm. The crop yields and the irrigation water applications were then input into the *Irriecon V2* model together with the system capital costs and other relevant data such as water tariffs, etc. *Irriecon V2* was configured for two scenarios, namely Landrate and Ruraflex. In addition, both scenario were analysed using electricity tariffs from the 2007/08, 2008/09 and 2009/10 years. This was included to demonstrate the impact of increasing electricity tariffs on farmers and their profitability.

4.2.2.2 Results and discussion

Presented in Table 4-4 below are the results obtained from the economic analysis from the *Irriecon V2* model. Take note that the values presented in Table 4-4 are in units Rand per area under cane. Furthermore, the tabulated values are the averages for the 15 cropping seasons. Presented in the second row is the year for which the electricity tariffs were used. i.e 07/08 indicates that the electricity tariffs for the year 2007/2008 were applied for all 15 cropping seasons.

Table 4-4 Output from *Irriecon* V2 model, expressed as an average in units R/area under cane, for scenario A and B.

Revenue	**Landrate**	**Ruraflex**	**Landrate**	**Ruraflex**	**Landrate**	**Ruraflex**
Tariff years	(07/08)	(07/08)	(08/09)	(08/09)	(09/10)	(09/10)
Cane sales	R 23,066	R 23,066	R 23,066	R 23,066	R 23,066	R 23,066
Irrigation Costs						
Mainline costs						
Mainline fixed costs	**R 976**	**R 1,000**	**R 1,002**	**R 1,036**	**R 1,024**	**R 1,030**
Mainline operating costs	**R 588**	**R 480**	**R 754**	**R 609**	**R 984**	**R 921**
Total mainline costs	R 1,564	R 1,480	R 1,756	R 1,645	R 2,008	R 1,952
System costs						
System fixed costs	R 121	R 121	R 121	R 121	R 121	R 121
System variable costs	R 490	R 490	R 490	R 490	R 490	R 490
Total system costs	R 612	R 612	R 612	R 612	R 612	R 612
Total irrigation costs	R 1,935	R 1,851	R 2,127	R 2,014	R 2,379	R 2,322
Other Direct Costs						
Planting costs	R 943	R 943	R 943	R 943	R 943	R 943
Ratooning costs	R 3,290	R 3,290	R 3,290	R 3,290	R 3,290	R 3,290
Harvesting costs	R 1,459	R 1,459	R 1,459	R 1,459	R 1,459	R 1,459
Haulage costs	R 3,970	R 3,970	R 3,970	R 3,970	R 3,970	R 3,970
Total other direct costs	R 9,662	R 9,662	R 9,662	R 9,662	R 9,662	R 9,662
Net Margin	R 11,228	R 11,312	R 11,036	R 11,148	R 10,784	R 10,841

Table 4-4 clearly shows that, with the exception of the mainline costs, all other costs were identical. This was as expected, since the irrigation system, watering regime and crop yield were all identical. Interestingly, for both scenarios the actual electricity consumed was the same, but the mainline costs reflected a difference. This difference reflected the variation in the tariff structure between the Landrate and Ruraflex options.

The mainline fixed costs comprised of interest and depreciation of equipment, insurance and electricity fixed costs, not shown in Table 4-4. Similarly mainline operating costs consisted of electricity and repairs and maintenance costs. As described before, all components were identical except for the electricity fixed and operating costs. As shown in Table 4-4, in the mainline fixed costs section, the Ruraflex option was generally more expensive then the Landrate option for all tariff years (07/08, 08/09 and 09/10). Inversely, for the mainline operating costs, the landrate option appeared to be more expensive then the Ruraflex option. In total, the Ruraflex option was cheaper than the Landrate option. Also, when looking at the landrate option only, the increase in tariffs and resultant decrease in net margins from the 2007/08 season to the 2009/10 season was evident. The same applies for the Ruraflex option.

To better gauge the impact of tariff hikes, the actual charges for a season are presented in Table 4-5, below. The electricity tariffs represented in Table 4-5 were simulated by the *Irriecon V2* model for the 1998/99 crop season. In that season, irrigation application as determined by *ZIMsched 2.0* amounted to 807.84 mm. *Irriecon V2* predicted that 97, 932 kWh of electricity was required to pump the required volume of water to the 60 hectare field. Table 4-5, therefore, illustrates how the electricity tariffs for a farmer with the above system would have varied for the different tariff options and the electricity tariff hikes.

Table 4-5 Break down of Model predicted electricity costs for irrigation on 60 ha in the Heatonville area during the 1998/1999 cropping season

Ruraflex						**Landrate**		
Fixed Costs						**Fixed Costs**		
	Service	Admin.	Network		**Total**	Basic	Network	**Total**
2007/2008	R 1,507	R 2,205	R 2,490		**R 6,202**	R 2,340	R 2,460	**R 4,800**
2008/2009	R 2,022	R 2,960	R 3,336		**R 8,318**	R 3,096	R 3,254	**R 6,350**
2009/2010	R 2,683	R 767	R 4,560		**R 8,009**	R 3,449	R 4,212	**R 7,661**
Variable Costs						**Variable Costs**		
	Reactive	Active	Voltage Surcharge	Transmission Surcharge	**Total**	Active		**Total**
2007/2008	R 403	R 21, 925	R 3,829	R 264	**R 26,421**	R 31,506		**R 31,506**
2008/2009	R 541	R 29, 423	R 5,138	R 354	**R 35,456**	R 42,276		**R 42,276**
2009/2010	R 689	R 47, 601	R 8,301	R 570	**R 57,161**	R 57,228		**R 57,228**
Total costs					**Ruraflex**			**Landrate**
2007/2008					R 32,623			R 36,306
2008/2009					R 43,774			R 48,626
2009/2010					R 65,170			R 64,889

There are three important things to point out in Table 4-5. The first was that the mainline fixed costs were higher, while the variable costs were cheaper, for the Ruraflex option. Since the variable costs were considerably higher than the fixed costs, the Ruraflex option, as shown before, was cheaper overall except for when the 09/10 tariffs were applied. This was the first deviation from the trends demonstrated by the average values in Table 4-4. This will be discussed later.

The second aspect to point out was the impact of increasing the tariffs from 2007/08 up to 2009/10. If the farmer was operating on the Landrate option, the electricity bill was predicted to increase from R 36, 306 to R 64, 889, an increase of 78%. Similarly, if the farmer was operating on the Ruraflex option, the bill was expected to increase from R 32, 623 to R 65, 170, an increase of 99%. This was worrying considering that the revenue from cane sales remained constant while these costs were inflating at such significant levels. This clearly highlights the need to develop innovative irrigation strategies to reduce the cost of irrigation and will be discussed in more detail in the next chapter.

The third and probably most significant point was related to the deviation in trends for the 09/10 tariff year when comparing the average values in Table 4-4 to the values for a single season as shown in Table 4-5. To recap, Table 4-4 with the averages, showed that the Landrate option was more expensive. Table 4-5 with single season values, on the other hand, showed that for the 09/10 prices, Landrate was cheaper. Relating to this was the inconsistency in the percentage increases for the Landrate and Ruraflex options. Why did the increase for Landrate amount to 78% while the increase for Ruraflex was 99%. It appears that the differences between Landrate and Ruraflex for the 07/08 and 08/09 were relatively big, but as result of the latest tariff hikes, these differences have almost disappeared. This is better demonstrated in Figure 4.10 below. Figure 4.10 is simply a graphical representation of the total electricity costs shown Table 4-5.

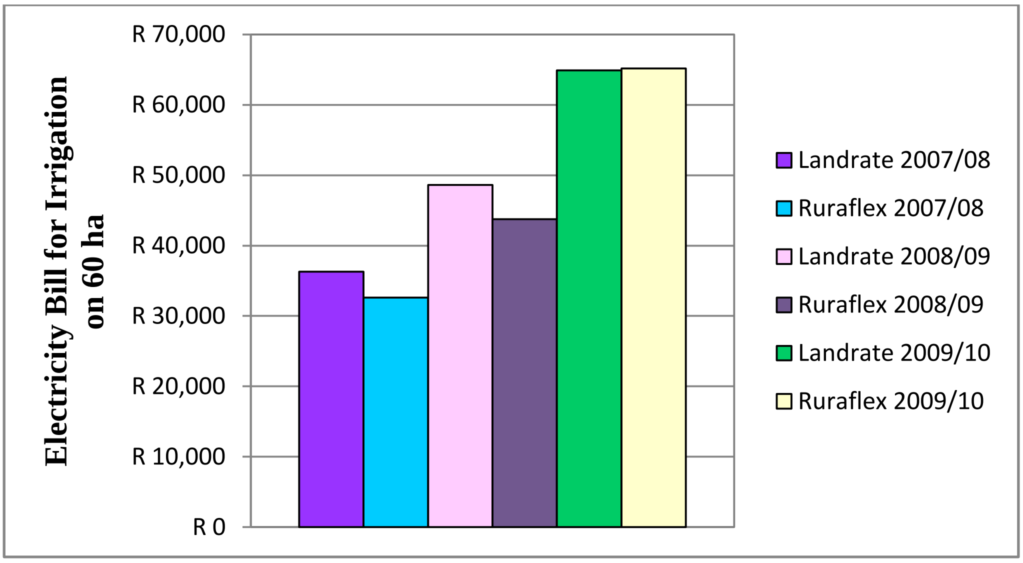

Figure 4.10 Graphical display of the total electricity costs for the 1998/99 crop season

From Figure 4.10, the difference between the Landrate and Ruraflex options for 2007/08 and 2008/09 were R 3, 683 and R 4, 852, respectively. The difference for 2009/10, however, was only R 281. This implies that the cost of electricity since the 2009/10 tariff increases reflected a better representation of the timing of energy consumption.

This concept is discussed in more detail below. In this exercise, the irrigation system was designed to operate for 24 hours a day. Hence the timing of electricity use, be it high or low demand or peak or off-peak periods, was identical for both scenarios. In addition, the actual electricity consumption was also identical for both systems. Hence, it would be expected that both scenarios would yield similar electricity costs.

The results demonstrate that prior to the 2009/10 tariff hike, the Ruraflex option was cheaper. The Ruraflex option, however, was designed to provide incentives for users to shift the use of electricity into off-peak periods. In other words, it was intended that users should be rewarded with lower tariffs if electricity use was shifted into low demand and off-peak periods. The results of this study, however, indicate that farmers may have been incorrectly rewarded for simply switching onto the Ruraflex option without shifting the timing of the electricity use. This appears to have been corrected for in the 2009/10 tariff hike.

4.2.3 Conclusions

Bringing this work back into the context of irrigation, the decision as to whether to operate on the Ruraflex or Landrate option is dependent largely on the timing of use of electricity and the actual quantity of consumption. Ruraflex has higher fixed costs but is balanced out by the lower variable costs component. At the present time, if timing and consumption are identical, both Ruraflex and Landrate yield similar costs.

This study, however, has highlighted the opportunities to reduce costs by shifting use of electricity into low demand and off-peak periods on the Ruraflex option. In terms of irrigation this implies reducing pump operating hours into standard and off-peak periods. Two strategies can be adopted. The first requires one to increase the system capacity so that the same volume of water can be applied over a shorter period of time. This option would have implications of capital investment since bigger pumps and pipes would be required. In addition, care must be taken to ensure water applications are well matched to the soils infiltration and water holding characteristics.

The second option, however, appeared more attractive and was investigated further. The second strategy was to simply reduce pump operation during the high demand and peak periods in order to decrease electricity tariffs. This, however, would result in reduced water applications and potentially yield penalties due to water stress. So the question posed is does the benefit of reduced electricity and water costs outweigh the penalties for yield loss? This question ties in with the concept of deficit irrigation and is explored further in the next chapter.

4.3 Design and Operating Strategies for Deficit Irrigation

Once again, the “irrigation assessment framework” provided the ideal platform to analyse and assess deficit irrigation strategies. The strength of the “assessment framework” was largely attributed to the ease with which tradeoffs between various parameters such as watering regimes, associated costs and yields could be quantified and assessed. In this chapter, a fairly well designed conservative system, assumed to be already installed in the field, was used to generate a number of deficit irrigation strategies by altering the systems hardware or operating rules. The “irrigation assessment framework” was then used to assess the performance of each strategy.

4.3.1 Description of approach and methodology

For this chapter, a high capacity irrigation system, with the ability to meet the crop water requirements during the peak summer growing months was designed for the Heatonville area. The system served as the base system and was designed to ensure that the crop experienced no water stress during the season. This base system served as the benchmark against which other deficit strategies could be compared. The base system made use of the VYRSA 35 sprinkler with a 4.4 mm brass nozzle. The sprinklers were designed to operate: at 21 m spacing, on a 12 hour stand time, with 352 kPa of pressure, delivering 48 mm on a 7 day cycle. This was equivalent to an application of 6.9 mm a day. The “114 mm TAW” soil from the previous chapter was used.

It should be noted that the crop water requirements and therefore the target depth (gross irrigation requirement) was determined following the methods laid out in the commonly used South African Irrigation Design Manual (ARC-ILI, 2004). The methods included traditionally accepted norms and commonly used equations for determining the net irrigation requirement from climate, crop and soils data. The problem, however, sets in when the Irrigation Design Manual recommends converting from net, to gross irrigation requirement using system efficiency. Generic system efficiencies, such as 80% for sprinkler systems, were recommended in the design manual. This implies that system capacity is increased from net to gross in order to apply more water to compensate for inefficiencies of the system. As pointed out in the literature review, traditional design methods, such as the one used in the base system, are conservative and aim to design for a high enough capacity so that no water stress is experienced. This was confirmed when the 6.9 mm base system was simulated in the *ZIMsched 2.0* model. The soil water balances for a dry and wet year, as simulated by the *ZIMsched 2.0* model, are shown in Figure 4.11 below.

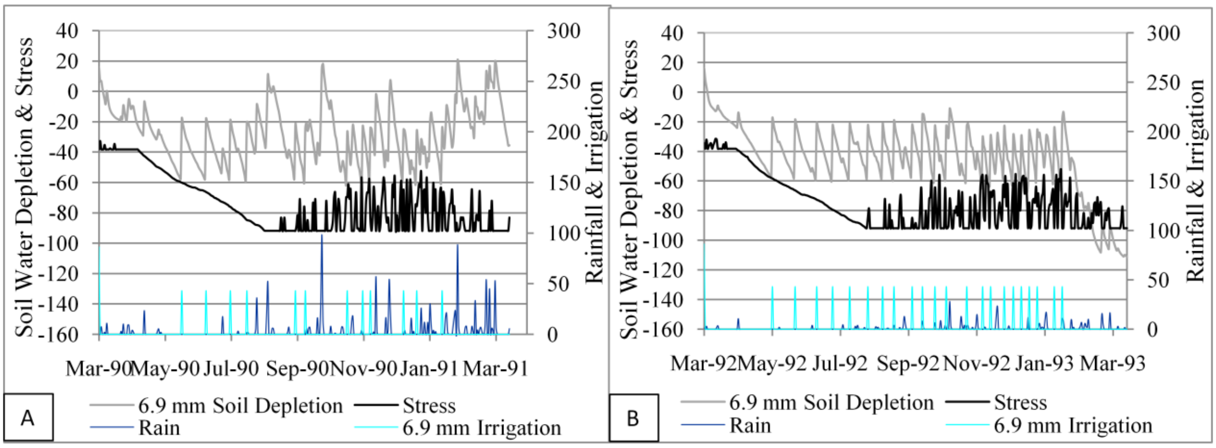

Figure 4.11 Soil water balance for the 6.9 mm base system for a specific season. A) Wet Year. B) Dry Year

Graph A in Figure 4.11, represents a wet year where 1225 mm of rainfall was received in 1990. In 1992, only 388 mm of rainfall was received and is depicted as the dry year in Graph B. As shown in Figure 4.11, the soil water depletion curve very rarely drops below the stress curve for both the wet and dry years, indicating no stress. For this reason the high capacity “base system” was assumed to be typical of what would be used on a farm for this particular soil and geographical location.

The idea then was to develop and assess deficit strategies with reduced watering capacities. It was assumed that the 6.9 mm system already existed and was operating successfully in the field. Hence, the development of deficit strategies was limited to those strategies which would make use of the existing hardware already in the field. This step was considered important so as to ensure that only implementable, realistic and appropriate strategies were developed for a grower. Furthermore, as concluded in the previous chapter, opportunities existed to reduce electricity costs on the Ruraflex option. Hence the Ruraflex option, based on 2009/10 prices was applied for all strategies. Essentially, two components were targeted. The first component addressed the design of irrigation systems and the use of hardware. The second component explored irrigation operating rules such as stand times and the potential to take advantage of off-peak pumping.

First consider the design component. As described in the literature review, deficit strategies allows for more flexible irrigation designs and variation from design norms. For this reason, variations of the 6.9 mm system, as described above, were developed and are shown in Table 4-6.

Table 4-6 Summary of systems developed to implement deficit irrigation

	System 1	System 2	System 3
Peak application associated with system strategy (mm/day)	6.9	4.8	4.0
Application per cycle (mm)	48	48	48
Cycle length (days)	**7**	**10**	**12**
Stand Time (hours)	12	12	12
No of sets/day	2	2	2

Three systems were developed. System 1, represent the base system as described in detail above. The major differences between System 1, System 2 and System 3 were the cycle length as highlighted in Table 4-6. Basically, all systems make use of the same sprinkler package and therefore apply the same amount of water per cycle, 48 mm. The difference in peak applications was therefore the result of applying the same amount of water over different periods. For example, in System 1, 48 mm applied once in 7 days equates to 6.9 mm a day, whilst for System 2, 48 mm applied once in 10 days equates to 4.8 mm a day. Implementing System 2, however, involved adding to the existing hardware of system 1. By increasing the cycle length, additional sprinkler positions on the laterals were required. System 2 was achieved by simply adding 3 lengths of lateral to the 6.9 mm system to create the sprinkler positions for the 3 additional days. This is shown in Figure 4.12, where the positions marked X and the shaded area represents the system hardware additions.

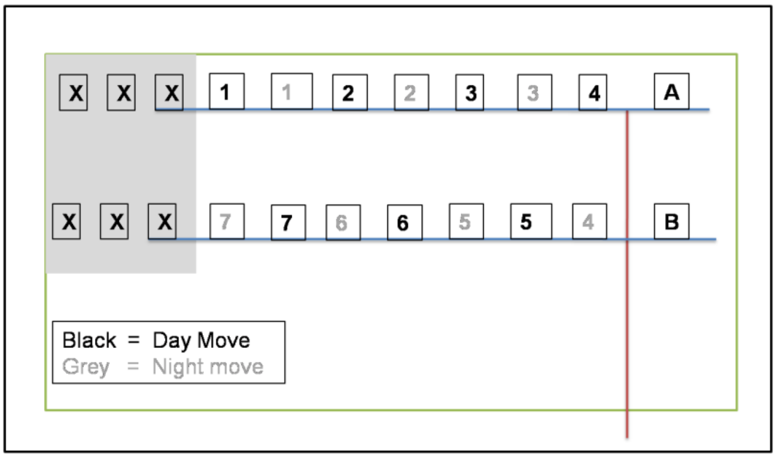

Figure 4.12 Illustration of modifications to the base system to obtain system 2

Similarly, system 3, involved increasing the cycle length to 12 days reducing the 48 mm application to a 4 mm a day system. Since these systems were designed to operate with one sprinkler per lateral, increasing the length of laterals did not have major impacts on the pipe hydraulics in terms of flow, friction, pipe diameter and required pressure. This implies that for the same pump, mainline, sub mainline and sprinklers, a much larger area can be irrigated by altering the cycle length and inserting the additional length of laterals as required. Systems 2 and 3 were therefore expected to cost less per hectare than system 1. These can be summarized diagrammatically as shown in Figure 4.13.

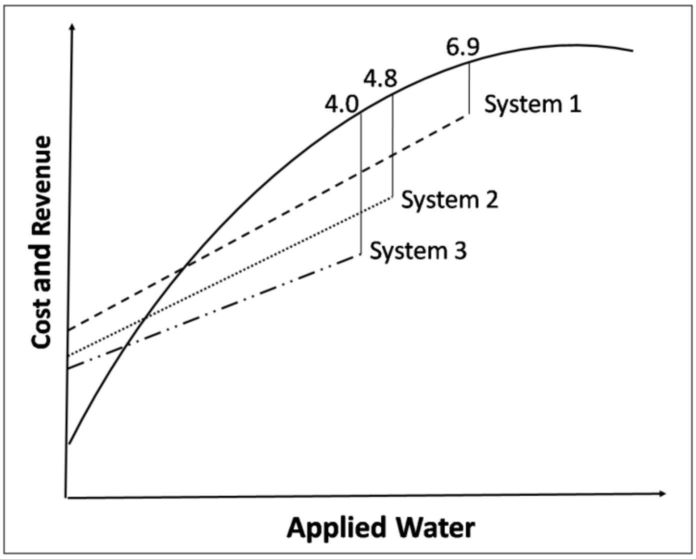

Figure 4.13 Schematic of conceptual variations between systems 1, 2 and 3

In this case, the base system made use of 66 sprinklers to apply 6.9 mm/day on 44.32 hectares at a cost of R 11 515 per hectare. The modified 4.8 mm system, uses 66 sprinklers to apply 4.8 mm/day on 62.05 hectares at a cost of R 10 439 per hectare. This resulted in a reduction in capital costs per hectare since the hardware was now spread over a greater area. Therefore, in Figure 4.13, System 2 was depicted with lower capital costs on the y intercept compared to system 1. In addition, the slope for System 2 was gentler due to anticipated reduction in water and electricity tariffs per hectare. Similarly, System 3 had lower capital and operating costs compared to both system 1 and 2. Systems 2 and 3, therefore, achieved the target of making use of the existing hardware from System 1, while applying a deficit irrigation strategy with reduced fixed and operating costs.

The next component explored irrigation operating rules and the opportunity to take advantage of off-peak pumping. Four strategies were developed and are presented in Table 4-7 below.

Table 4-7 Summary of strategies developed to implement deficit irrigation

	System 1			
Strategy	A	B	C[1]	D[2]
Peak application associated with system strategy (mm/day)	6.9	4.6	6.9 & 4.6 deficit	6.9 mm fixed winter and summer cycle
Application per cycle (mm)	48	32	off-peak = 32 and Peak = 48	Winter = 32 Summer = 48
Cycle length (days)	7	7	7	7
Stand Time (hours)	12	8	8 (germination + tillering) & 12 (Yield Formation)	Winter = 8 & Summer = 12
No of sets/day	2	2	2	2

1 For strategy C, system operated on two 8 hour stand times per day during germination and tillering, and two 12 hour stand times per day during the yield formation phase.

2 For strategy D, system operated on fixed cycle (i.e. with no scheduling) with two 8 hour and two 12 hour stand times in winter and summer, respectively

It should be noted upfront, that strategies A, B, C and D all make use of exactly the same system hardware, in this instance System 1. The difference, as highlighted in Table 4-7, was that the stand time for each strategy was varied. Altering the stand time therefore reduces water application and operating costs. This is shown in Figure 4.14, where all systems have the same y intercept, indicating identical capital costs but varying slopes to indicate varying water and electricity tariffs. The rationale for the strategies was as follows: Strategy A was designed to operate on a 12 hour cycle utilising the full capacity of the system. Hence strategy A, as shown in Figure 4.14, was anticipated to apply the most water and achieve the highest yields, provided no anaerobic conditions were created.

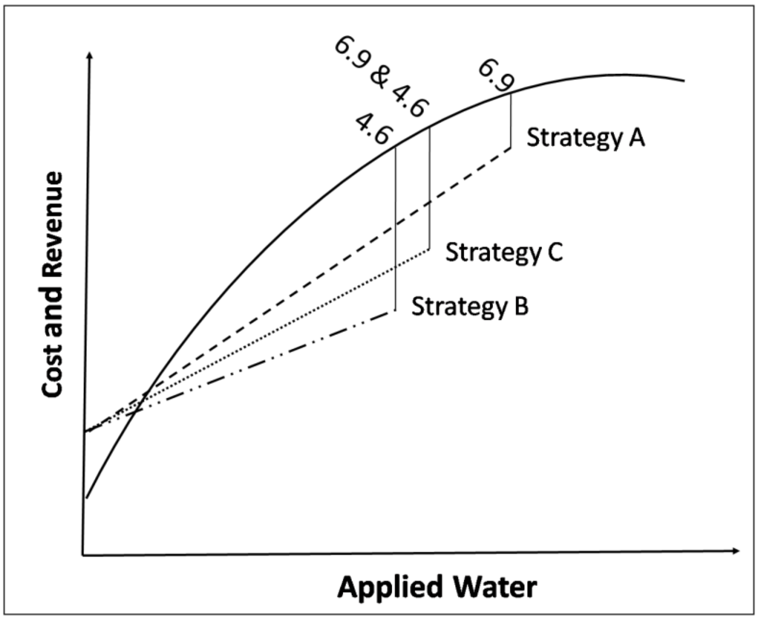

Figure 4.14 Schematic of conceptual variations between strategies A, B and C

Strategy B, made use of the same hardware as A, but only operates for two 8 hour sets in a day instead of two 12 hour sets. This allowed for shifting the use of electricity into standard and off-peak hours. Considering the Ruraflex option in Figure 4.9 from the previous section, the first 8 hour set can take place during the standard period between 10h00 and 18h00. The second 8 hour set can run during the off-peak period between 22h00 and 06h00. Reducing the stand time, however, reduces the system capacity to 4.6 mm/day, thereby incurring crop stress and loss of revenue from yield losses.

Strategy C consisted of a combination of strategy A and B. As explained previously, for the sugarcane crop, water stress in the establishment phase during tillering did not impact significantly on final yields. Hence strategy C aimed to make use of strategy B during the establishment phase and the higher capacity strategy A in the vegetative and yield formation phases. In general, the sugarcane crop requires 30 days for emergence and a further 90 days for tillering (FAO, 2009). Hence reduced irrigation can occur for 120 days from planting without significantly impacting on final yields. In addition, if the crop was planted in April, the low crop water requirements in the germination and tillering phase partially coincide with the electricity high demand period, from June to August. Hence reduced applications and pumping costs during periods of elevated electricity costs will be of greater benefit. This is shown in Table 4-8, below.

Table 4-8 Timeline illustrating deficit strategy during specific crop phases and expensive high energy demand periods

Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	March
Emergence + Tillering				Canopy development + yield formation							Maturation
		High Demand Season			Low Demand Season						
4.6 mm strategy B					6.9 mm strategy A						

Hence, as shown in Table 4-8, it was decided that strategy B was used until the end of the high demand period. The *ZIMsched 2.0* model was, therefore, configured to apply strategy B for the first 150 days, until the end of August, and strategy A for remaining period until dry off. In other words, this translated into operating the system on two 8 hour sets for the first 150 days and then on two 12 hour sets for the remainder of the irrigating season. This was also represented in Figure 4.14, where strategy C was anticipated to deliver an intermediate water application and yield for the same system fixed costs.

Finally, strategy D was developed to illustrate the importance of scheduling. In strategy D, the irrigation was applied on a fixed summer and winter cycle, as shown in Table 4-7. In strategy D, irrigation was applied in accordance with cycle length irrespective of soil water depletion and crop stress levels. No scheduling was used except, irrigation was delayed when rainfall, greater than 10 mm was received. Shown in Figure 4.15, was the anticipated result if strategy D was applied with systems 1 and 2. As shown in Figure 4.15, this strategy was anticipated to incur high costs whilst irrigating excessively.

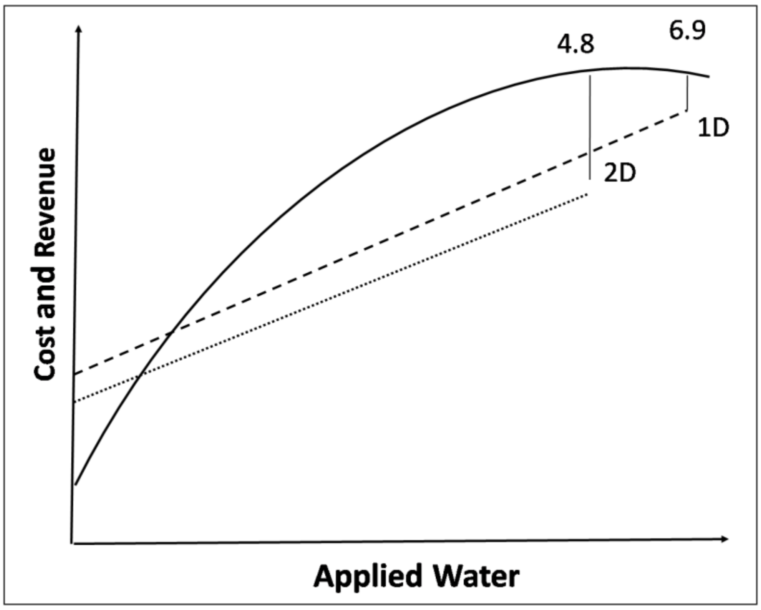

Figure 4.15 Schematic of irrigation strategy D with no scheduling for two different systems with different peak design capacities, namely 4.8 mm/d and 6.9 mm/day

The combination of the proposed deficit irrigation systems and strategies are summarized in Table 4-9, below. The idea was to assess the significance of the reduced watering capacity and resultant yield loss versus the reduction in capital and operating costs.

As was completed in Chapter 4.2, the *ZIMsched 2.0* model was configured with 15 years of weather data for the Heatonville area. The performance of each scenario was simulated for the 15 cropping seasons. The water and yield outputs were then entered into the *Irriecon V2* model together with the other relevant costs, to determine the economic performance of each strategy. A dry land (no irrigation) scenario was also simulated in order to quantify the impact of converting dry land area into irrigated area by using water savings from the deficit irrigation strategies. This will be discussed in more detail later. The results are presented below.

Table 4-9 Summary of irrigation strategies developed to implement the deficit concept

	System 1				System 2				System 3		
Strategy	A	B	C	D	A	B	C	D	A	B	C
Peak application associated with system strategy (mm/day)	6.9	4.6	6.9 & 4.6 deficit	6.9 mm fixed summer and winter cycle	4.8	3.2	4.8 & 3.2 deficit	4.8 mm fixed summer and winter cycle	4.0	2.7	4.0 & 2.7 deficit
Application per cycle (mm)	48	32	Peak = 48 or off-peak = 32	Summer = 48 Winter = 32	48	32	peak = 48 or off-peak = 32	Summer = 48 Winter = 32	48	27	peak = 48 or off-peak = 32
Cycle length (days)	7	7	7	7	10	10	10	10	12	12	12
Stand Time (hours)	12	8	12 or 8	12 or 8	12	8	12 or 8	12 or 8	12	8	12 or 8
No of sets/day	2	2	2	2	2	2	2	2	2	2	2

Strategy A – 2 × 12 hour stand times per day

Strategy B – 2 × 8 hour stand times per day → same hardware, no peak pumping

Strategy C – 2 × 12 hour stand time in low demand off-peak period and 2 × 8 hour stand time in high demand peak period (Same hardware)

Strategy D – Fixed winter & summer cycle irrigation → no scheduling except for rainfall delay calculation

System 1 – 7 day cycle with 14 sprinkler positions on lateral

System 2 – 10 day cycle with 20 sprinkler positions → longer lateral → greater areas covered for same sub mainline, mainline and pump.

System 3 – 12 Day Cycle with 24 sprinkler positions → longer lateral → even greater area covered for same sub mainline, mainline and pump.

4.3.2 Results

The average annual irrigation applications and yields as predicted by the *ZIMsched 2.0* model are shown in Table 4-10. As expected, the fixed cycle system with no scheduling used the most water. Not surprisingly, these systems also delivered lower yields, indicating crop stress due to over irrigation and potentially anaerobic conditions. The 6.9 mm fixed cycle system (1D), on average used 1318 mm annually. This strategy far exceeded what was representative, in terms of water application, for the Heatonville area (Greaves, 2007). For this reason the strategy 1D was considered impractical and discarded. The base system (1A) delivered on average 140 ton/ha for an average annual water use of 855 mm.

Table 4-10 Summary of the average irrigation water applications and yield

System & Strategy (as per Table 4-9)	Average annual water (mm)	Average yield (ton/ha)
6.9 mm fixed cycle (1D)	1318	136.00
4.8 mm fixed cycle (2D)	937	133.49
6.9 mm (1A)	855	140.98
6.9 & 4.6 deficit (1C)	785	140.51
4.8 mm (2A)	783	139.11
4.8 & 3.2 mm deficit (2C)	759	138.75
4.0 mm (3A)	745	136.96
4.0 & 2.7 mm deficit (3C)	712	136.18
4.6 mm (1B)	705	137.61
3.2 mm (2B)	636	132.24
2.7 mm (3B)	593	127.35

Conversely, the 2.7 mm strategy delivered the lowest yield for the lowest water application. The difference between the base 6.9 mm and 2.7 mm strategies amounted to a yield loss of 13.63 tons/ha for a water savings of 262 mm of water. So the crucial question was: would the cost savings for not applying the 262 mm of water make up for the 13 tons/ha yield loss? The answer is provided in the economic analysis in Table 4-11, below.

Table 4-11 Economic performance for each scenario expressed as an average of the 15 cropping seasons in units Rand per area under cane.

System	System 1 – 7 day cycle			System 2 – 10 day cycle				System 3 – 12 day cycle			Dry land
Strategy	A	B	C	A	B	C	D	A	B	C	
	6.9 mm	4.6 mm	6.9 & 4.6 mm	4.8 mm	3.2 mm	4.8 & 3.2 mm	Fixed Cycle	4.0 mm	2.7 mm	4.0 & 2.7 mm	
Revenue											
Cane sales	25, 974	25, 336	25, 863	25, 594	24, 354	25, 544	24, 563	25, 201	23, 434	25, 054	13,815
Irrigation Costs											
Mainline costs											
Mainline fixed costs[1]	1, 118	1, 118	1, 118	981	981	981	981	927	927	927	0
Mainline operating costs[2]	984	681	918	988	653	916	1, 105	968	627	874	0
Total mainline costs	2, 102	1, 799	2, 037	1, 969	1, 634	1, 897	2, 086	1, 894	1, 554	1, 800	0
System costs											
System fixed costs[3]	162	162	162	115	115	115	115	97	97	97	0
System variable costs[4]	541	471	523	522	425	506	624	497	397	475	0
Total system costs	702	632	685	637	540	622	739	594	494	572	0
Total irrigation costs	2, 805	2, 432	2, 721	2, 606	2, 174	2, 519	2, 825	2, 488	2, 047	2, 372	0
Other Direct Costs											
Planting costs	943	943	943	943	943	943	943	943	943	943	943
Ratooning costs	3, 290	3, 290	3, 290	3, 290	3, 290	3, 290	3,290	3, 290	3, 290	3, 290	3,290
Harvesting costs	1, 643	1, 643	1, 643	1, 643	1, 643	1, 643	1,517	1, 643	1, 643	1, 643	874
Haulage costs	4, 471	4, 471	4, 471	4, 471	4, 471	4, 471	4,129	4, 471	4, 471	4, 471	2,378
Total other direct costs	10, 347	10, 347	10, 347	10, 347	10, 347	10, 347	9,879	10, 347	10, 347	10, 347	7,485
NET MARGIN	12, 822	12, 708	12, 821	12, 730	12, 215	12, 780	11, 723	12, 548	11, 638	12, 551	6,330

1 = Interest, depreciation and insurance on all underground pipes and pumping system + electricity fixed costs

2 = Electricity variable costs + repairs and maintenance (repairs and maintenance expressed as percentage of fixed cost)

3 = Interest and Depreciation on sprinkler package only

4 = Water tariffs + labour + repairs and maintenance (repairs and maintenance expressed as percentage of fixed cost)

The answer to the above question is no. The cost savings for not applying the 262 mm of water does not make up for the yield loss. As shown in Table 4-11, the net margin for the 2.7 mm system was lower than that for the 4.8 mm fixed cycle system. Even though both fixed and operating costs for irrigation were much lower for the 2.7 mm system, the cost of yield loss was much greater. This trend applied for all scenarios.

Fixed costs - hardware

Elaborating further, system 1, irrespective of the applied strategies, has the same mainline and system fixed costs since all of the strategies (1A, 1B, 1C and 1D) make use of the exact same hardware. Similarly, this applies to systems 2 and 3. As was anticipated in Figure 4.13, system 3 and 2 were cheaper in units Rand per area under cane since the same sprinklers, sub mainlines and mainlines were used to irrigate a larger area by increasing the cycle length. In this case, the mainline fixed cost for 12 day “system 3” cost R 927 per area under cane, compared to the 10 day “system 2” and 7 day “system 1”, which cost R 981 and R 1, 118 per area under cane, respectively. Similar trends apply for the system fixed costs.

Operating costs – water and electricity

Unlike the fixed costs though, the operating/variable costs for each scenario varies. The mainline operating costs were dependent on the use of electricity while the system variable cost was a function of water tariffs. As expected, systems applying more water on a 12 hour stand time, incurred higher mainline operating and system variable costs. For example the mainline operating costs for the 6.9 mm and 4.6 mm system were R 984 and R 681 per area under cane, respectively. This demonstrates the economic benefit of shifting electricity use to lower costing standard and off-peak hours. Similarly, the system operating costs for the 6.9 mm system and 4.6 mm system was R 541 and R 471 per area under cane, respectively. This demonstrated the impact of reduced water applications and therefore reduced water tariffs. Also made apparent in this analysis was the fact that the cost of electricity was higher than the cost of water.

Saving irrigation costs versus losing revenue from yield loss

The impact of the irrigation costs appears to be smaller than revenue from yields. For example, when comparing the 6.9 mm base system to the 2.7 mm system, the water savings was 262 mm and the yield loss was 13.63 tons/ha. The difference in irrigation costs, from Table 4-11, amounts to R 757 per area under cane. The difference in revenue from cane sales, however, amounts to R 2, 540 per area under cane. This implies that the direct costs of water and electricity are considerably smaller in comparison to cost of yield losses. At this stage it appears that applying a deficit strategy to conserve water and reduce costs, while incurring yield loss, does not benefit a grower financially. The exception in this case was for strategy C, were water was held back at non critical growth stages. This resulted in water savings with minimal crop stress and therefore reasonably high yields and net margins.

Opportunity cost of water

The concept of deficit irrigation, however, cannot be ruled out. The value of a deficit strategy can be realised in the opportunity cost of water. In other words, increased profits can be realised if water savings from a deficit strategy is used to convert dry land cane into irrigated cane, assuming that land is not limiting. This is demonstrated in Table 4-12 below.

In Table 4-12, the irrigable area ratio is an indicator of the additional dry land area that can be irrigated with water savings. For example, in Table 4-10, the “fixed cycle”, 2D, and “2.7 mm” strategies on average used 937 mm and 593 mm per annum, respectively. Hence, for every hectare converted from the fixed cycle to the 2.7 mm strategy, a water savings of 262 mm would be realised. An irrigable area ratio was then used to determine what dry land area could be converted with the water savings. This is shown in Table 4-12. The net margins, including dry land margins, from Table 4-11 are carried through to Table 4-12. The irrigable area ratio was then applied to the net margins above dry land to determine the relative potential increase in net margins when dry land cane was converted to irrigated area with the water savings.

Table 4-12 Potential increase in net margins if dry land cane is irrigated with water savings from deficit strategies in units Rand per area under cane

Systems	System 2	System 1			System 2			System 3			
Strategies	D	A	B	C	A	B	C	A	B	C	
	Fixed 4.8 mm summer & 3.2 mm winter cycle	6.9 mm	4.6 mm	6.9 & 4.6 mm	4.8 mm	3.2 mm	4.8 & 3.2 mm	4.0 mm	2.7 mm	4.0 & 2.7 mm	Dry land
Net Margin	11,723	12,822	12,708	12,821	12,703	12,215	12,780	12,548	11,638	12,551	6,330
Net partial margin above dry land (R)	5,392	6,492	6,377	6,491	6,400	5,884	6,450	6,218	5,307	6,221	0
Irrigable area ratio[1]	1	1.10	1.33	1.19	1.20	1.47	1.23	1.26	1.58	1.32	0
Relative potential increase in margin obtained by converting dry land cane area to irrigated cane area with water savings[2] (R)	0	617	2,091	1,258	1,261	2,786	1,507	1,605	3,069	1,966	0
Net margin totals after converting dry land area to irrigated with water savings (R)	**11,723**	**13,439**	**14,799**	**14,079**	**13,991**	**15,001**	**14,287**	**14,153**	**14,707**	**14,517**	**6,330**
% increase	**0%**	**14.6%**	**26.2%**	**20.1%**	**19.3%**	**28.0%**	**21.9%**	**20.7%**	**25.5%**	**23.8%**	

[1] For example, the fixed cycle strategy uses 937 mm so the irrigable area ratio is 937/937 = 1, whereas the 2.7 mm strategy uses 593 mm so the equivalent ratio is 937/593 = 1.58 (See Table 4-10 for average water use of each strategy).

[2]The relative potential increase in net margins from converting dry land cane was determined as follows:

$$\begin{matrix}\text{Relative potential increase}\\\text{in net margins}\end{matrix} = \left(\begin{matrix}\text{net margins}\\\text{above dry land}\end{matrix} \times \text{irrigable area ratio}\right) - \begin{matrix}\text{net margins}\\\text{above dry land}\end{matrix}$$

As shown in Table 4-12, an increase in profits can be realised by using water savings to convert dry land cane into irrigated cane. This was only applicable, however, if area was not limiting. In most cases in South Africa, water is usually the limiting resource, not land. Continuing with the previous example, for every hectare converted from the fixed cycle to the 2.7 mm strategy, the 262 mm water savings could be used to irrigate an additional area of 0.58 ha. This translated into an increase in net margins by R 3, 069. Hence, the 2.7 mm strategy has the ability to generate a relative increase in net margin to R 14, 707 compared to R 11, 723 for the fixed cycle strategy. Similarly the other strategies also possess the ability to generate increases in net margins ranging from a 14.6 % to a 28 % increase. In this case study, the 3.2 mm strategy (2B) returned the highest relative increase in net margins amounting to R 15, 001.

The irrigable area ratio indicates that the systems and strategies applying the smallest amount of water have the ability to benefit the most from converting dry land cane into irrigated cane. In this case, that corresponds to strategy B for each system, i.e. the 4.6 mm, 3.2 mm and 2.7 mm strategies. These systems save more water and were therefore able to convert larger dry land areas as shown by the relatively higher irrigable area ratios in Table 4-12. These systems, therefore also realised the highest final net margins after factoring in the dry land conversion. In this particular exercise, for these circumstances, the 3.2 mm system yielded the highest net margin after realising the opportunity cost of water. This was an interesting result considering that strategy B applied the lowest amount of water and therefore incurred the most stress and delivered the lowest yields. Not only did strategy B achieve higher profits, but it also possesses the potential to reduce the country’s electricity load during peak hours. Strategy B operated on two 8 hour stand times and therefore avoided pumping during peak periods, saving the grower in terms of electricity costs and benefiting the country at a time when energy conservation was crucial.

4.3.3 Conclusions

In the above exercise, the direct cost of water and electricity versus the cost of yield loss was clearly illustrated. To summarise, reducing the cost of water and electricity by under irrigating had a big impact on yield and therefore profit margins. In South Africa, the direct cost of electricity and water appear to be small in comparison to the cost of yield losses. Hence, cost savings from applying less water did not offset yield losses. The opportunity cost of water, however, can justify the implementation of deficit strategies. In other words, the financial benefits of deficit strategies were only realised when the water savings were used to convert dry land cane into irrigated cane. This was only applicable when land was not limited, as is the case on most farms in South Africa. Hence, provided the opportunity cost of water is realised, deficit strategies can help conserve water and electricity while yielding higher profits.

The strength and value of the irrigation assessment framework and the individual analytical models was again clearly demonstrated. In this chapter, various solutions/alternatives for a specified context were assessed with relative ease. Other scenarios and contexts could just as easily be analysed.

Finally, deficit systems which applied the least amount of water yielded the highest increase in net margins after realising the opportunity cost of water. Reduced water applications results in crop stress and this suggests that it may prove difficult to convince farmers to implement deficit strategies. The implementation of deficit strategies, due to the precise nature and narrow margins for error, would require precise irrigation scheduling and monitoring of the soil and/or crop responses. Monitoring tools will not only help to implement these strategies, but will also assist to gauge the performance of such strategies. Proof of performance, through near real time monitoring, will help instil confidence in growers. These issues are addressed in the next chapter

5. IN-FIELD MONITORING AND EVALUATION TOOLS

Thus far, the focus has been on the innovative design and operation of irrigation strategies and systems to utilise water and energy more efficiently. This chapter was included to provide tools to a farmer in order to monitor and evaluate the performance of irrigation strategies. The question posed was, if a recommended strategy from a previous chapter was to be implemented, how would the performance of the strategy be assessed at a field scale? It was envisaged that the successful implementation of any irrigation strategy was largely correlated to the ability to manage and monitor the implementation of the strategy. In addition to monitoring and assessing irrigation strategies, monitoring systems also have value as decision support mechanisms for irrigation scheduling. Tools informing the timing and volume of water application can prevent excess irrigation and therefore save on water and electricity costs. For these reasons, irrigation monitoring tools were researched and investigated. The intention was to refine and field test a prototype system.

In this chapter, three systems are evaluated. The first system was a continuous soil moisture monitoring system comprising a hobo data logger and watermark soil water potential sensors. This section focused largely on tools used to monitor the soil water balance. The next two systems presented were the Alti4 and Campbell Scientific systems. These systems followed a more holistic approach where sensors were used to monitor the atmosphere, the crop and the soil water balance simultaneously. The work completed included:

- Identification and researching data logger and sensor combinations,
- calibrations, where necessary,
- construction and synthesis of housing units for field installation,
- costing of systems,
- to a certain degree field installation, testing and assessment.

The criteria for assessing the systems, in order of priority, were as follows: ease of use, cost, robustness and accuracy. In the subsequent sections, a technical description of the components and the merits and challenges of each system is presented, starting with the "Continuous Soil Moisture Monitoring System".

5.1 Continuous Soil Moisture Monitoring System

As specified above the objective was to refine and field test a prototype system. Below is the methodology or path that was undertaken to achieve this task:

- Review existing soil moisture monitoring tools and select appropriate sensor based on the review,
- find a suitable data logger,
- calibrate the logger and sensor combination,
- source appropriate apparatus to house the data loggers in the field and protect them from the elements,
- install the monitoring system in farmer's fields,
- download and evaluate the data.

5.1.1 A review of soil water measurement and applicable sensors

A detailed review of soil water sensors is given by IAEA (2008). Pertinent aspects of the review are summarised here as follows. In the irrigation sector, soil water status may be measured in terms of volumetric water content or soil water potential. Soil water content is a description of how much water is present in a given volume or depth of soil, expressed typically in m^3 water per m^3 soil (White, 2003). The Neutron Probe, capacitance sensors and Time and Frequency Domain Reflectometers can be used to measure soil water content. The Neutron Probe and Time Domain Reflectometers (TDR) are very accurate methods of monitoring soil water status. The equipment, however, is relatively expensive and requires specialized knowledge to both record measurements and interpret the data. Furthermore, in the case of the Neutron Probe it is time consuming and labour intensive to gather the data from the fields. The Neutron Probe also makes use of radioactive materials and therefore a strict safety programme regarding the operation, transporting and storage of the equipment is necessary. In addition the Neutron Probe cannot accurately measure the soil water content in the top 20 cm of the soil layer (White, 2003). Capacitance sensors are relatively inexpensive compared to Neutron Probes and TDR instruments and are becoming increasingly more popular. The IEAE (2008) stated, however, that the volume of soil sensed by capacitance sensors is so small that it may not be representative. A universal challenge with measuring soil water content is to determine whether the water content measured is too wet, i.e. above the drained upper limit (DUL), or too dry, i.e. below the water content at which the plant experiences stress (Charlesworth, 2000).

Soil water potential, on the other hand, is a measure of the suction energy required by the crop to extract water, and is, therefore, a more direct indicator of potential crop stress and whether or not the soil is above the DUL. Tensiometers and porous type instruments such as gypsum blocks and Watermark sensors can be used to monitor soil water potential. Tensiometers are limited to soil water potentials above -85 kPa (White, 2003). Should the soil dry out to water potentials below -85 kPa, air enters the device breaking the vacuum with which the tensiometer operates. For this reason, tensiometers are high maintenance apparatus. Gypsum blocks are inexpensive but a major problem is that the gypsum block breaks down and dissolves over a period of time and for this reason the calibration relationship between gypsum block readings and soil water potential is not fixed..

"The Watermark is a granular matrix sensor, similar to a gypsum block. It consists of two concentric electrodes embedded in a porous reference matrix material, which is surrounded by a synthetic membrane for protection against deterioration. A stainless steel mesh and rubber outer jacket makes the sensor more durable than a gypsum block. The porous sensor exhibits a water retention characteristic in the same way, as does a soil. So, as the surrounding soil wets and dries, the sensor also wets and dries. Movement of water between the soil and the sensor results in changes in electrical resistance between the electrodes in the sensor. The electrical resistance can then be converted to soil water potential through a calibration equation" (Chard, 2008). It should be noted that the Watermark sensor is sensitive to soil temperature and soil temperature needs to be monitored and accounted for in the calibration equation (Shock *et al.,* 1998). Watermark sensors, however, are compact, robust, easy to use, relatively inexpensive and widely accepted by irrigation scientists for their ability to account for changing soil moisture conditions (Vellidis *et al.*, 2008). Furthermore, watermark sensors operate over a broader range when compared to tensiometers and are more robust than gypsum blocks.

From the above assessment of soil moisture sensors, the Watermark soil water potential sensor was selected for use. The next step was to find an appropriate logger data logger.

5.1.2 H8 Hobo data logger and Watermark combination

The 'H8 Hobo' four-channel data loggers from the Onset Computer Corporation were selected following the already completed work on Watermark sensors reported by Allen (2000). The H8 Hobo loggers were readily available and provided a relatively inexpensive source of continuous hourly data. Furthermore, the loggers were small, inconspicuous and require only a small watch-type battery and therefore are not likely to be tampered with or stolen. The Onset Hobo Logger uses DC current to excite the sensor. The Watermark sensors, however, are more suited to high frequency AC excitation. DC excitation can cause polarisation over time by causing the cations or anions to migrate to the electrodes. The Hobo excites all sensors simultaneously and then proceeds to read each channel in succession, completing readings in as little as 10 to 40 milliseconds. Hence, very little time exists for migration to occur and polarisation is unlikely to be a problem (Allen, 1999).

Electrolysis, however, occurs at the electrodes of sensors when the excitation lingers for more than 2 milliseconds. Electrolysis results in formation of micro gas bubbles that alter the resistance of the water medium and therefore the sensor reading. In the case of the H8 Onset Hobo logger, the channels are excited for different periods of time and the associated formation of the micro gas bubbles affects the resistance readings of the different channels. Nevertheless, for most practical purposes, any resulting bias in the readings can be addressed by using a different calibration relationship for each channel (Allen, 1999).

5.1.3 Calibration

Three watermark soil water potential sensors and a soil temperature sensor were attached to the Onset H8 Hobo Data logger. All sensors were then placed in a saturated soil medium in a pressure plate chamber in a laboratory at the University of KwaZulu-Natal in South Africa. The pressure plate chamber was then used to systematically exert pressure on the soil forcing water to drain from the soil. The pressure plate chamber provided a controlled environment in which the soil water potential was determined and compared to the voltages logged by the Onset Hobo logger. Using regression methods, relationships were developed to relate soil water potential to voltage readings for each channel, taking into account the soil temperature. The regression relations, together with the recorded data, are illustrated in Figure 5.1 below.

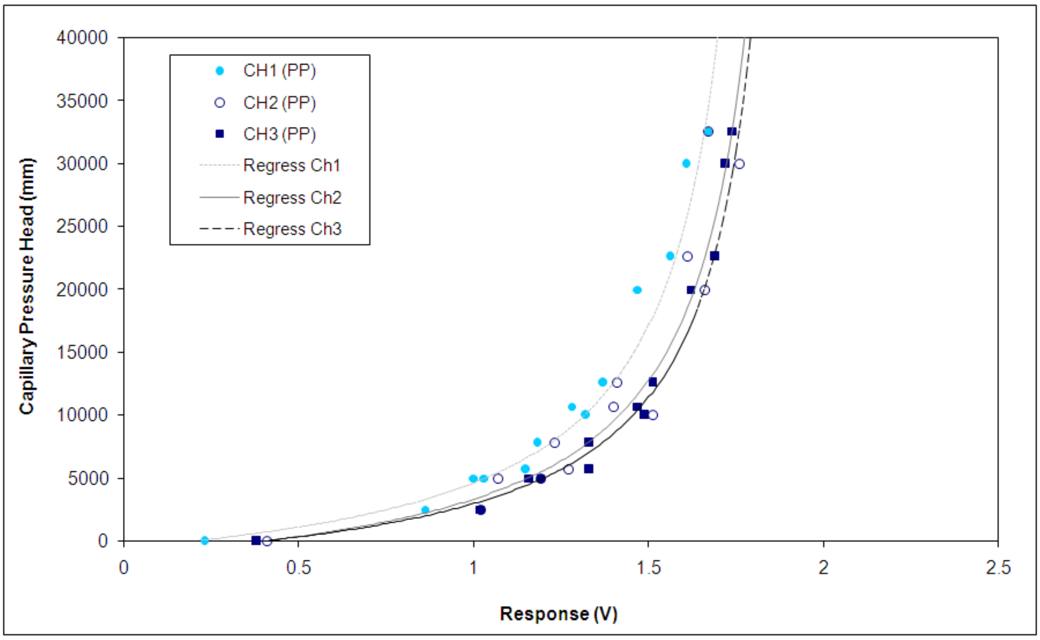

Figure 5.1 Calibration curve of Onset Hobo Logger and Watermark sensor. CH1, CH2 and CH3 refer to Channels 1 to 3 of the Hobo Logger and PP refers to data from the pressure plate apparatus

As illustrated in Figure 5.1, higher voltage responses were recorded for channels 2 and 3 when compared to channel 1 for the same capillary pressure head. This illustrates the variable resistance in the water medium due to electrolysis and hence the need for calibration of each channel separately. The accuracy of the calibrations can also be assessed by referring to Figure 5.1. Whilst there is potential to refine the calibration relationships, especially for channel 2, the relationships were considered to be adequate for the study objectives.

5.1.4 System housing and costs

A general purpose, weather resistant electrical box (code: RL1 – HP) was sourced from ARB Electrical Wholesalers (Pty) Ltd. (2008) to house the data logger. The box was 150 x 150 x 100 mm deep with a hinged screw on lid as shown in Figure 5.2. A 20 mm hole was drilled into a side wall to allow for the cables from the Watermark sensors to be connected to the data logger.

Figure 5.2 General purpose box used to house Onset Hobo data logger (ARB Electrical Wholesalers (Pty) Ltd., 2008)

The total cost of the soil water potential monitoring system was R 3450 as shown in Table 5-1

Table 5-1 Cost break down of soil water potential monitoring system in 2007

Description	Quantity	Cost
Watermark Sensors	3	R 1, 770
Soil Temperature Probe	1	R 340
Onset Hobo Logger	1	R 1, 200
General Purpose Box	1	R 140
	Total	R 3, 450

5.1.5 Installation of soil moisture monitoring system

In order to assess the hypothesis of under irrigation from a previous benchmarking study (Greaves, 2007), the continuous water potential monitoring system was installed in two farms. Three watermarks were installed in the cane row at depths of 15cm, 30 cm and 60 – 80 cm, dependant on site conditions. A standard soil auger was used to auger a hole to the required depth. The soil removed from the hole was sieved to remove rocky material, leaves and grass and mixed with water to obtain a thick slurry. The slurry mixture was then poured into the hole, approximately 5 cm deep, to create a seat for the deepest Watermark sensor. A PVC pipe was fitted around the collar of the Watermark sensor and used to locate the sensor snugly into the slurry at the correct depth. The PVC pipe was removed and the slurry mixture and soil were then backfilled into the hole in layers until the required depth for the next sensor was attained. The backfill was firmly tapped in using the handle of an old broomstick to ensure good contact between the sensor and the soil. The remaining 2 sensors were placed in the same hole in the same manner at 30 cm and 15 cm depths. The Soil Temperature Probes were placed in the same hole just above the 30 cm Watermark sensor. The cables were then threaded through the hole in the housing unit and connected to the Onset Hobo logger. Silicone was used to fix the cables in place and seal any gaps in order to protect the logger from water. Finally, the lid of the housing unit was screwed on and the box was placed on the ground in between the sugarcane, out of harm's way.

5.1.6 Results

The system was used to record field data for the 2007/08 season and the detailed description of the findings are presented by Jumman and Lecler (2008) in Appendix E. Shown in Figure 5.3 is the soil water potential data captured for this study. In Figure 5.3, the water potential is represented in kPa on the Y-Axis, where a higher kPa value indicates a drier soil. Inman-Bamber (2002) reported that the threshold water potential for stress in sugarcane is approximately 100 kPa. Studying Figure 5.3, it can be seen that the stress threshold of 100 kPa is exceeded for large periods of time.

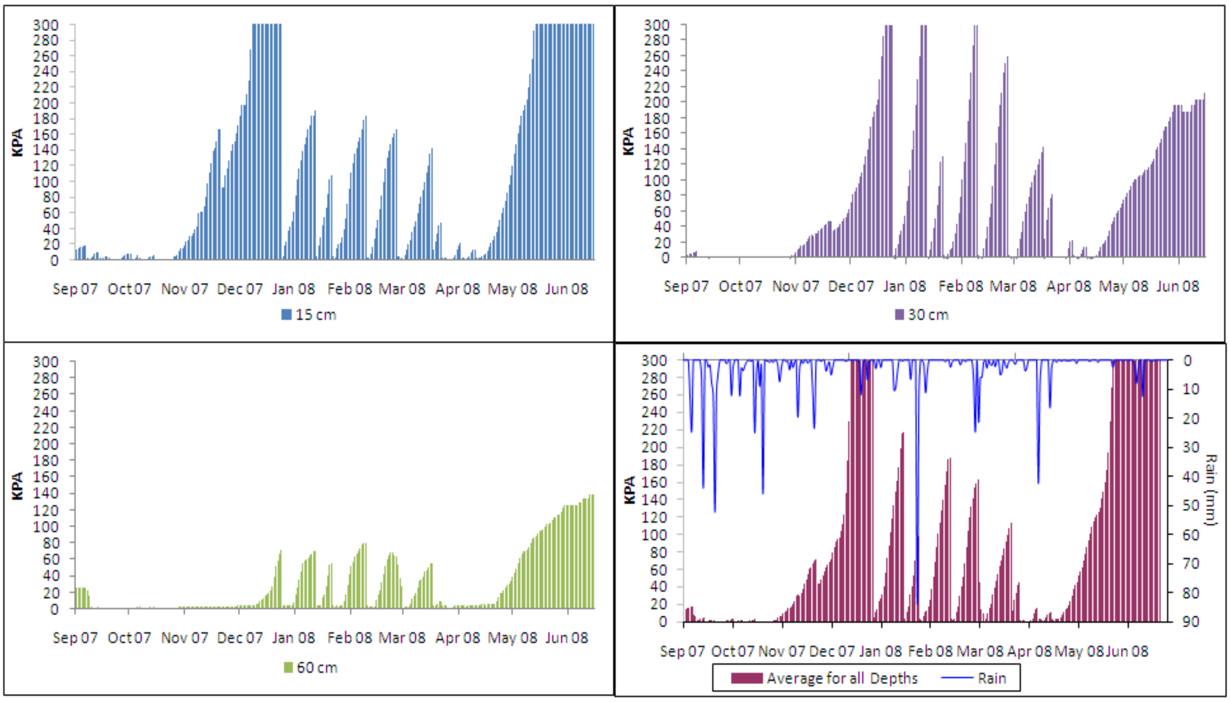

Figure 5.3 Time series of soil water potentials for each depth and average of all depths[1]

1: The average soil water potential was calculated as the average of the three values obtained from the different depths.

The concluding remarks for this study are summarized as follows. The Watermark soil water potential sensors proved to be a valuable tool in substantiating Greaves's (2007) hypothesis of under-irrigation. Availability of continuous soil water potential data assisted farmers to monitor the performance of their irrigation strategies and identify areas for improvements.

The Watermark sensor and Onset Hobo data-logger combination provided a relatively cheap and robust system to capture valuable soil water potential data. Downloading data, however, can be tedious and time consuming if data are required on a frequent basis, as required, for example, to make irrigation application decisions. A user was required to travel to the logger and use a laptop with appropriate cables to download the data. Remote access to data, via GPRS, for example, was not available for the hobo loggers at the time of the study but would have been preferred. Nevertheless, monitoring systems such as the one described, can provide valuable information, for as little as R 3 450, to inform irrigation management decisions and contribute to optimising the use of water for crop production. This will be of great benefit to individual farmers and the wider community.

In the next section, systems allowing for remote access to data were investigated. These systems followed a holistic approach where components of the atmosphere crop and soil moisture were monitored. These systems were compiled, priced and tested for robustness and ease of use. Installation and gathering of field data for a cropping cycle, however, was beyond the scope of this project.

5.2 Alti 4 Sugarcane Monitoring Growth Station

Effective and accurate monitoring, in order to maximise water use efficiency, is considered to be best achieved by physically monitoring the integrated soil-plant-atmosphere continuum (Hoffman and Martin, 1992). Smit (2006), following Inman Bamber (1995), developed the first growth monitoring station for sugarcane at the South African Sugarcane Research Institute. In comparison to the Watermark and Hobo logger system, the growth station offers a more holistic approach. The growth station was designed to measure and capture important crop, soil and climatic data for field trials in the research environment. In previous versions of the growth station the main use of this tool was to understand crop physiology and reactions to environmental constraints in a research environment. In this version, however, the focus was more on monitoring the irrigation water balance with an emphasis on assessment criteria, such as ease of use, cost and robustness. It was envisaged that the tool would be used by farmers for irrigation management (Kennedy, 2008). In the context of deficit irrigation or precision engineering, where strategies are susceptible to dry conditions and tolerances for error are small, real time data from monitoring tools will assist to verify recommendations from scheduling models and instil confidence in farmers. Hence, the development and enhancement of the growth station was important. The main modification to the growth station was the inclusion of a new Alti 4 data logger supplied by Kennedy Besproeiing (Kennedy, 2008).

5.2.1 Data logger

The Alti 4 data logger comprised 4 analogue and two pulse channels with a lithium ion battery pack consisting of two batteries rated at 3.6 volts @ 12 Amp hours each. The logger is capable of logging at 5 minute time intervals at the maximum capacity. For this project a one hour logging interval was used. Each analogue channel provides 2.5 volts at 50 milliamps for 50 milliseconds, for sensor excitation. The lithium ion battery pack was also used to provide power for remote communication/transfer of data. The Alti 4 data logger makes use of GSM/GPRS facilities to transfer data, once a day, to a central server which then could be accessed from anywhere in the world via the world wide web. A monthly subscription fee is payable for this service. The life expectancy of the battery if operated as described above is 5 years (Kennedy, 2008). This is a substantial advantage over many other loggers which typical make use of more expensive solar panels or cumbersome rechargeable batteries (CS Africa, 2009). The trade off for alternative logging options is either cheaper lower power requirements with no remote access to data, as demonstrated by the Hobo data logger in the previous section, or more expensive higher power requirements for remote access. The Alti 4 loggers appear to have the competitive edge with the correct balance between cost and power requirements for remote access to data. This will be elaborated on further in the costing section. The Alti 4 data logger hardware, including sim card and battery, was encased and sealed from water in a 60 mm diameter × 330 mm long hard plastic tube as shown in Figure 5.4.

Figure 5.4 Alti 4 data logger

The Alti 4 logger, shown above, is compact, robust and inconspicuous because the battery and hardware components are sealed and hidden within the casing. As noted above, several sensors were connected to the Alti 4 data logger to monitor the soil-plant-atmosphere continuum. Presented below is a description of the importance of each monitoring component and, technical information of the instruments if unique or new.

5.2.2 Temperature and rainfall

The upper limit of crop production is set by the climatic conditions and genetic potential of the crop (Doorenbos and Kasam, 1979). Monitoring the relevant climatic parameters, therefore, provides insight as to what the potential for crop growth was. The two major atmospheric components that are generally monitored are air temperature and rainfall. Air temperature serves as an indicator of solar radiation energy available for growth and vapour pressure deficits to drive evapotranspiration (Schulze 1995). Lower temperatures are indicative of slower growth due to natural, uncontrollable, constraints in the field. Reduced growth, however, may also be experienced during high temperature periods when the plants experience water stress. Rainfall contributes to determining the soil water balance and, therefore, real time rainfall data is significant to managing and implementing irrigation strategies. For these reasons, measurement of air temperature and rainfall was incorporated into the Alti 4 growth Station. The technical specifications for air temperature sensors and rainfall gauges are not discussed as they are easily accessible "off the shelf components" from companies such as Campbell Scientific (CS Africa, 2009).

5.2.3 Plant growth

Inman-Bamber (1995) reported that leaf and stalk extension rate are the best indicators of crop water status in sugarcane. The extension of stalks and leaves shut down before photosynthesis stopped on the onset of stress. Stalk extension contributed to the process of yield development and was, therefore, reported to be more relevant then leaf extension (Inman-Bamber, 1995).
In a study in Australia, mini-pans were used to calibrate the evaporation from these pans to the crop water requirements via stalk extension rates for a given soil type and time of year (Attard, 2002). Hence robust scheduling techniques were developed by measuring stalk extension and relating it to the evaporation from mini pans.

Furthermore, monitoring the extension rate of sugarcane stalks allows one to determine the allowable degree of water deficits before yields are significantly penalised. In Australia, in order to achieve maximum yields, the relative stalk extension rate is allowed to drop to 50% of the maximum stalk extension rate before irrigation is applied. Inman-Bamber (2003) and (2005) indicated that if irrigation was applied when relative stalk extension rate dropped to 30% of the maximum, less water will be applied resulting in decrease in cane yields but not sucrose content. Hence, in the context of irrigation optimisation and precision engineering, the ability to continuously monitor stalk extension is important.

In the past stalk extension was laboriously measured with a ruler (Inman-Bamber, 1995). Inman-Baber (1995) used a growth transducer (potentiometer) to automatically measure and log plant elongation. Limitations of this system, however, included extensive rigging to mount in the field, wind disturbances and technical problems with the data logger (Smit *et al.,* 2005). Smit (2006) improved on this system and registered a patent titled “Apparatus for measuring the growth of a plant”. This instrument, referred to as the Potentiometer, was used in the Alti 4 growth station as shown in Figure 5.5.

The potentiometer consisted of a Spectrol 10 KΩ 10-turn potentiometer mounted on a light weight, 10 mm aluminium tubing that clamps onto the cane stalk. A fishhook was secured to the youngest visible node of stalk and an 80 g brass counterweight inside the tubing keeps the non-stretchable dial cord under constant tension. Winding over a pully on the potentiometer was enough to allow approximately 300 mm travel. The system works such that, as the stalk extends, the hook and the dial cord extends causing the pulley and shaft of the potentiometer to rotate. This rotation in turn alters the position of the variable resistor. Hence as the stalk extends, voltage output as a result of varied resistance changes. Hence for a fixed input voltage of 2.5 volts, the linear displacement of the cord (stalk extension) can be related to the output voltage of the potentiometer.

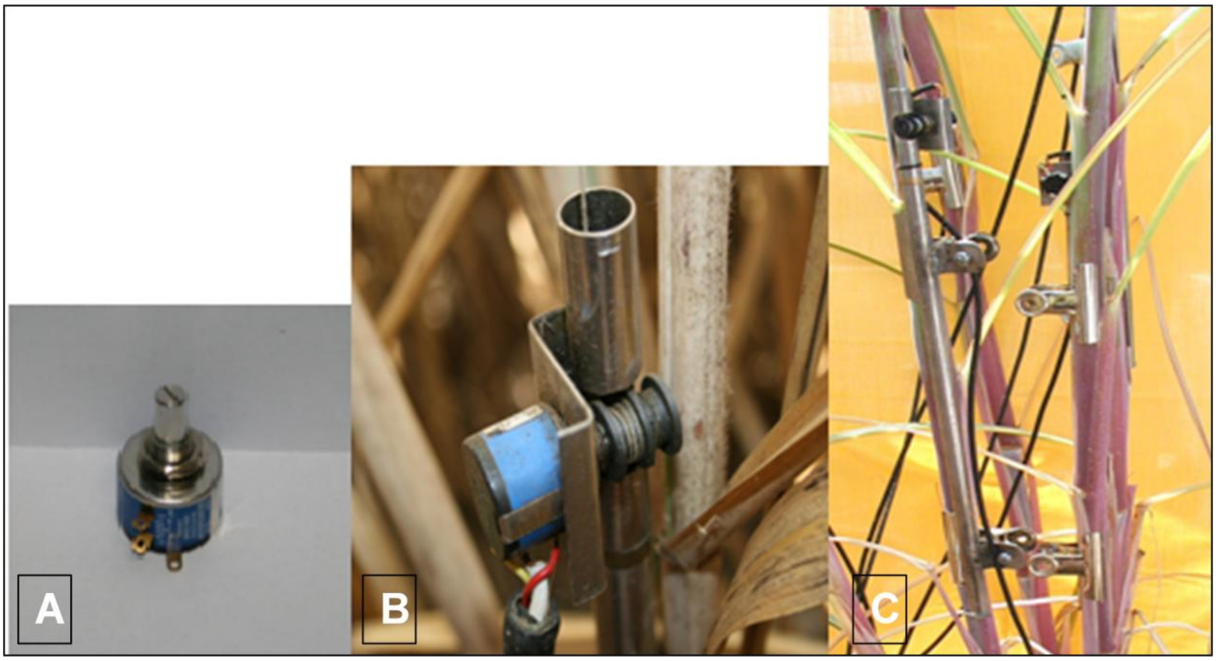

Figure 5.5 A) Spectrol 10 KΩ potentiometer. B) Non stretch Dial chord mounted on pulley which in turn is mounted on Potentiometer shaft. C) Plant growth measuring device with Alumium tubing mounted on sugarcane stalks

Limitations of the apparatus include susceptibility to rust. Nevertheless, as will be shown in a costing section, the sensor was relatively cheap to replace when required. In addition, there was a need to re-attach the hook on the new node of stalk as the crop grew. This proved a time consuming and laborious exercise and room does exist for improvement. Furthermore, only one stalk was monitored at any given time and questions were posed regarding how representative would a single stalk be of the entire field? Nevertheless, the apparatus still provides valuable data and was to be used until better options were available.

5.2.4 Soil moisture

As before, the Watermark sensor was preferred to measure soil water potential. Migration and electrolysis issues, however, pertaining to DC loggers and Watermark sensors were discussed in Section 5.1.2. These issues were brought back into question with the growth station and the new Alti 4 logger combination. The time period between excitation and logging and hence, the interference due electrolysis and/or migration on data for the Alti 4 logger was unknown. For this reason, the newly launched MPS-1 water potential sensor, illustrated in Figure 5.6, was used. Similar to the Watermark, the MPS-1 sensor makes use of porous ceramic disks, with a water retention characteristic that wets and dries out as the soil wets and dries out (Decagon, 2008). In the case of the MPS-1, however, the dielectric permittivity of the porous ceramic plates was measured. This was different from the watermark sensor which measured the electrical conductance of the porous material. For this reason, electrolysis, the formation of micro gas bubbles which alters electrical resistance, was not a concern for the MPS-1 sensor. The MPS-1 sensor therefore appears to be better suited to the Alti 4 data logger.

Figure 5.6 Illustration of the new Dielectric MPS-1 Water Potential Sensor (Decagon, 2008)

“Water content and water potential are related by a relationship unique to a given material. The ceramic used with the MPS-1 has a wide pore size distribution and is consistent between disks. So, if the water content of the ceramic is measured accurately, along with a measurement of actual water potential, then a calibration curve is generated that will give a standard calibration for the MPS-1 in terms of water potential. This calibration is not dependent on the type of soil into which the MPS-1 was installed” (Decagon, 2008). This was attractive to the author bearing in mind the ease of use of the MPs-1 sensor and reduced complexity of data processing for farmers.

In addition, when compared to the Watermark sensor, the MPS-1 measures soil water potential from -10 kPa at saturation down to -500 kPa (Decagon, 2008), which is significantly more than the -200 kPa achieved by the Watermark and Hobo logger combination in the pressure plate chamber (Jumman and Lecler 2008). The MPS-1 also appeared fairly robust and accurate with a resolution of 1 kPa from -10 to -100 kPa and 4 kPa from -100 -500 kPa (Decagon, 2008). Furthermore, the MPS-1 sensitivity to temperature and salinity is negligible in the context of irrigation. "The MPS-1 does exhibit some sensitivity to temperature change. This was primarily due to changes in the dielectric permittivity of the ceramic and water due to temperature change. For most field applications (i.e. installation depth > 15 cm) this sensitivity is negligible. For shallower applications or lab studies over highly variable temperature ranges, a temperature correction may be desirable" (Decagon, 2008). Similarly, MPS-1 sensors demonstrated a, low, 2 % sensitivity to changes in salinity ranging from 0.01 dS/m to 10 dS/m (Decagon, 2008). The MPS-1, therefore, appears to be a better suited sensor for the Alti 4 logger.

5.2.5 Alti 4 Growth Station - configuration and cost

The configuration of the Alti 4 Growth Station is shown in Figure 5.7, below. It was important for the system to be robust and well protected against the environmental elements. These included protection against theft, rodents/pests and climatic factors such as wind and the suns UV rays. The configuration and attributes are described below.

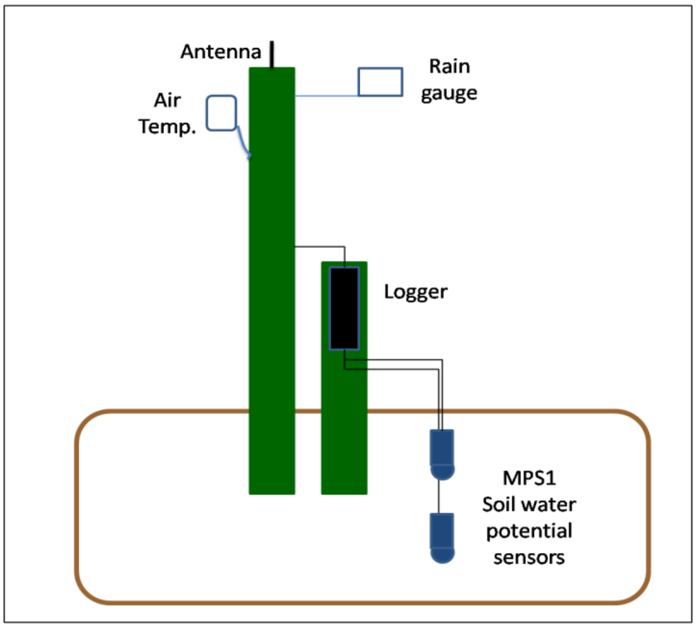

Figure 5.7 Configuration of the Alti 4 Growth Station

The growth station was configured such that the logger was housed in a 1.5m long × 63mm diameter PVC plumbing vent pipe, which was painted green and planted vertically amongst the sugarcane. This allowed for all cables running from sensors to the logger to be housed within the pipe. A second pipe, 3.5 m long × 63 mm diameter, planted immediately next to the logger, was used to mount the antennae, rain gauge and temperature sensors at canopy level for a fully grown crop. Sensors were fixed on the pipe using hose clamps, thus allowing for easy adjustment of vertical position during different crop growth stages. It was important for the antenna, rain gauge and temperature sensor to be mounted at canopy level. The antenna – to ensure maximum opportunity for cell phone signal, rain gauge – to prevent interception losses and capture rainfall records correctly, and air temperature – to accurately capture the potential energy available for growth and evapotranspiration. The 3.5 m PVC vent pipe was also painted green and proved to be very steady and, for security reasons, blended in well with the environment. The MPS1 soil water potential sensors were installed in the ground as shown in Figure 5.7. Furthermore, the stalk extension potentiometers were mounted on the sugarcane stalks. This is not shown in Figure 5.7. The costs of the Alti 4 growth station were broken down as follows.

Table 5-2 Cost break down of Alti 4 Growth Station

	Description	**Unit Price**	**Quantity**	**Total**
1	Alti4 data logger + Alti two cell battery pack + antenna	R 4, 891.00	1	R 4, 891.00
3	Ech20 air temperature sensor with gill screen	R 1, 891.00	1	R 1, 891.00
4	Panoramic professional 0.2mm rainfall gauge	R 3, 100.00	1	R 3, 100.00
5	Stalk extension potentiometer	R 200.00	1	R 200.00
6	Decagon MPS1 soil water potential sensors	R 1, 428.00	2	R 2, 856.00
7	Housing (PVC plumbing pipe)	R 193.00	1	R 193.00
	Total (excl. VAT)			R 13, 131.00

As shown in Table 5-2, the capital investment for the system is R 13, 131. In addition, a monthly subscription fee is payable for the remote transfer of data. This consists of a R50 and R 160 sim card and web server hosting fee, respectively. Hence, the operating costs amount to R 210 per month. The Alti 4 logger made use of the General Packet Radio Service (GPRS) transmission technology to transfer the data via the cell phone network. In this project, data were logged every hour and only transferred to the website once a day. If GPRS was not available, however, a backup sms system was on hand. The backup system used the Global System for Mobile (GSM) communication where the data were transferred via sms at a charge of 50 cents per sms.

5.2.6 Installation and preliminary results

The Alti 4 logger, antenna, rain gauge, two potentiometers and two MPS-1 sensors together with the upright pipes, as shown in Figure 5.7, were installed at the Automatic Short Furrow (ASF) trial at Ukulinga in Pietermaritzburg. Installation of the MPS-1 sensor proved to be relatively easy. After digging the hole, with an auger, the soil was simply wetted and packed around the ceramic plates. As described in Section 5.1.4 for the Watermarks, a PVC pipe was fitted around the collar of the sensor and was used to seat the MPS-1 snugly at the bottom of the hole. Sensors were placed in between the furrow and cane row at depths of 20 cm and 60 cm. A mixture of soil and water was backfilled and lightly compacted into the hole. Preliminary soil water potential results from the ASF trial in Ukulinga are shown in Figure 5.8 below.

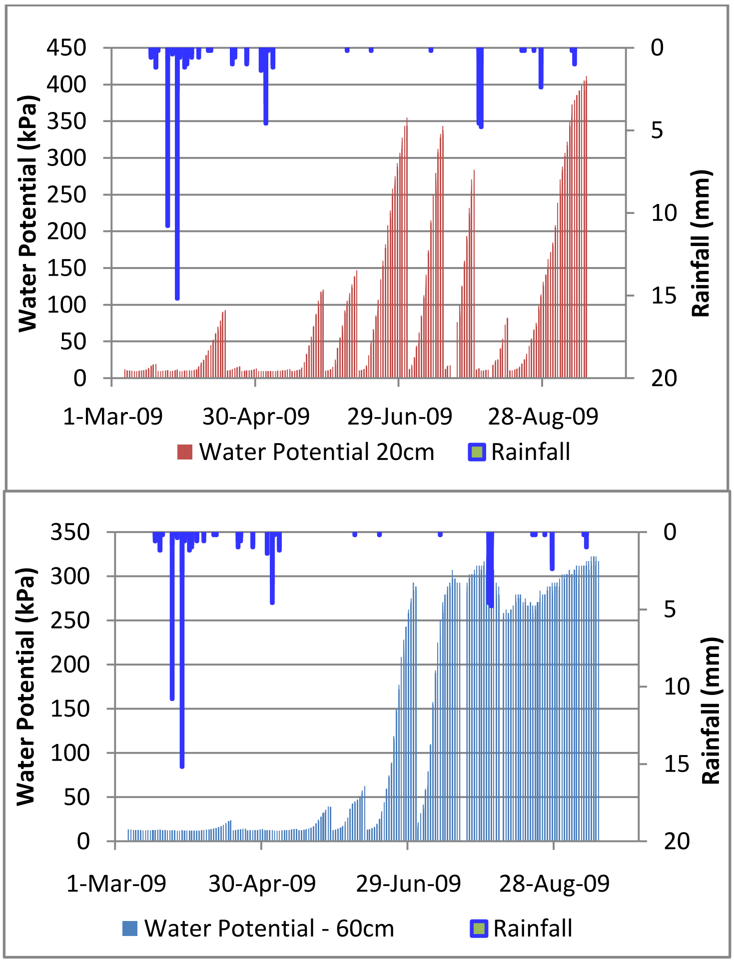

Figure 5.8 Preliminary results from MPS-1 sensors and rain gauge from the Automatic Short Furrow trial in Pietermaritzburg

As shown in Figure 5.8, the MPS-1 sensors responded relatively well to both rainfall and irrigation. The sensors also detected the dry off period before harvest in September sufficiently well. In addition the remote transfer of data via the website proved useful and was often used to verify irrigation scheduling as determined by a different scheduling model. Gathering stalk extension data from the potentiometers proved difficult even though they were developed and tested by Smit *et al*. (2005). This was because a person was needed on site to reattach the dial chord after it became fully extend from stalk growth. This can be problematic on remote sites, for example, as was the case for this study. Nevertheless, the system is relatively easy to install. Remote access to data increases the ease of use for growers and irrigation advisors. The system also proved to be relatively robust and well suited to the harsh agricultural environment.

One of the concerns with the Alti 4 growth station was the dependency on Kennedy Besproeiing and more specifically, Mr. James Kennedy. In the event of logger software failure or technical problems with the web page, for example, Mr. Kennedy at the time of this study was the only available/appropriate person who could address such problems. This could prove problematic if Mr Kennedy, say for instance, was not in the country. Considering, that adoption of irrigation scheduling tools in South Africa was largely inhibited by perceived complexity and lack of support services (Stevens, 2006), dependency on a single individual may prove to be risky in business terms for farmers. For this reason, an alternative Campbell scientific monitoring system was investigated. This is presented in the next section.

5.3 Campbell Scientific Growth Station

Campbell Scientific inc., established in 1974 in the United States of America (CS Africa, 2009), is a prominent company that manufactured data loggers, data acquisition systems and monitoring and measuring instruments. In addition to being well established and reputable in South Africa, Campbell Scientific Inc. have also demonstrated excellent technical support with researchers from SASRI for several years. Hence, a Campbell Scientific logger was purchased and investigated as an alternative to the Alti 4 logger. The temperature sensor, rain gauge, potentiometer and MPS-1 sensors were all used as in the Alti 4 system. Only the data logger and data transfer mechanisms changed. Below is a description of:

- the characteristics and practical configuration of the selected logger,
- system costs,

- and merits and challenges of the system.

5.3.1 CR200 Campbell Scientific data logger and sensor configuration

The primary reason for selecting the CR200 logger was that it was the lowest cost data logger in the Campbell Scientific range (CS Africa, 2009). In addition, the CR200 channel configuration and small size was well suited for this application. The CR200 consisted of 2 excitation channels, 5 individually configured single ended output channels and 2 pulse channels. The excitation channel range was programmable for either 2.5 or 5 volts, while the analogue output voltage range was 0 – 2500 mVolts. Other specifications included a 12 bit A/D converter, maximum scan rate of once per second, measurement resolution of 0.6 volts, 1 switched battery port and 2 control ports, battery voltage range 7 – 16 Volts DC, an on board 12 Volt DC, 7 amp hour, lead acid battery charger and communications options via RS 232 (CS Africa, 2009). The only limitation of the CR200 was that the 2 excitation channels were not adequate to provide power for exciting all the sensors. Figure 5.9 below, illustrates the configuration of the sensors and the CR200 data logger. Due to only two excitation channels being available in this logger, two MPS-1 sensors had to be connected to Excitation channel 1 as indicated in Figure 5.9. The limitation occurs in that the MPS-1 sensor requires a minimum of 25 milliamps for excitation and the CR200 cannot provide this for both sensors simultaneously.

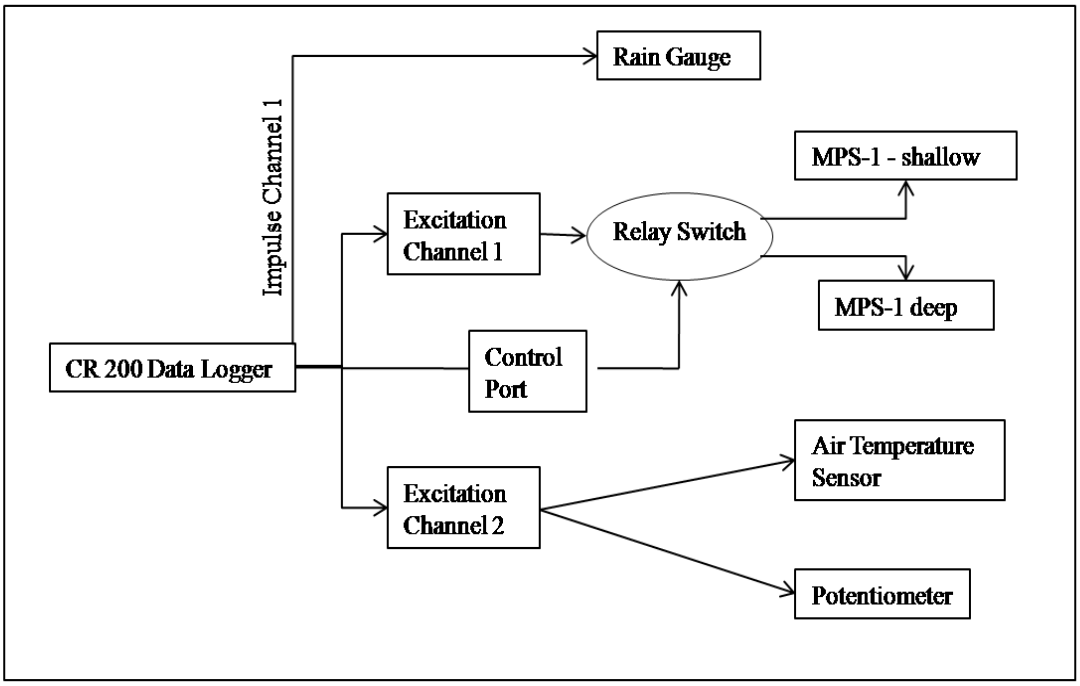

Figure 5.9 Schematic of CR 200 and Sensor configuration

For this reason, a relay switch was used. The relay switch allows the data logger to excite one MPS-1 sensor at a time, sequentially. In other words, the relay switch was used to activate and scan, say, the shallow MPS-1 only. On completion of scanning, the shallow MPS-1 was deactivated and the deep MPS-1 activated and scanned. In this way the power requirements of each MPS-1 sensor was met and the limitation dealt with. The remaining excitation channel was used to connect to and excite the air temperature sensor and the potentiometer. The power requirements of the potentiometer and temperature probe were not as high as the MPS-1 sensors and therefore could be excited simultaneously. Finally, the panoramic 0.2 mm rain gauge was connected to the impulse channel. Hence, an impulse channel and a single ended output channel were still available for future additions such as wind speed if required.

The other limitation with the Campbell Scientific system is the relationship between costs, battery life and remote communication of data. The CR200 logger, for this application, made use of a 12 volt rechargeable battery rated at 12 amp hours. Unlike the Alti 4 system, GPRS and GSM options were available independently. For both GPRS and GSM options, two modems were required. A field and an office bound modem. In this case a Meastro 100 GSM/GPRS modem was used as the field unit and a SAMBA 75 GPRS/GSM modem was proposed for the office. Hence, in addition to the powering up the sensors, the battery was also used to power the Meastro 100 GSM/GPRS modem.

The data logger was programmed to scan and log sensor readings every hour and then transfer the data via GSM/GPRS once a day. Operating in this manner implied that the battery would have to be recharged periodically. The battery life before recharging was required was determined theoretically to be 8 months (Hoy, 2009). In terms of “ease of use”, this system was less attractive as maintenance/labour/time requirements to recharge batteries were relatively higher when compared to the Alti 4 system. In addition, the costs of the system as shown in Table 5-3 were also higher when compared to the Alti 4 system.

Table 5-3 Cost break down of Campbell Scientific Growth Station

	Description	Unit Price	Quantity	Total
1	CR200 data logger + Antenna	R 5, 083.50	1	R 5, 083.50
2	12V sealed rechargeable battery	R 210.60	1	R 210.60
3	Meastro 100 GSM/GPRS modem	R 2, 011.50	1	R 2, 011.50
4	Ech20 Air Temperature Sensor with Gill Screen	R 2, 266.66	1	R 2, 266.66
5	Panoramic Professional 0.2mm Rainfall Gauge	R 2, 776.95	1	R 2, 776.95
6	Stalk Extension Potentiometer	R 200.00	1	R 200.00
7	Decagon MPS1 Soil Water Potential Sensors	R 1, 581.25	2	R 3, 162.50
8	Campbell Control Relay	R 95.00	1	R 95.00
9	Housing (PVC plumbing pipe + general purpose electrical box)	R 411.32	1	R 411.32
10	Samba 75 set Falcom modem + sim card set up fee	R 2, 802.09	1	R 2, 802.09
11	LoggerNet Software	R 4, 366.00	1	R 4, 366.00
	Total (excl. VAT)			R 23, 386.12

The capital investment required for this system was R 23, 386.12, significantly higher than the Alti 4 system. The difference was largely attributed to the additional costs of the CR 200, the office based Samba modem and the LoggerNet software. It should also be noted that, as in the case of the Alti 4 system, the PVC vent pipe was used as a frame to mount the sensors and/or house the cables. Due to the size of the CR200 logger, however, a general electrical box, mounted onto the PVC pipe, was required to house the data logger, the modem and the battery. The dimensions of the box were 32 cm long × 28 cm wide × 150 cm deep, at a cost of R 218.32.

As mentioned previously, remote communication via GSM or GPRS was available. For the GSM option, a fax modem via a landline in the office can be used to communicate to the field unit. The operating costs for GSM, however, were considered too high and therefore only the GPRS option was accounted for in Table 5-3. In addition to the capital costs for the Samba 75 modem, operating costs for the GPRS system were also allocated. The operating costs consisted of a 24 month cell phone data bundle subscription charged at R 152.62/month. The Campbell Scientific system appears to be a reliable and robust system. The major challenge, however, was the additional capital costs when compared to the Alti 4 system.

5.4 Conclusions

In this chapter three monitoring systems were evaluated. The first system was a continuous soil water potential monitoring system consisting of the Hobo logger and Watermark sensors. The second and third systems were more holistic and aimed to monitor the atmosphere – plant – soil continuum. The Watermark and Hobo combination proved to be relatively easy to use, cheap and robust. Field testing of the system also allowed for the gathering of valuable continuous data which substantiated the hypothesis that farmers were under irrigating. The challenge for this system was related to the effort associated with manually downloading data since no remote access was available.

For this reason options such as the Alti 4 and CR200 logger which allowed for remote access to data were investigated. Field testing and gathering of data for an entire season, for Alti 4 and Campbell Scientific systems, was beyond the scope of this project. Nevertheless, both systems were compiled, priced and assessed with a relatively small degree of field testing of the Alti 4 system. Both systems proved to be robust and very easy to use. The Campbell Scientific system, however, was disadvantaged in that battery life spans were shorter and batteries would have to be recharged periodically. Furthermore, the capital cost for the Campbell Scientific system was considerably larger than the Alti 4 system. In short, the combination of low cost, good battery life, remote access to data and holistic monitoring provided the Alti 4 system with the competitive edge. Development and assessment of these tools now provide the platform for precise irrigation monitoring and management, as was desired.

6. DISCUSSION AND CONCLUSIONS

In the context of the current water shortages, rapidly increasing electricity tariffs and increasing strain on farmers to remain profitable, the primary focus of the work reported in this dissertation was to:

- Develop a decision support framework with analytical tools to holistically assess the performance of alternative irrigation scenarios, both from a design and operating perspective.
- Apply the framework to investigate potential solutions for: over irrigation on shallow soils, increasing electricity tariffs, and to assess the potential benefit of deficit irrigation strategies.
- Develop infield monitoring tools for easy implementation of irrigation strategies that require precise management.

Descriptions of how well the objectives were achieved and the major outcomes of the study are presented below.

6.1 Framework development

Sugarcane was the target crop and for this reason, the existing *ZIMsched 2.0* and *Irriecon* V2 models, with the algorithms specific to sugarcane were selected as components of the framework to simulate the water budget and holistically assess the economics, respectively. In terms of water balance and crop yield prediction models, many options such as *ACRU*cane, *SAsched* and CANESIM were available. *ZIMsched 2.0*, however, was selected for its ability to account for different levels of uniformity and the impact of over and under irrigation on yield. An irrigation design and costing tool was then developed in order to prepare irrigation hardware costs that were representative of the irrigation constraints simulated in the *ZIMsched 2.0* model. Finally, *Irriecon* V2, an economic assessment tool, was used to determine the net margins above allocated costs for the various scenarios and irrigation strategies.

The synthesis of these tools into a decision support framework provided the platform for rapid and efficient generation and assessment of irrigation scenarios, strategies and solutions. The assessment framework followed a holistic approach since interacting parameters were accounted for. These included irrigation system capability in terms of water use and yield and the associated irrigation costs. The irrigation costs included capital costs for systems hardware and operating costs such as labour, maintenance and water and electricity tariffs. A holistic approach was considered important since it allows for sensible assessment of the trade-offs between system uniformity, watering capability and the associated irrigation system costs versus revenue from yield. In addition the cost for agronomic practices such as planting, herbicide and fertiliser application and harvesting, transport and haulage costs were also accounted for.

All three of the tools were spreadsheet-based allowing for a high degree of transparency and flexibility. This flexibility was vital for the generation of unique scenarios and strategies such as those that were required for the deficit strategies. The *ZIMsched 2.0* model, in particular, allowed for easy programming to control water applications during peak and off-peak electricity tariff periods and "high" and "low" irrigation demand periods. In addition, the graphic illustration of the soil water budget in the *ZIMsched 2.0* model, proved to be useful when comparing and understanding the dynamics between strategies. For example, visual representation of the water budget allowed for easy identification of the excess runoff for the 12 hour stand time system in the shallow soils investigation.

Irriecon V2, in contrast required intensive input data from many different disciplines. These include data relating to herbicides and fertiliser application, as well as sugarcane planting, harvesting, haulage and transport in addition to irrigation. For this reason, the tool is relatively complex and potentially limited to only very knowledgeable users. The tool, however, once configured correctly, is valuable and relatively easy to apply. Other potential users such as agricultural/irrigation consultants could obtain assistance from SASRI to furnish the model with the necessary input data/information. *Irriecon V2* also provided the economic assessment output in units of Rand per area under cane. This functionality allowed for easy comparison of systems designed for slightly different sized areas but of a similar scale.

Finally, the development of the irrigation design and costing tool formed a pivotal component in the framework. Accounting for the cost of irrigation hardware was an essential component in assessing the performance of any irrigation strategy. The tool provided a relatively quick and efficient method to generate alternative irrigation designs and representative costs for these design options. The versatility of a spreadsheet-based tool also allowed for easy modifications to designs. This was particularly useful for the shallow soils investigation, where an additional set of sprinklers and hydrant control valves were incorporated to convert the 12 hour stand-times in an initial design to 8 hour stand times, and the deficit chapter, where cycle length and accordingly lateral length was increased to reduce the peak design capacity.

The irrigation assessment framework provided an ideal platform to research and investigate potential solutions for some of the current and crucial issues in the South African irrigated sugarcane industry.

6.2 Application of Framework

The framework and associated tools were used to assess potential solutions, for a specific set of conditions, to some of the current and major issues facing the industry. In the process, the strength and significance of the assessment framework were highlighted. Below is a more detailed description of the outcomes for each section.

6.2.1 Shallow soils

Considering that a large portion of the industry constitutes shallow soils and in the context of increasing demand for more effective and efficient use of water, poorly matched irrigation systems, even though cheaper, need to be improved upon. Traditionally shallow soils were irrigated with sprinkler systems were labour was required to move sprinklers. Since it was impractical for labour to move sprinklers at night, a 12 hour stand time was typically used. This, however, often results in excess water application per cycle.

The irrigation assessment framework was used to demonstrate that a 28% increase in capital costs in order to modify the system hardware and better match water application to the soil, delivered higher net margins compared to the typically cheaper system. This was primarily the result of reduced runoff from a better matched system and therefore more water infiltrating into the soil to become available to the crop. In this case, the stand time was reduced to 8 hours in order to match water application to the soil profile. The irrigation system was equipped with an additional set of sprinklers and shut-off valves at every lateral allowing for an irrigation supervisor to simply drive along a sub-mainline and activate or deactivate the appropriate sprinklers for the night move. Hence, no labour was required to move sprinklers at night. This highlighted the importance of considering impacts of the water balance on crop yields during the design phase, in order to show the potential value of more "expensive" systems.

It is therefore recommended, that the trade-off between system costs for automation or semi-automation in this case and effective water application be well investigated. A better matched system can increase profitability and, potentially more importantly, reduce the environmental impacts of over irrigation and runoff. The usefulness of the irrigation assessment framework to conduct such investigations was also clearly demonstrated.

6.2.2 Electricity tariffs

In South Africa, many electricity tariff options are available to farmers in South Africa. The difference in tariff structures, however, is complex and determining the best option can be difficult for irrigation designers, consultants and farmers. In this study, the *Irriecon* V2 model was used to investigate the differences between the Ruraflex and Landrate options.

The Ruraflex option had higher fixed costs, but also provided opportunity for significant savings if electricity use was shifted into off-peak and standard periods. At the time of the investigation, if the irrigation system was operated continuously for 24 hours, both the Ruraflex and Landrate options incurred similar electricity costs. This however, was only true for the 2009/2010 tariff prices. It appears that in the past, irrigators may have been incorrectly rewarded for operating on the Ruraflex option without shifting use of electricity into off-peak and standard periods.

In addition, tariff increases over the last three years, for this specific scenario would have increased the electricity bill in excess of 70%. This was concerning, considering that revenues from cane sales were not increasing. It also highlighted the need for irrigation strategies that reduce electricity use during peak and high demand periods, and therefore take advantage of the incentives provided by the Ruraflex option.

6.2.3 Deficit irrigation

Highlighted in this study was how commonly accepted design norms and standards can be conservative. Typically, generic design procedures deliver irrigation systems with peak design capacities that prevent the crop from experiencing water stress. A deficit approach allowed for deviation from these norms and illustrated how peak system design capacities, associated system costs and system operating rules can be manipulated to reduce costs. The trade-off, however, was reduced water applications, crop stress and therefore reduced revenues from cane sales.

In this study it was shown that the direct cost savings of water and electricity were small in comparison to revenue loss for a range of deficit irrigation strategies. This implied that deficit strategies were only feasible if the opportunity cost of water was realized by using water savings to convert dry land cane into irrigated cane. This was only applicable if land was not limiting. In this study, the increase in relative profitability, after the dry land conversion, ranged from 14 to 28 %. In addition, deficit strategies made use of water and electricity resources efficiently. Water application, in some instances, was kept out of the electricity peak periods. Such strategies could prove to be of great benefit to the country, especially in the current context of increasing demands for energy conservation.

Deficit irrigation is precise in nature and implementation of deficit irrigation strategies requires a high level of management and monitoring. The author recommends that these be well thought-out during the planning phase. Monitoring tools such the growth stations with soil water potential sensors and stalk extension potentiometers should be considered to monitor the soil water budget and crop growth/stress status. In addition, crop production functions and optimum water applications for the specific region, climate and soils should be well understood before irrigation hardware, peak design capacities and deficit strategies are selected. Misinformed designs, in the form of excessive peak system capacities leading to high capital and operating costs, could limit the potential benefit a deficit irrigation strategy can deliver.

It appears that farmers will require a large amount of support in order to successfully implement a deficit strategy. In the author’s opinion, this is because deficit strategies incur substantial crop stress which will not be easy on the grower’s eye. Investment in innovative methods will be required to communicate and increase the understanding of these concepts and mechanisms. This may also include improving the knowledge and understanding of extension staff as well. In the sugar industry at present, extension officers serve as the channel for dissemination of research to the growers. Extension officers, however, are more focused on advice relating to pest and diseases, variety choices and fertiliser and herbicide requirements rather than irrigation practices. Understanding of irrigation principles and the ability to give irrigation advice is often lacking. Hence, as the primary advisors to farmers, extension officers will play a vital role in the implementation of deficit irrigation strategies.

Furthermore, a stressed sugarcane crop will be more susceptible to pests and diseases. In addition, thought must be given to fertiliser application rates. Theoretically, if stress is going to be induced in the crop, therefore limiting crop growth, fertilize requirements should also be reduced. In other words, savings could be realised if fertilisers are applied for a reduced yield potential. Hence deficit irrigation strategies may have far reaching consequences and highlights the need for holistic assessment. The desktop study completed in this document proves that the fundamental concepts provide opportunities to use scarce resources more wisely and improve the grower's profitability. Field trials, however, may be required to capture the impacts of pests and diseases as well as explore the opportunities to reduce fertiliser applications.

6.3 Monitoring Systems

Implementation of deficit irrigation strategies requires precise management. Easy to use, robust and relatively cheap monitoring tools were perceived to be vital for the successful implementation and management of deficit irrigation strategies. It was envisaged that monitoring tools will provide data to reassure farmers of the status of their crop, irrespective of visual appearance. In this section, three monitoring systems were developed and assessed.

The first system was a continuous soil water potential monitoring system which made use of the Watermark sensors and H8 four-channel Hobo data logger. This system proved to be relatively cheap and very robust. The system, however, required the user to travel out to site and download the data manually. This was considered an expensive and tiresome exercise, especially if data were required frequently for decision making. For this reason, this system was considered better suited for long term monitoring. The Watermark system was installed on two farms and provided valuable evidence of under-irrigation, at a relatively small cost.

The next two systems were the Alti 4 and Campbell Scientific growth stations. These systems followed a more holistic approach where temperature, rainfall, plant stalk extension and soil water potential were monitored. The only difference between the two systems was the data loggers. The Cr 200 data logger was used for the Campbell Scientific system. Both systems, however, had relatively high capital and operating costs. The Alti 4 system was the cheaper of the two, amounting to a capital investment of R 13 131 and an operating cost of R 210/month. In addition, the Alti 4 appeared to have the competitive advantage by striking the better balance between battery life, remote communication and costs.

In conclusion, the configuration for both the Alti 4 and Campbell system was robust and well suited to the agricultural environment. A PVC pipe installed vertically provided a steady frame for mounting of sensors and housing for the cables. In addition, by painting the pipe green, the system was fairly inconspicuous and, for security reasons, blended in well with the sugarcane.

Furthermore, both systems were relatively easy to use since data could be accessed remotely via either GPRS or GSM. Remote access to data was very attractive in terms of easy decision making and irrigation monitoring. These tools are envisaged to encourage more precise management of irrigation systems.

6.4 Recommendations

In this section, recommendations for future work that were beyond the scope of this study are presented. They are as follows:

- To refine the existing design and costing tool to account for local losses and to cost, in more detail, the sundry components such as compression couplings for pipes, foot valves and block valves.
- Use design and costing tool to evaluate sensitivity of the alternative irrigation layouts, as discussed in Section 3.2.2.2, to steeper slopes and differing soils.
- Modification of the irrigation design and costing tool or development of similar tools to design and cost other types of irrigation systems, for example drip systems. In this way, the appropriate design tool could be substituted into the framework when needed. This would allow for easy comparison of strategies for different irrigation systems. For example, Sprinkler versus drip versus travelling big gun as was completed by Armitage *et al.* (2008) in Appendix C.
- Incorporate the Nightsave electricity tariff option in to the *Irriecon V2* model. This would then allow for further investigation of the Nightsave option.
- Investigate the potential to reduce peak pumping hours by increasing irrigation system capacity. Increasing the system capacity will allow for the required water volumes to be applied in shorter time intervals. In this way, pumping and therefore the use of electricity are restricted to within the off-peak and standard time periods. Concerns with this approach, however, include possibly applying water in excess of the soil infiltration rate resulting in loss through runoff. Furthermore, higher capital costs for the increased system capacity may prove to be a barrier for implementation. It is recommended that these issues be investigated further.
- Research and test different battery options for the Campbell Scientific growth station. The opportunity may exist for lithium-ion batteries, such as those used for the Alti 4 logger, to be used in the Campbell Scientific system.

- In addition, strategies for implementation and use of the infield monitoring tools need to be developed. For example, the monitoring system will only be representative of a point in the field. How does one decide where to install the unit and how many units are required for a specified area. One option was to install the unit in a position which was fairly representative of the soils of the entire field. This unit could then be used to increase the understanding of the irrigation strategy taking into account the soils and crop response. This could potentially include calibration of stress and refill points in the soil profile. Once adequate knowledge and understanding is gained, the monitoring unit could be moved to a different part of the field or to a new field altogether. Further work is required to develop a plan of how best these tools can be used.
- Furthermore, the crop growth station provides many opportunities to capture growth responses to various treatments in the research environment. For example, relationships between soil types, stalk growth, time of year and irrigation requirements can be developed by monitoring the water balance over a period of time together with crop growth rates. Similar work was completed in Australia, were mini-pans were used to calibrate the evaporation from these pans to the crop water requirements via stalk extension rates for a given soil type and time of year (Attard, 2002). Similarly, the growth stations can be used to gather data in order to develop robust scheduling techniques, for different regions and soil types in South Africa.

  Another example could be using the tool to measure the impact on stalk growth rate and water extraction in a compacted soil compared to an un-compacted soil. The applications of these growth stations are far and wide and could prove extremely valuable to the research fraternity for the collection of data and generation of knowledge about crop response to different environments and management.

Concluding, all objectives of the project were achieved. This work now provides the irrigated sugarcane industry with a platform of computer-based tools and methods to generate and assess potential irrigation solutions for a range of scenarios and contexts. Application of the tools within this study provided valuable opportunities to research, develop and assess irrigation solutions for challenges such as over irrigation on shallow soils and rapidly increasing electricity tariffs. In addition, the computer-based tools were also used to assess deficit irrigation strategies. Finally, in-field monitoring tools were also assessed to allow for easy management and assessment of strategies when implemented.

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APPENDIX A: AQUACROP PARAMETERS FOR MAIZE

I.2 Maize [1]

1. Crop Phenology			
Symbol	Description	Type (1), (2), (3), (4)	Indicative values / ranges
1.1 Threshold air temperatures			
T_{base}	Base temperature (°C)	Conservative (1)	8.0
T_{upper}	Upper temperature (°C)	Conservative (1)	30.0
1.2 Development of green canopy cover			
	Soil surface covered by an individual seedling at 90% emergence (cm2/plant)	Conservative (2)	6.50
	Number of plants per hectare	Management (3)	50000 - 100000
	Time from sowing to emergence (growing degree day)	Management (3)	50 - 100
CGC	Canopy growth coefficient (fraction per growing degree day)	Conservative (1)	0.012 - 0.013
CC_x	Maximum canopy cover (%)	Management (3)	Almost entirely covered
	Time from sowing to start senescence (growing degree day)	Cultivar (4)	Time to emergence + 1200 - 1500
CDC	Canopy decline coefficient (fraction per growing degree day)	Conservative (1)	0.010
	Time from sowing to maturity, i.e. length of crop cycle (growing degree day)	Cultivar (4)	Time to emergence + 1450 - 1750
1.3 Flowering			
	Time from sowing to flowering (growing degree day)	Cultivar (4)	Time to emergence + 600 - 900
	Length of the flowering stage (growing degree day)	Cultivar (4)	150 - 200
	Crop determinacy linked with flowering	Conservative (1)	Yes
	Excess of potential fruits (%)	Conservative (2)	Very small
1.4 Development of root zone			
Z_n	Minimum effective rooting depth (m)	Management (3)	0.30
Z_x	Maximum effective rooting depth (m)	Management (3)	Up to 2.80
	Shape factor describing root zone expansion	Conservative (1)	1.3
	Time from sowing to maximum rooting depth (growing degree day)	Cultivar (4) Environment (3)	Function of root expansion rate: 1.5 - 2.5 cm/day

[1] Table generated directly from the calibration reported by Hsiao et al., 2009. AquaCrop — the FAO crop model to simulate yield response to water: III. Parameterization and testing for maize. Agron. J. (in press).

I.2 Maize continued

2. Crop transpiration			
Symbol		Type (1), (2), (3), (4)	Indicative values / ranges
Kcb_x	Crop coefficient when canopy is complete but prior to senescence	Conservative (1)	1.03
	Decline of crop coefficient (%/day) as a result of ageing, nitrogen deficiency, etc.	Conservative (1)	0.30
	Effect of canopy cover on reducing soil evaporation in late season stage	Conservative (1)	50
3. Biomass production and yield formation			
3.1 Crop water productivity			
WP*	Water productivity normalized for ETo and CO_2 (gram/m^2)	Conservative (1)	33.7 (2000)
	Water productivity normalized for ETo and CO_2 during yield formation (as percent WP* before yield formation)	Conservative (1)	100
3.2 Harvest Index			
HI_o	Reference harvest index (%)	Cultivar (4)	48 - 52
	Building up of HI (period in growing degree days)	Cultivar (4)	Until 10% green canopy remains
	Possible increase (%) of HI due to water stress before flowering	Conservative (1)	None
	Coefficient describing positive impact of restricted vegetative growth during yield formation on HI	Conservative (1)	Small
	Coefficient describing negative impact of stomatal closure during yield formation on HI	Conservative (1)	Strong
	Allowable maximum increase (%) of specified HI	Conservative (1)	15

I.2 Maize continued

4. Stresses			
Symbol		Type [1], [2], [3], [4]	Indicative values / ranges
4.1 Soil water stresses			
$p_{exp,lower}$	Soil water depletion threshold for canopy expansion - Upper threshold	Conservative [1]	0.14
$p_{exp,upper}$	Soil water depletion threshold for canopy expansion - Lower threshold	Conservative [1]	0.72
	Shape factor for Water stress coefficient for canopy expansion	Conservative [1]	2.9
p_{sto}	Soil water depletion threshold for stomatal control - Upper threshold	Conservative [1]	0.69
	Shape factor for Water stress coefficient for stomatal control	Conservative [1]	6.0
p_{sen}	Soil water depletion threshold for canopy senescence - Upper threshold	Conservative [1]	0.69
	Shape factor for Water stress coefficient for canopy senescence	Conservative [1]	2.7
	Sum(ETo) during stress period to be exceeded before senescence is triggered	Conservative [1]	0
p_{pol}	Soil water depletion threshold for failure of pollination - Upper threshold	Conservative [1]	0.80 (Estimate)
	Vol% at anaerobiotic point (with reference to saturation)	Cultivar [4] Environment [3]	Moderately tolerant to water logging
4.2 Soil fertility stress			
		(calibration)	
4.3 Air temperature stress			
	Minimum air temperature below which pollination starts to fail (cold stress) (°C)	Conservative [1]	10.0 (Estimate)
	Maximum air temperature above which pollination starts to fail (heat stress) (°C)	Conservative [1]	40.0 (Estimate)
	Minimum growing degrees required for full biomass production (°C - day)	Conservative [1]	15.0 (Estimated)

(1) Conservative generally applicable
(2) Conservative for a given specie but can or may be cultivar specific
(3) Dependent on environment and/or management
(4) Cultivar specific

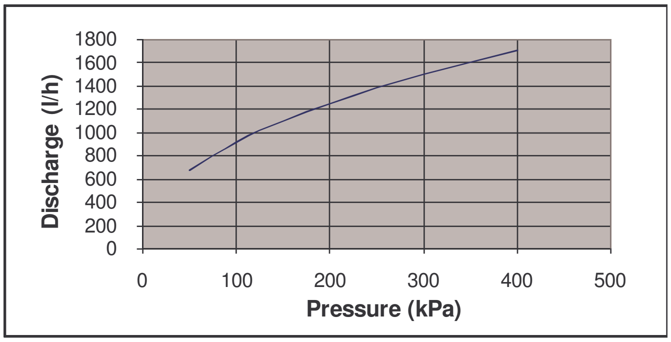
APPENDIX B: AN EXAMPLE OF ARC SPRINKLER TEST DATA

RESULTS OF TESTS ON THE VYRSA 35 BRASS SPRINKLER, EQUIPPED WITH THE FOLLOWING NOZZLES:

MAIN NOZZLE: 4.4 mm SPREADER: 2.4 mm

Page:	1 of 2
Report no:	S04001
Date:	2004

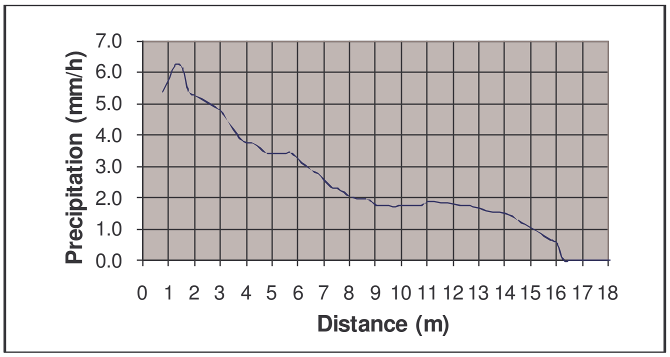
Pressure (P) and discharge (Q) relationship:



Discharge formula: $Q = 114.94 \times P^{0.4498}$

Pressure (kPa)	Discharge (l/h)
50	668
100	912
150	1095
200	1246
250	1377
300	1495
350	1602
400	1701

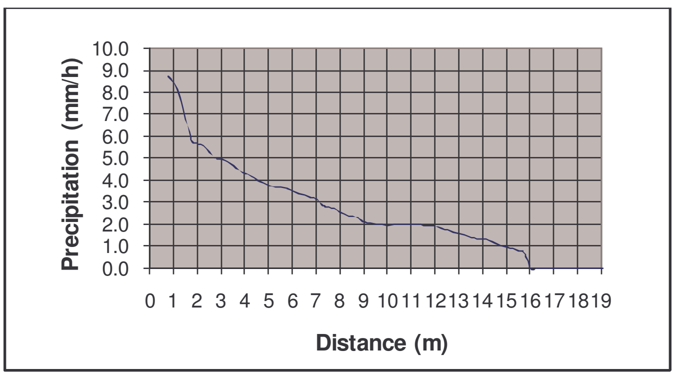
Precipitation profiles :



Maximum spacing for CU>=84%, DU>=75% and application rate >=3mm/h:

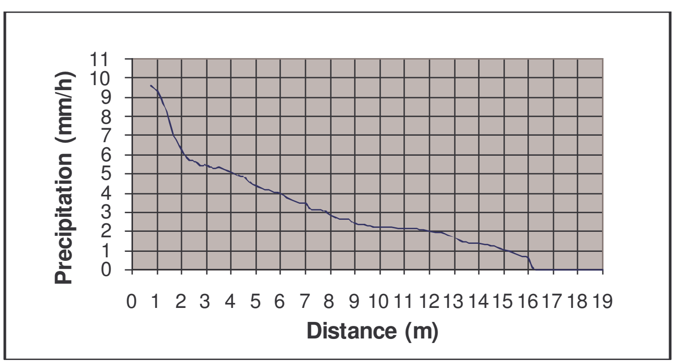
Test pressure:	**300**	**kPa**
Type of spacing:	Triangular	
Maximum sprinkler spacing:	30	m
Maximum lateral spacing:	15	m
Average application rate:	3.6	mm/h
Maximum radius:	16.25	m

Rotation test	1st 1/4	2nd 1/4	3rd 1/4	4th 1/4
Time (s)	6.42	6.49	6.32	6.30
RPM	2.34	2.31	2.37	2.38



Test pressure:	**352**	**kPa**
Type of spacing:	Triangular	
Maximum sprinkler spacing:	30	m
Maximum lateral spacing:	15	m
Average application rate:	3.9	mm/h
Maximum radius:	16.00	m

Rotation test	1st 1/4	2nd 1/4	3rd 1/4	4th 1/4
Time (s)	6.59	6.79	6.36	6.31
RPM	2.28	2.21	2.36	2.38



Test pressure:	**400**	**kPa**
Type of spacing:	Triangular	
Maximum sprinkler spacing:	30	m
Maximum lateral spacing:	15	m
Average application rate:	4.2	mm/h
Maximum radius:	16.25	m

Rotation test	1st 1/4	2nd 1/4	3rd 1/4	4th 1/4
Time (s)	6.85	6.96	6.73	6.49
RPM	2.19	2.16	2.23	2.31

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Vyrsa 35 Brass	Main nozzle: 4.4 mm	Spreader: 2.4 mm	Page: 2 of 2
Results of the coefficient of uniformity (CU), distribution uniformity (DU) and application rate tests for various pressures and sprinkler spacings.			Report no: S04001
			Date: 2004

Test pressure = 300 kPa							Test pressure = 352 kPa							Test pressure = 400 kPa						
Spacing		Appl.	Triangular		Rectangular		Spacing		Appl.	Triangular		Rectangular		Spacing		Appl.	Triangular		Rectangular	
Spr.	Lat.	rate	spacing		spacing		Spr.	Lat.	rate	spacing		spacing		Spr.	Lat.	rate	spacing		spacing	
m	m	mm/h	CU%	DU%	CU%	DU%	m	m	mm/h	CU%	DU%	CU%	DU%	m	m	mm/h	CU%	DU%	CU%	DU%
15	7.5	13.4	90	83	93	89	15	7.5	14.7	91	85	94	91	15	7.5	16.1	91	86	94	91
15	9	11.7	88	81	96	92	15	9	12.7	90	85	96	93	15	9	13.9	91	86	96	93
15	12	8.9	87	82	90	85	15	12	9.7	90	86	92	89	15	12	10.6	90	87	92	90
15	15	7.2	89	83	91	84	15	15	7.7	92	88	92	86	15	15	8.5	93	88	93	88
15	18	6.0	91	87	87	78	15	18	6.5	93	91	90	83	15	18	7.1	94	91	91	84
15	21	5.1	90	84	85	77	15	21	5.5	89	85	87	81	15	21	6.1	89	86	87	81
15	24	4.5	80	70	80	74	15	24	4.8	80	69	80	72	15	24	5.3	79	70	79	73
15	27	4.0	72	58	72	63	15	27	4.3	69	55	69	58	15	27	4.7	68	55	68	57
15	30	3.5	62	44	62	43	15	30	3.8	58	39	58	38	15	30	4.2	57	39	57	38
18	9	9.8	88	83	94	91	18	9	10.6	91	88	95	92	18	9	11.6	91	88	95	93
18	12	7.5	89	85	90	85	18	12	8.1	92	88	91	87	18	12	8.9	92	89	92	89
18	15	6.0	93	89	87	78	18	15	6.5	95	92	90	83	18	15	7.1	95	92	91	84
18	18	5.0	92	85	87	77	18	18	5.4	92	86	90	82	18	18	5.9	93	89	90	84
18	21	4.3	85	78	87	83	18	21	4.6	86	78	88	85	18	21	5.1	87	80	88	85
18	24	3.7	79	66	82	74	18	24	4.0	79	67	80	73	18	24	4.4	79	68	79	73
18	27	3.3	72	58	72	57	18	27	3.6	68	57	69	55	18	27	3.9	68	56	68	55
18	30	3.0	60	47	60	45	18	30	3.2	57	40	57	39	18	30	3.5	57	40	57	39
21	12	6.4	88	80	86	80	21	12	6.9	90	83	87	82	21	12	7.6	91	85	87	83
21	15	5.1	92	85	85	77	21	15	5.5	93	88	87	81	21	15	6.1	93	89	87	81
21	18	4.3	89	84	87	83	21	18	4.6	89	86	88	85	21	18	5.1	91	87	88	85
21	21	3.7	85	77	90	85	21	21	4.0	86	80	88	81	21	21	4.3	86	80	88	82
21	24	3.2	79	65	81	68	21	24	3.5	79	68	79	67	21	24	3.8	78	69	78	68
21	27	2.8	70	62	70	55	21	27	3.1	68	59	68	53	21	27	3.4	67	59	67	53
21	30	2.5	60	47	59	44	21	30	2.7	57	39	57	37	21	30	3.0	57	39	56	37
24	12	5.6	86	76	79	71	24	12	6.1	89	82	79	72	24	12	6.7	90	83	78	72
24	15	4.5	89	82	80	74	24	15	4.8	91	85	80	72	24	15	5.3	91	86	79	73
24	18	3.7	86	81	82	74	24	18	4.0	87	82	80	73	24	18	4.4	88	83	79	73
24	21	3.2	81	70	81	68	24	21	3.5	83	75	79	67	24	21	3.8	83	77	78	68
24	24	2.8	76	65	73	59	24	24	3.0	76	68	74	58	24	24	3.3	75	69	74	58
24	27	2.5	68	64	67	53	24	27	2.7	66	57	66	49	24	27	2.9	66	57	65	48
24	30	2.2	59	43	59	40	24	30	2.4	56	35	56	34	24	30	2.6	56	35	55	33
27	15	4.0	88	85	72	63	27	15	4.3	90	85	69	58	27	15	4.7	90	85	68	57
27	18	3.3	84	72	72	57	27	18	3.6	84	75	69	55	27	18	3.9	84	75	68	55
27	21	2.8	76	65	70	55	27	21	3.1	78	69	68	53	27	21	3.4	77	71	67	53
27	24	2.5	72	69	67	53	27	24	2.7	71	67	66	49	27	24	2.9	70	66	65	48
27	27	2.2	66	61	63	46	27	27	2.4	63	51	61	40	27	27	2.6	62	50	61	39
27	30	2.0	59	36	59	33	27	30	2.1	55	30	54	26	27	30	2.3	54	30	53	27
30	15	3.6	89	82	62	43	30	15	3.9	87	80	58	38	30	15	4.2	86	80	57	38
30	18	3.0	78	66	60	45	30	18	3.2	78	66	57	39	30	18	3.5	78	66	57	39
30	21	2.5	71	66	59	44	30	21	2.8	71	63	57	37	30	21	3.0	70	62	56	37
30	24	2.2	69	65	59	40	30	24	2.4	65	56	56	34	30	24	2.6	64	55	55	33
30	27	2.0	64	50	59	33	30	27	2.1	58	40	54	26	30	27	2.3	56	41	53	27
30	30	1.8	57	25	56	20	30	30	1.9	49	20	48	15	30	30	2.1	48	22	47	18

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APPENDIX C: IMPLEMENTATION OF THE *IRRIECON V2* DECISION SUPPORT TOOL TO ASSESS NET RETURNS TO IRRIGATION SYSTEMS (Armitage *et al.,* 2008)

IMPLEMENTATION OF THE *IRRIECON* V2 DECISION SUPPORT TOOL TO ASSESS NET RETURNS TO IRRIGATION SYSTEMS

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Abstract

Irriecon V2 is a spreadsheet-based tool that can be used to determine detailed capital, operating and marginal costs of various irrigation scenarios. Cost implications relating to affected farming practices, including fertiliser, herbicide, planting, harvesting and haulage operations, are incorporated in the tool. In this paper, the costs of and net returns to three different irrigation systems that are being evaluated in the Empangeni area, namely big gun, dragline and drip, are described. Farm level data were obtained from interviews with local farmers. Irrigation system design parameters and investment cost data were based on detailed and representative system designs and bills of quantities. Predicted crop yield and irrigation water use information for the various irrigation systems were simulated using the *ZIMsched* 2.0 irrigation systems model. Infield performance characteristics of the various irrigation systems, for example, the distribution uniformity of applied water, which is used as an input variable in *ZIMsched* 2.0, were based on data derived from Mobile Irrigation Laboratory evaluations. The results have applicability to irrigation system selection and design, farm management decision making, and for policy makers when assessing the economic impact of changing an irrigation system to drive irrigation water use efficiency in agriculture.

Keywords: irrigation, systems, economics, model, modelling

Introduction

Sugarcane farmers are coming under increasing pressure to demonstrate that they are managing the water used for irrigation efficiently and effectively. In many catchments the bulk of the available water is diverted to irrigated agriculture, and savings in this sector are viewed as a primary source for meeting competing demands. Recommendations to change or upgrade irrigation and/or water management systems need to be assessed from both a hydrological and an economic perspective. Prior to the development of *Irriecon* V2 there was no easily available tool that could be used either to refute or demonstrate the economic consequences of existing and/or proposed irrigation scenarios at the detailed, on-farm level.

A project was thus initiated at the South African Sugarcane Research Institute (SASRI) to develop a detailed economic analysis tool to assess farm specific scenarios related to irrigation, such as system design specifications, repairing/upgrading irrigation systems, comparing various Eskom tariff structure options, and/or changing farm and water management approaches relating to irrigation. The tool developed, *Irriecon* V2, is complementary to the original *Irriecon* decision support programme (DSP). *Irriecon* was designed for the 'broad-brush' assessment of irrigation feasibility, whereas *Irriecon* V2 is a much more detailed cost calculator. *Irriecon* V2 is based on the integration of:

- rigorous farm specific irrigation costing procedures developed at the University of the Free State during a Water Research Commission funded project (Oosthuizen *et al.*, 2005),
- procedures to assess related farming costs which were developed for the Economics of Trashing (EOT) DSP (Wynne and van Antwerpen, 2004).

The outcome is a spreadsheet-based tool which can be used to determine detailed capital, operating and marginal costs of various irrigation scenarios. Cost implications relating to associated/affected farming practices, including fertiliser, herbicide, planting, harvesting and haulage operations are incorporated in the tool. In this paper, application of *Irriecon* V2 to assess various irrigation strategies and systems for potential irrigation development in the Empangeni area is reported.

Methodology

Yield simulations

A combination of field-derived information on irrigation systems performance and simulations with an irrigation system/crop yield simulation model, were used to predict crop response to various irrigation systems, system constraints, soils, seasonal climates and watering strategies. The *ZIMsched* 2.0 irrigation system/crop yield simulation model was used for the study. ZIMsched 2.0 can be used to evaluate the impact on crop production of different irrigation strategies by taking into account the effects of different water application targets, scheduling practices, irrigation systems and irrigation system performance measures, using commonly available data and information (Lecler, 2004).

The irrigation systems scenarios that have been simulated were selected based on information derived from, amongst others, Mobile Irrigation Laboratory evaluations in the Empangeni area and are described in Table 1.

Table 1. Summary of assumptions used in the big gun, dragline and drip irrigation systems with different irrigation strategies.

Parameter	Big gun		Dragline		Drip	
Gross application (mm)	53	27	42	42	3.5	5.83
Minimum cycle (days)	10	10	10	15	1	1
Soil texture	SaLm*	SaLm	SaLm	SaLm	SaLm	SaLm
Soil drainage	Good	Good	Good	Good	Good	Good
Soil depth (m)	1.5	1.5	1.5	1.5	1.5	1.5
Soil TAM** (mm)	144	144	144	144	144	144
Evaporation losses	15%	15%	15%	15%	0%	0%
% TAM at which an irrigation application was initiated[4]	50%	50%	50%	50%	50%	50%
Uniformity index	CU[1] 55	CU[1] 55	CU[2] 80	CU[2] 80	SU[3] 88	SU[3] 88

*SaLm = sandy loam, **TAM = total available moisture

[1]Coefficient of Uniformity (CU) – values based on infield evaluations conducted by some of the authors.

[2]Coefficient of Uniformity (CU) – values assumed are for top performing systems (Reinders, 2001).

[3]Statistical Uniformity (SU) – values assumed are for top performing systems (Reinders, 2001).

[4]Irrigation applications only took place provided the accumulate time since the previous irrigation application exceeded the minimum cycle time.

A high potential, deep and well drained sandy loam soil representative of the Empangeni east area was used in the different irrigation system simulations. Ten years (1997 to 2006) of weather data from the Felixton automatic weather station were used in the simulations. Water applications were simulated to take place when 50% of the total available moisture (TAM) had been depleted for all of the different systems provided the minimum irrigation cycle time constraints were satisfied. This is a more aggressive deficit system than is generally employed for drip irrigation systems. For the purpose of this research a deficit of 50% was used for the drip systems to maintain a relatively drier soil profile, reduce losses through deep percolation and runoff, and at the same time ensure that evaporative demand was met by rainfall and irrigation water.

The CU for sprinkler systems was proposed by Christiansen (1942). It is a measurement of the uniformity of the depth of water application across the irrigated area. A CU of 55 was assumed for the big gun systems, reflecting a relatively low uniformity in water application. Infield evaluations of big gun systems had shown that CUs ranged from 29 to 83 but were generally below 60. The values obtained were highly dependent on windspeed and the orientation of the system travel path in relation to the wind direction. A CU of 80 was assumed for the dragline systems representing a high uniformity in water application by a top performing system. The SU is used to describe the uniformity of a drip irrigation block, because water is not applied to the whole field area (Pitts *et al*., 1996; Koegelenberg and Breedt, 2002). For the sub-surface drip systems a SU of 88 was assumed for a top performing system.

Irrigation system designs

In order to determine the costs of the various irrigation system options for the economic analysis, representative irrigation designs for the various irrigation systems were undertaken by Zululand Irrigation (Pty) Ltd. The irrigation designs for the various irrigation systems and irrigation strategies were based upon the optimisation of irrigation system performance and irrigated area. Although this resulted in different irrigation areas between the various systems, it permits comparisons between the irrigation systems to be undertaken on the basis that the irrigation system fixed costs are allocated over the optimum cane area matched to the system design specifications. The designs included a detailed bill of quantities and associated costs, and were undertaken assuming the Suid-Afrikaanse Besproeiings Instituut (South African Irrigation Institute) (SABI) design norms. A summary of the various system design parameters is presented in Tables 2, 3 and 4.

Analysis of irrigation system economic margins

The *Irriecon* V2 model was applied to the yield simulation results obtained from *ZIMsched* 2.0 in order to assess the economic margins associated with the various options. *Irriecon* V2 is a program developed by SASRI and SA Cane Growers' Association. It is based on irrigation costing methods reported in Water Research Commission Report No. 974/1/05 (Oosthuizen *et al*., 2005), but also includes utilities to account for other farming costs (e.g. crop establishment, ratoon maintenance, harvesting and transport) that may be impacted on by various irrigation strategies. It must be noted that the economic margins reported in this paper reflect only partial cane margins after rewarding all production factors that may be directly impacted on by changes in irrigation systems or irrigation strategies. Other fixed and variable costs not directly affected by irrigation are ignored in this paper, as are foreign factor costs such as management, rent, leases and interest on capital for land acquisition.

The *Irriecon* V2 model is designed to capture detailed fixed and variable irrigation input costs and fixed and variable agronomic input costs that may be impacted upon by changing irrigation practices. A summary of the main irrigation inputs used in the model is presented in Table 5.

Table 2. Summary of the costs of the various big gun irrigation system options.

Component	Big gun 53 mm/10 (54 ha) (R)	Big gun 27 mm/10 (72 ha) (R)	Insurance (%)[1]	Main-tenance (%)[2]	Salvage value (%)[3]	Expected life (yrs)
Mainline and hydrants	176 584	97 581		0.2	30	20
Trench costs	10 147	12 247				20
Travellers	[4]417 000	[5]310 500		2	10	10
Pump unit	75 992	72 175	0.83	2	15	15
Delivery and field work	2 000	2 000				
Subtotal	681 723	494 503				
Total per ha	**12 625**	**6 868**				

[1,3]% of purchase price [2]% of purchase price/1 000 hours per year
[4]Travellers (Model 90/300 × 3) [5]Travellers (Model 100/300 × 2)

Table 3. Summary of the costs of the various dragline irrigation system options.

Component	Dragline 42 mm/10 (63.63 ha) (R)	Dragline 42 mm/15 (95.45 ha) (R)	Insurance (%)[1]	Main-tenance (%)[2]	Salvage value (%)[3]	Expected life (yrs)
Mains and sub-mains	275 796	362 979		0.2	30	20
Trench costs	61 210	89 894				20
Flexible risers	11 864	17 680		2		10
Tripod assembly	44 639	44 639		2		10
Pump station	84 785	84 785	0.83	2	15	15
Subtotal	478 294	599 977				
Total per ha	**7 517**	**6 286**				

[1,3]% of purchase price [2]% of purchase price/1 000 hours per year

Table 4. Summary of the costs of the various drip irrigation system options.

Component	Drip 3.5 mm/1 (R)	Drip 5.8 mm/1 (R)	Insurance (%)[1]	Main-tenance (%)[2]	Salvage value (%)[3]	Expected life (yrs)
Mains and sub-mains	167 941	219 892		0.2	30	20
Trench costs	40 076	42 148				20
Micro distribution equipment:	505 982	507 263		1.5		7
Filter bank:	64 383	83 633	0.6	5		10
Pump station:	44 252	48 047	0.83	2	15	15
Sub total:	822 634	900 983				
Total per ha	**16 453**	**18 020**				

[1,3]% of purchase price [2]% of purchase price/1 000 hours per year

Table 5. Summary of irrigation system inputs for the different irrigation systems and irrigation strategies used in *Irriecon* V2.

Parameter	Big gun 53 mm/10	Big gun 27 mm/10	Dragline 42 mm/10	Dragline 42 mm/15	Drip 5.83 mm/1	Drip 3.5 mm/1
Electricity						
Landrate	100%	100%	100%	100%	100%	100%
Landrate option	2	2	2	2	2	1
Basic charge (R/month)	192.30	192.30	192.30	192.30	192.30	192.30
Network charge (R/month)	310.80	310.80	310.80	310.80	310.80	202.20
Energy charge (R/kWh)	0.3028	0.3028	0.3028	0.3028	0.3028	0.3028
Absorbed power (kW)	41.63	25.83	50.89	50.89	26.56	18.56
Power factor of the motor (h)	0.9	0.9	0.9	0.9	0.9	0.9
Pump rate design value (m^3/h)	165	86	160	160	120	74
Water						
Water charge (cents/m^3)	3.44	3.44	3.44	3.44	3.44	3.44
WRM* charge (cents/m^3)	0.62	0.62	0.62	0.62	0.62	0.62
Research levy (R/ha)	3.68	3.68	3.68	3.68	3.68	3.68
Other						
Irrigated area (ha)	54.0	72.0	63.6	95.5	50.0	50.0
Labour hours/1 000 m^3 **	0.68	0.68	1.65	1.65	0.40	0.40

*WRM = water resource management, **Hoffman *et al.* (2007).

The estimation of repairs and maintenance costs of the differing systems were based on a percentage of purchase per 1 000 hours irrigation, as suggested by Oosthuizen *et al*. (2005). The capital recovery method for estimating depreciation and interest costs was employed in this study.

The costing of other farming activities was based on information obtained from local growers and prices published in July 2007. A summary of the costings is presented in Table 6.

Table 6. Summary of agronomic costs for the different irrigation systems and irrigation strategies used in *Irriecon* V2.

Cost	Measure	Big gun	Dragline	Drip
Planting costs	R/ha	9 429	9 429	9 724
Ratoon maintenance costs		3 155	3 155	2 509
Harvesting costs	R/ton	12.02	12.02	12.02
Transport costs		47.69	47.69	47.69

Irriecon V2 is designed to provide an estimate of the total farm margin after accounting for all costs that may be affected by changes in irrigation systems or combinations of irrigation systems. However, for the purpose of this paper the *Irriecon* V2 model was used to evaluate the economic performance of each irrigation system separately. As explained above, the irrigated area of the different irrigation systems varied according to the optimisation of the system design for a given capacity, and for this reason it was possible to apply only a set cost per ton for the harvesting and transport cost components of the analysis, as these would otherwise be affected by economies of scale and capacity utilisation.

Results

Results obtained include simulations of irrigation water applied, runoff and deep percolation losses, crop yields and economic margins of the associated irrigation systems and management strategies.

Irrigation water applied

The amounts of irrigation water applied simulated for the Big gun, dragline and Drip systems for the different scenarios are shown in Figure 1.

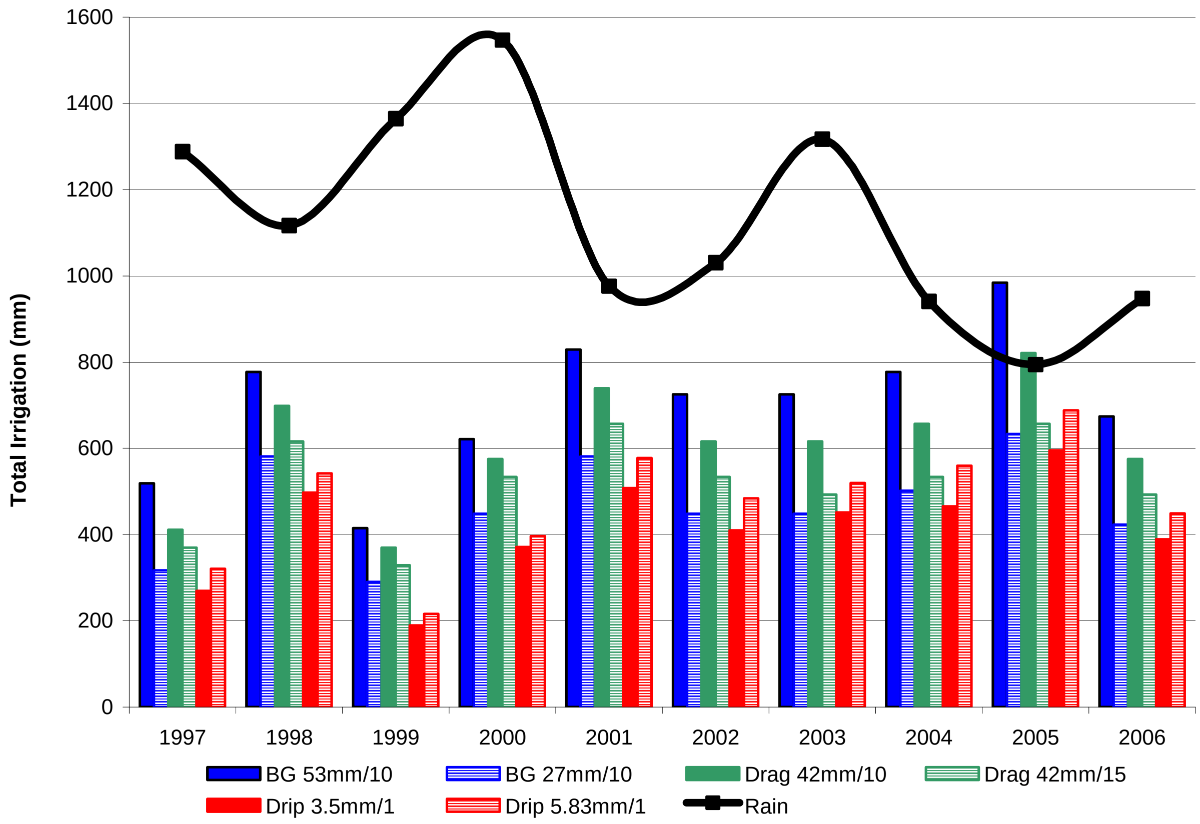

Figure 1. Simulated irrigation water applied by big gun (BG), dragline (Drag) and drip irrigation systems with different irrigation strategies, over the period 1997 to 2006.

It can be seen in Figure 1 that there was wide variation in required water application rates between the various irrigation systems according to their design capacity. The big gun system applying 53 mm in 10 days and the dragline systems required the highest water application rates, while the drip irrigation systems were the most effective water saving technology of the three systems, and also exhibited the lowest variation between water application requirements.

Runoff and deep percolation losses

The runoff and deep percolation losses simulated for the big gun, dragline and drip systems for the different scenarios are shown in Figure 2.

The choice of irrigation system and irrigation strategy was shown to have a substantial influence on runoff and deep percolation. These were particularly high for the big gun system capable of applying 53 mm in 10 days, while the losses in the big gun system applying 27 mm in 10 days were also high relative to the total amount of irrigation water applied. The high range in these losses highlights the importance of selecting an appropriate management strategy with big gun systems. Overall, the losses simulated under the drip systems were least sensitive to the system design capacity.

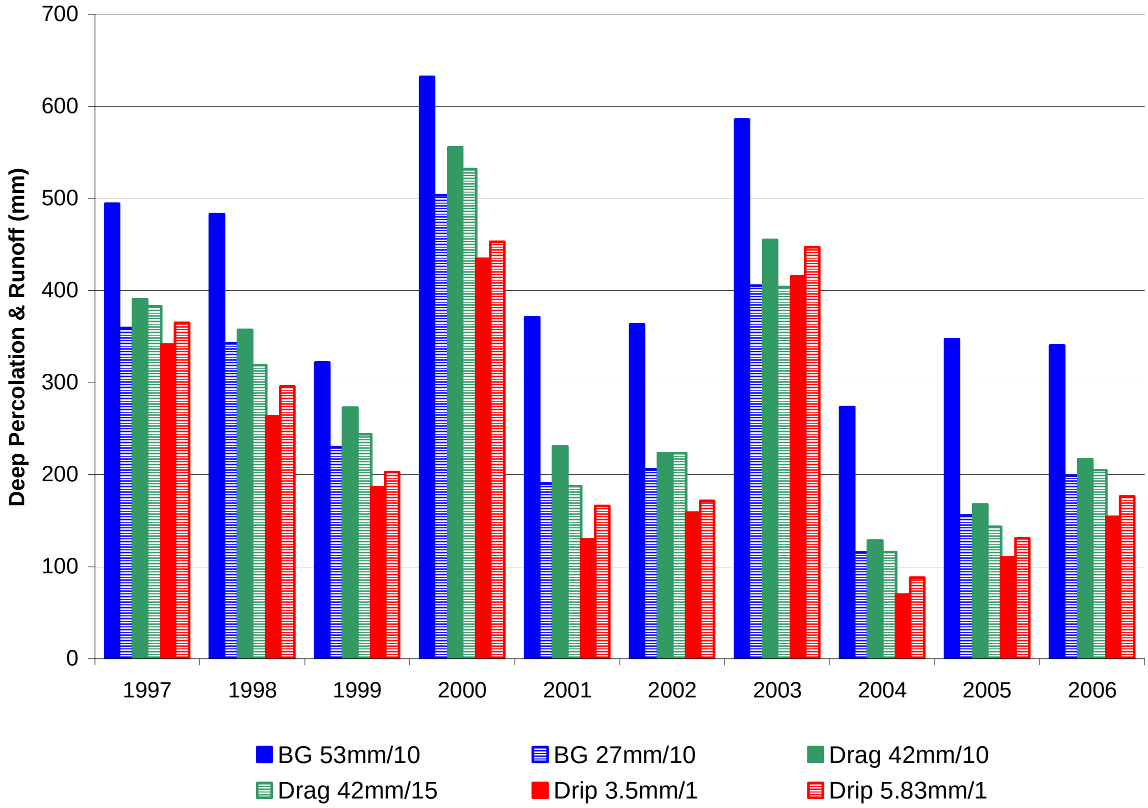

Figure 2. Simulated runoff and deep percolation losses for the big gun (BG), dragline (Drag) and drip irrigation systems with different irrigation strategies, over the period 1997 to 2006.

Crop yields

The cane yields simulated for the big gun, dragline and drip systems for the different scenarios are shown in Figure 3.

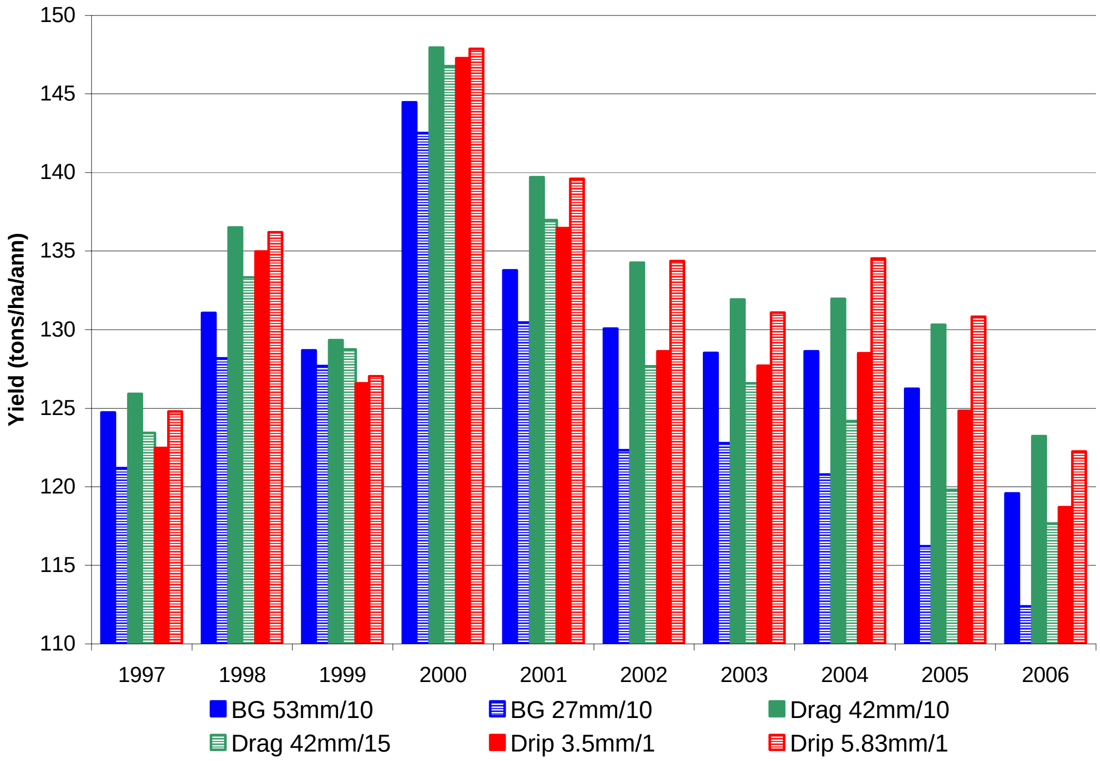

Figure 3. Simulated cane yields for the big gun (BG), dragline (Drag) and drip irrigation systems with different irrigation strategies, over the period 1997 to 2006.

Simulated crop yields were highest for the dragline system with a capacity of 42 mm in 10 days, for the drip system with a capacity of 5.83 mm per day and to a lesser extent for the drip system with a capacity of 3.5 mm per day. The simulated big gun systems yields were relatively lower despite their higher irrigation water application levels, with the higher capacity big gun system having comparable yields to the lower capacity drip irrigation system. These results need to be viewed in the context of assumptions regarding the soils and climate, i.e. a deep sandy clay loam with a TAM of 144 mm and average rainfall for the seasons simulated a relatively high 1 132 mm/annum. Simulations on shallow soils and in regions of less rainfall will show markedly different trends.

Table 7 provides a summary of the average annual water application, losses and crop yields for the different irrigation systems and irrigation strategies.

Table 7. Summary average irrigation water application, losses and cane yields for the big gun, dragline and drip irrigation systems with different irrigation strategies.

System	Maximum capacity	Average annual irrigation (mm)	Average annual runoff and deep percolation losses (mm)	Average annual cane yield (tons/ha)
Big gun	53 mm in 10 days	704.6	421.2	130
Dragline	42 mm in 10 days	607.6	299.7	133
Drip	5.83 mm per day	475.1	249.4	133
Big gun	27 mm in 10 days	467.1	270.4	124
Dragline	42 mm in 15 days	521.4	275.5	128
Drip	3.5 mm per day	414.4	226.1	130

A separate simulation completed under dryland conditions indicated that estimated rainfed yields in the study area would have been on average 97 tons cane/ha/annum[1] over the 10-year period. All of the irrigation systems simulations show a considerable yield response over rainfed conditions, and the viability of these yield responses was tested using the *Irriecon* V2 model. The results are discussed in the following section.

Financial results

The financial results simulated for the big gun, dragline and drip systems for the different scenarios are shown in Table 8.

The results from Table 8 show that simulated partial cane margins for the dragline systems were higher than the big gun and drip systems. The dragline system with a capacity of 42 mm in 10 days achieved the highest cane margin of R11 278/ha, some R263/ha higher than the dragline system with a capacity of 42 mm in 15 days. The higher simulated profitability of the dragline systems is attributable to their relatively higher cane yields and lower fixed irrigation system costs compared to the other systems.

The big gun system cane margins were similar between the two different irrigation strategies. The lower capacity strategy applying 27 mm in 10 days achieved a slightly better partial cane margin than the higher capacity strategy applying 53 mm in 10 days. This underscores the importance of selecting an appropriate management strategy with this type of system.

[1]It must be noted that the study area is considered to be a high potential cane production area, and the simulated yield results reported in this paper are therefore not representative of the average industry cane producer.

Table 8. Summary of financial results for the big gun, dragline and drip irrigation systems with different irrigation strategies, and for a dryland simulation in the study area.

Revenue/Costs	Big gun		Dragline		Drip		Dryland
	53 mm/10	27 mm/10	42 mm/10	42 mm/15	5.83 mm/1	3.5 mm/1	
REVENUE	**R/ha**	**R/ha**	**R/ha**	**R/ha**	**R/ha**	**R/ha**	**R/ha**
Cane sales	23 870	22 876	24 477	23 667	24 459	23 851	17 852
IRRIGATION COSTS							
Mainline costs							
Mainline fixed costs	575	341	663	541	865	690	–
Mainline operating costs	616	514	671	581	539	563	–
Total mainline costs	1 191	855	1 333	1 122	1 404	1 252	–
System costs							
System fixed costs	963	554	121	89	1 837	1 832	–
System variable costs	680	554	367	319	512	609	–
Total system costs	1 643	1 108	488	408	2 349	2 440	–
Total irrigation costs	2 835	1 963	1 821	1 530	3 753	3 693	–
OTHER DIRECT COSTS							
Planting costs	943	943	943	943	972	972	928
Ratooning costs	2 741	2 741	2 741	2 741	2 180	2 180	2 773
Harvesting costs	1 510	1 447	1 549	1 497	1 548	1 509	1 130
Haulage costs	5 992	5 743	6 145	5 941	6 140	5 987	4 481
Total other direct costs	11 186	10 874	11 377	11 123	10 840	10 649	9 312
NET PARTIAL MARGIN	9 849	10 039	11 278	11 015	9 866	9 508	8 539
Index (Dryland = 100)	115.3	117.6	132.1	129.0	115.5	111.3	100.0

Partial cane margins were lowest for the smaller capacity drip system while the higher capacity drip system yielded a partial margin similar to the higher capacity big gun system. The relatively lower drip system returns are due largely to their significantly higher fixed irrigation costs compared to the other systems. Fixed costs in the drip systems were R1 164 to R1 627/ha higher than the big gun systems, and R1 892 to R1 918/ha higher than the dragline systems respectively, due to their higher annual ownership costs.

A further financial analysis was undertaken assuming that the availability of water was limited relative to availability of land, as is likely to be the case in many of the water stressed catchments. For this analysis the area which could be irrigated using the same amount of water for each system was determined. The margins shown in Table 8 were then multiplied by these area ratios to indicate what the total returns could be on a relative basis if the same quantity of water was used on different areas with each system. The results are shown in Table 9.

Analysis of the results in Table 9 indicate that in a water stressed situation the smaller capacity big gun and dragline systems irrigating a larger cane area are more profitable than the larger capacity systems using the same quantity of water but irrigating a smaller cane area, and the balance of the area being farmed as dryland cane. The extra capital costs of the larger capacity systems would not be warranted under such circumstances as the availability of water would limit the ability of a grower to use the additional irrigation system capacity and add more water. The opportunity cost of water is shown to be much greater than the direct costs of water. However, the opposite is found to be true for the drip system, where a higher total margin would be achieved by employing the higher capacity irrigation system on a smaller cane area, with the balance of the area remaining as dryland. The reason for this is that the difference between the irrigation costs for the large and small capacity drip systems was relatively small. Furthermore, the pump selected by the designers for the smaller capacity drip system operated at a lower efficiency relative to the pump used on the larger capacity drip system.

Table 9. Summary of financial results for the different irrigation systems where the area irrigated using each strategy was adjusted so that the same volume of water was used for each strategy.

Parameter	Big gun		Dragline		Drip	
	53 mm/10	27 mm/10	42 mm/10	42 mm/15	5.83 mm/1	3.5 mm/1
Net partial margin above dryland (R/ha)	1 310	1 500	2 739	2 476	1 327	969
Relative irrigable area[1]	1	1.51	1.16	1.35	1.48	1.7
Relative potential increase in margin obtained by converting dryland cane area to irrigated cane area for a given amount of water (R)	1 310	2 265	3 177	3 343	1 964	1 647

[1]For example, the 53 mm 10-day cycle big gun system uses 705 mm, so the irrigable area ratio is 705/705 = 1, whereas the 3.5 mm per day drip system uses 414 mm, so the equivalent ratio is 705/414 = 1.7 (see Table 7 for average water use of each strategy).

Conclusion

Results shown in this paper are for a specific context where different irrigation systems and strategies were compared assuming relatively good soils and high mean annual precipitation. Thus the potential differences in the performance of the systems from an agronomic perspective were largely negated and overshadowed by the economic considerations. The relatively inexpensive dragline systems resulted in the highest returns per hectare. Due to labour and theft issues with dragline irrigation, many growers are considering big gun irrigation systems as a preferred option; however, the potential margin for these systems was less than for the dragline systems.

The opportunity cost of water can, however, have a substantial influence on the selection of an appropriate irrigation strategy. Irrigation systems and strategies that use less water relative to competing systems allow a relatively larger area to be irrigated. Depending on the increase in margin over dryland margins, this may result in a low water use system being the most profitable system. For example, the low capacity big gun system resulted in similar cane margins to the high capacity Big gun system where water was unlimited. However, if availability of water limited the area that could be converted to irrigation, the lower capacity big gun system could be used to irrigate a relatively larger area and this would result in higher farm profit than the higher capacity big gun system. Selection of an irrigation system with appropriate capacity was shown to have major profitability implications under both land and water limited production constraints.

Although the drip systems had the best performance from an agronomic perspective they yielded the lowest margins, and conversion to drip irrigation in this situation would have been the least profitable option.

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APPENDIX D: IRRIGATED SUGARCANE PRODUCTION FUNCTIONS (Lecler and Jumman, 2009)

SHORT COMMUNICATION

IRRIGATED SUGARCANE PRODUCTION FUNCTIONS

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Abstract

With the ongoing implementation of the 1998 National Water Act in South Africa, irrigation water requirements of sugarcane are coming under increasing scrutiny. To provide some perspective to the many questions being posed, irrigated sugarcane production functions are presented in this paper. The production functions are unique in that they show not only the response of sugarcane to various levels of irrigation water applied, but include the impacts of irrigation systems that are either well or poorly maintained as indicated by the irrigation distribution uniformity. It was shown that poor irrigation distribution uniformities cannot be corrected by simply increasing the amount of water applied. Thus, the typical practice of increasing irrigation water application amount to account for low irrigation uniformities in net to gross irrigation water requirement calculations, can lead to substantial wastage. The impacts of reduced irrigation water allocations on crop yields should not be generalised, even for a specific location. For the case studies reported, near maximum crop yields in Komatipoort required at least 1 150 mm of irrigation water on shallow, 0.6 m deep sandy clay loam soils compared with only 900 mm on 1.2 m deep sandy clay loam soils.

Keywords: irrigated sugarcane, crop yields, deficit irrigation, distribution uniformity

Introduction

With the ongoing implementation of the 1998 National Water Act in South Africa, and the associated initiatives to potentially re-allocate water, the irrigation water requirements of sugarcane are coming under increasing scrutiny. There are also uncertainties surrounding conversion of net irrigation water requirements to gross irrigation water requirements (Burt and Styles, 2007), i.e. water contributing to crop evapotranspiration requirements and yield versus water withdrawn from a source. To provide some perspective on these issues, irrigated sugarcane production functions which relate crop yield response to the gross amount of irrigation water exiting sprinkler nozzles or emitters, are presented in this paper. The production functions show the response of sugarcane to various levels of irrigation water applied and are for either well or poorly maintained irrigation systems and for deep and shallow soils.

Methodology

A sugarcane yield and irrigation systems simulation model named *ZIMsched* 2.0 was used for the analysis. *ZIMsched* 2.0 was developed by Lecler (2004) to predict how field derived indices of irrigation systems performance, such as the coefficient of uniformity (CU) (Koegelenberg and Breedt, 2003), impacted on sucrose yields and the various components of the water balance. The model has been verified against trial data for a range of soil conditions, seasonal climates, and irrigation scheduling strategies.

Fourteen years (1985-1999) of daily climate data from the Komatipoort (Tenbosh) weather station (25°22'S, 31°55'E) were used for the study reported here. Gross irrigation water applications of 42 mm, i.e. the amount of water exiting the sprinkler nozzles expressed as a depth equivalent value, were simulated to take place at various soil water depletion levels and/or irrigation cycle times in order to reflect different irrigation scheduling strategies and degrees of water stress. A sandy clay loam soil with a depth of 0.6 m and total available water content (TAWC) of 57 mm was assumed for the shallow soil scenario. A 1.2 m deep profile with a TAWC of 114 mm was assumed for the deep soil scenario. Poor system design and maintenance was represented by a CU of 60% and ideal system design and maintenance was represented by a CU of 80%. Based on research results reported by McNaughton (1981), Tolk *et al*. (1995) and Thompson *et al*. (1997) it was assumed that 10% of the water exiting the sprinkler nozzles was lost to non-beneficial spray evaporation and wind-drift.

Results

The results reported reflect the sugarcane response to the gross amounts of irrigation water exiting the sprinkler nozzles. Any conveyance losses within a field or between the field and the irrigation water source are not accounted for. Polynomial trend lines were fitted to the data using standard Microsoft Excel functionality. The simulated relationships between seasonal water applications either as the total amount of irrigation and rain water, or irrigation water only, and predicted sucrose yields, expressed as a percentage of the maximum potential sucrose yield, are shown in Figure 1.

There were substantial differences in sucrose yields for different uniformities and soil depths, for the same water application amount. For instance, a seasonal water application of 1 100 mm on the shallow soil resulted in 90% and 80% of the potential sucrose yield for well and poorly maintained sprinkler irrigation systems respectively. On a deep soil, the corresponding maximum sucrose yield was 98% and 85%. In both soils, a well maintained system, represented by a more uniform application of water, i.e. a CU of 80%, resulted in substantial gains in crop yield relative to the system with a CU of 60%. The impacts of uniformity were not as great on the deep soils relative to the shallow soils.

Increasing the amount of irrigation water applied to compensate for non-uniform water application is a common practice or even recommendation (Burt and Styles, 2007). The results shown in Figure 1 illustrate that this practice resulted in only small increments of yield gain for a large amount of additional irrigation water. Furthermore, no matter how much additional water was applied, the yield potential of the irrigation system with a CU of 80% was never attained by the system with a CU of 60%. It is likely that, with poor uniformities, portions of a field that are receiving relatively low amounts of water and which benefit from increasing water applications are offset by yield losses on other parts of the field which then receive excessive water and suffer due to increasingly anaerobic soil conditions.

For the shallow soil scenarios, sucrose yields declined rapidly when irrigation water applications were reduced to below approximately 1 150 mm. For the deep soil scenarios, the corresponding irrigation threshold was approximately 900 mm. This illustrates that crop response to water applications cannot be generalised and differences in crop response to specific environments should be considered in assessing potential economic impacts of water allocations.

The variation in the sucrose yield response to applied water increased when irrigation water applications were reduced. This highlights the increasing risk of economic losses with lower water applications when drought conditions occur.

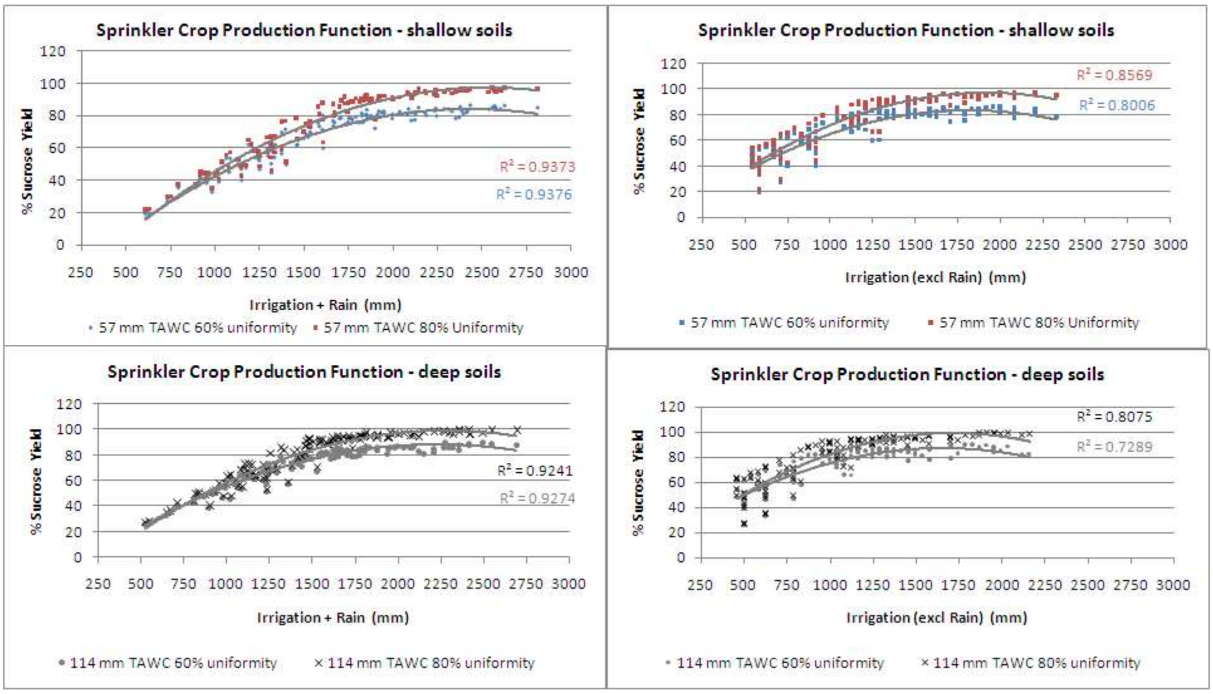

Figure 1. Sugarcane crop production functions for Komatipoort. The information shown is for sprinkler irrigation for soils with a TAWC of 57 mm and 112 mm and for irrigation uniformities represented by a CU of 60% and a CU of 80%. Irrigation and rain amounts are gross amounts.

Conclusions

The typical practice of simply increasing the amount of irrigation water applied to compensate for irrigation systems with a low CU was shown to be largely ineffective. Thus, when converting net irrigation water requirements to gross irrigation water requirements, no adjustment for low irrigation uniformities should be made. Low irrigation uniformity should be specifically addressed through better design, evaluation and maintenance practices. Improving the uniformity of irrigation water applications was shown to have substantial crop yield benefits, particularly on the relatively shallow soils.

Crop yield response to irrigation cannot be generalised into one production function, even for a specific location. Thus, an allocation of water which may be suitable for a particular farm and soil may result in substantial yield penalties for another farm with a different soil, even where both farms are in the same climatic region.

The production functions shown here are for different soils and irrigation uniformities, but for only one type of irrigation system. Application of appropriately representative crop yield and irrigation water balance simulation models such as *ZIMsched* 2.0 should be extended to investigate crop responses to different types of irrigation systems and operating strategies.

The results of such simulations provide the information necessary to determine optimum strategies for making the most effective and efficient use of water, and can be used in re-allocation scenarios as part of the water licensing process.

Acknowledgements

The authors would like to record their sincere appreciation for support from the Water Research Commission.

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APPENDIX E: A CONTINUOUS SOIL WATER POTENTIAL MEASUREMENT SYSTEM FOR IRRIGATION SCHEDULING ASSESSMENT (Jumman and Lecler, 2008)

A CONTINUOUS SOIL WATER POTENTIAL MEASUREMENT SYSTEM FOR IRRIGATION SCHEDULING ASSESSMENT

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Abstract

In this study, the application of a relatively inexpensive continuous soil water monitoring system to assess crop model predictions of under- or over-irrigation was investigated. Three Watermark soil water potential sensors and a soil temperature sensor were linked with a relatively inexpensive 'Hobo' data-logger capable of recording hourly measurements. These measurement systems were installed in four sugarcane fields with the Watermark sensors at three depths, namely: 15 cm, 30 cm and 60-80 cm, dependent on site conditions. Prior to installation the Watermark sensors were calibrated using pressure plate apparatus in a laboratory. In-field data were recorded from August 2007 to July 2008, a period covering the sugarcane growing season. Continuous monitoring of the soil water potential provided strong evidence to support the hypothesis that the fields were under-irrigated at certain critical times and adequately or possibly over-irrigated at other times. At one site, the crop experienced water stress for as much as 50% of the critical summer growth period. Early in the season, when sugarcane water requirements are relatively low, soil water potential was less than 50 kPa, indicating adequate water for almost 100% of the early growth period. Monitoring systems such as the one described, can add value in providing information to inform irrigation management decisions and contribute to optimising the use of water for crop production to the benefit of individual farmers and the wider community.

Keywords: Soil Moisture Monitoring, Soil Water Potential, Watermark Sensors, Irrigation assessment, Sugarcane.

Introduction

In an irrigation benchmarking study undertaken by Greaves (2007), farm water use and corresponding crop yield observations were compared to a range of simulated irrigation water requirements and crop yields. Greaves's (2007) study, which was undertaken on a prominent sugarcane irrigation scheme in KwaZulu-Natal provided strong evidence that farmers in the scheme were under-irrigating and that there was potential to improve crop yields by increasing irrigation water applications. It was further concluded, through field evaluations, that the peak design capacity of the irrigation systems were not the cause of reduced irrigation applications. Greaves (2007) recommended the use of in-field soil water monitoring to substantiate the hypothesis of under-irrigation.

In the broader context, scarce water resources and increasing competition for water from other sectors (NWRS, 2004) has increased the pressure on irrigators to use water more efficiently. Development and application of tools to monitor soil water status in order to assess the performance of irrigation systems and scheduling practices could become increasingly important. In the study reported in this paper, the application of a relatively inexpensive continuous soil water monitoring system to assess Greaves's (2007) crop model predictions of under-irrigation on farms was investigated. Typically, stakeholders, including the Department of Water Affairs and Forestry (DWAF), do not often perceive that farmers would be under-irrigating and the validity of the crop model benchmarks reported by Greaves (2007) were under debate.

Soil Water Measurement

A detailed review of soil water sensors is given by IAEA (2008). Pertinent aspects of the review are summarised here as follows. In the irrigation sector, soil water status may be measured in terms of volumetric water content or soil water potential. Soil water content is a description of how much water is present in a given volume or depth of soil, expressed typically in m^3 water per m^3 soil. The Neutron Probe, capacitance sensors and Time and Frequency Domain Reflectometers can be used to measure soil water content. The Neutron Probe and Time Domain Reflectometers (TDR) are very accurate methods of monitoring soil water status. The equipment, however, is relatively expensive and requires specialized knowledge to both record measurements and interpret the data. Furthermore, in the case of the Neutron Probe it is time consuming and labour intensive to gather the data from the fields. The Neutron Probe also makes use of radioactive materials and therefore a strict safety programme regarding the operation, transporting and storage of the equipment is necessary. Capacitance sensors are relatively inexpensive compared to Neutron Probes and TDR instruments and are becoming increasingly more popular. The IEAE (2008) stated, however, that the volume of soil sensed by capacitance sensors is so small that it may not be representative. A universal challenge with measuring soil water content is to determine whether the water content measured is too wet, i.e. above the drained upper limit (DUL), or too dry, i.e. below the water content at which the plant experiences stress (Charlesworth, 2000).

Soil water potential, on the other hand, is a measure of the suction energy required by the crop to extract water, and is, therefore, a more direct indicator of potential crop stress and whether or not the soil is above the DUL. Tensiometers and porous type instruments such as gypsum blocks and Watermark sensors can be used to monitor soil water potential. Tensiometers are limited to soil water potentials above -75 kPa. Should the soil dry out to water potentials below -75 kPa, air enters the device breaking the vacuum with which the tensiometer operates. For this reason, tensiometers are high maintenance apparatus. Gypsum blocks are inexpensive but a major problem is that the gypsum block breaks down and dissolves over a period of time and for this reason the calibration relationship between gypsum block readings and soil water potential is not fixed..

"The Watermark is a granular matrix sensor, similar to a gypsum block. It consists of two concentric electrodes embedded in a porous reference matrix material, which is surrounded by a synthetic membrane for protection against deterioration. A stainless steel mesh and rubber outer jacket makes the sensor more durable than a gypsum block. The porous sensor exhibits a water retention characteristic in the same way, as does a soil. So, as the surrounding soil wets and dries, the sensor also wets and dries. Movement of water between the soil and the sensor results in changes in electrical resistance between the electrodes in the sensor. The electrical resistance can then be converted to soil water potential through a calibration equation" (Chard, 2008). Watermark sensors are compact, robust, easy to use, relatively inexpensive and widely accepted by irrigation scientists for their ability to account for changing soil moisture conditions (Vellidis *et al.*, 2008). Furthermore, watermark sensors operate over a broader range when compared to tensiometers and are more robust than gypsum blocks. It should be noted that the Watermark sensor is sensitive to soil temperature and soil temperature needs to be monitored and accounted for in the calibration equation (Shock *et al.*, 1998).

Methodology

Based on the assessment of soil water measurement options, Watermark sensors were selected as the best option for measuring soil water status in this project. The next steps were to:

- find a suitable data logger,

- calibrate the logger and Watermark sensor combination to relate the readings to soil water potential,
- source appropriate apparatus to house the data loggers in the field and protect them from the elements,
- install the Watermark-based soil water potential system in farmer's fields,
- download and evaluate the water potential data.

The 'H8 Hobo' four-channel data loggers from the Onset Computer Corporation were selected following the work reported by Allen (2000). The H8 Hobo loggers were readily available and relatively inexpensive. Furthermore, the loggers were small, inconspicuous and require only a small watch-type battery and therefore are not likely to be tampered with or stolen. The Onset Hobo Logger uses DC current to excite the sensor. The Watermark sensors, however, are more suited to high frequency AC excitation. DC excitation can cause polarisation over time by causing the cations or anions to migrate to the electrodes. The Hobo excites all sensors simultaneously and then proceeds to read each channel in succession, completing readings in as little as 10 to 40 milliseconds. Hence, very little time exists for migration to occur and polarisation is unlikely to be a problem (Allen, 1999). Electrolysis, however, occurs at the electrodes of sensors when the excitation lingers for more then 2 milliseconds. Electrolysis results in formation of micro gas bubbles that alter the resistance of the water medium and therefore the sensor reading. In the case of the H8 Onset Hobo logger, the channels are excited for different periods of time and the associated formation of the micro gas bubbles affects the resistance readings of the different channels. Nevertheless, for most practical purposes, any resulting bias in the readings can be addressed by using a different calibration relationship for each channel (Allen, 1999).

Calibration

Three watermark soil water potential sensors and a soil temperature sensor were attached to the Onset H8 Hobo Data logger. All sensors were then placed in a saturated soil medium in a pressure plate chamber in a laboratory at the University of KwaZulu-Natal in South Africa. The pressure plate chamber was then used to systematically exert pressure on the soil forcing water to leave the soil. The pressure plate chamber provided a controlled environment in which the soil water potential was determined and compared to the voltages logged by the Onset Hobo logger. Using regression methods, relationships were developed to relate soil water potential to voltage readings for each channel, taking into account the soil temperature. The regression relations, together with the recorded data, are illustrated in Figure 1 below.

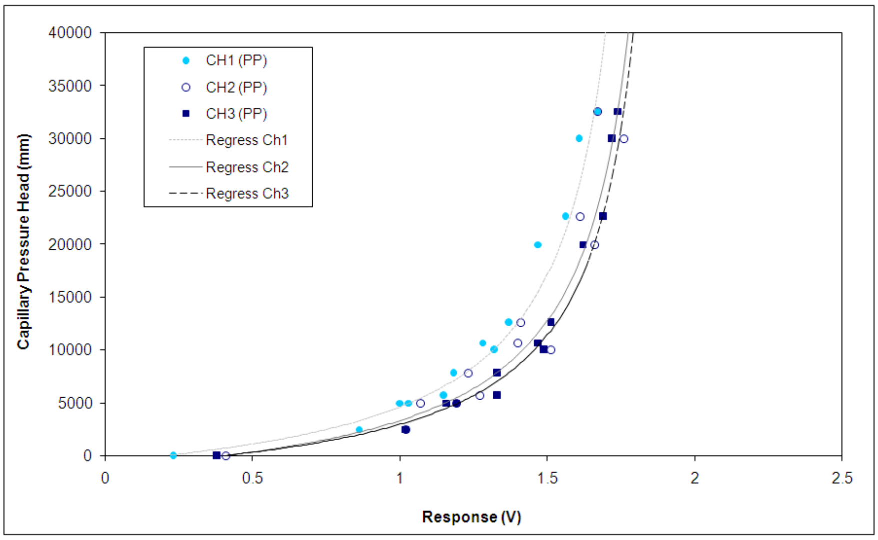

Figure 1 Calibration curve of Onset Hobo Logger and Watermark sensor. CH1, CH2 and CH3 refer to Channels 1 to 3 of the Hobo Logger and PP refers to data from the pressure plate apparatus.

As illustrated in Figure 1, higher voltage responses were recorded for channels 2 and 3 when compared to channel 1 for the same capillary pressure head. This illustrates the variable resistance in the water medium due to electrolysis and hence the need for calibration of each channel separately. The accuracy of the calibrations can also be assessed by referring to Figure 1. Whilst there is potential to refine the calibration relationships, especially for channel 2, the relationships were considered to be adequate for the study objectives.

A general purpose, weather resistant electrical box (code: RL1 – HP) was sourced from ARB Electrical Wholesalers (Pty) Ltd. (2008) to house the data logger. The box was 150 x 150 x 100 mm deep with a hinged screw on lid as shown in Figure 2. A 20 mm hole was drilled into a side wall to allow for the cables from the Watermark sensors to be connected to the data logger.

Figure 2 General purpose box used to house Onset Hobo data logger (ARB Electrical Wholesalers (Pty) Ltd., 2008)

The total cost of the soil water potential monitoring system was R 3450 as shown in Table 1.

Table 1 Cost break down of soil water potential monitoring system

Description	**Quantity**	**Cost**
Watermark Sensors	3	R 1770
Soil Temperature Probe	1	R 340
Onset Hobo Logger	1	R 1200
General Purpose Box	1	R 140
	Total	R 3450

Installation

Two sugarcane farmers, within the same irrigation scheme, agreed to participate in this project. A total of 4 sites, 2 on each farm, were selected. All the selected fields were irrigated by dragline sprinkler irrigation systems. The watermarks were installed in the cane row at depths of 15cm, 30 cm and 60 – 80 cm, dependant on site conditions. A standard soil auger was used to auger a hole to the required depth. The soil removed from the hole was sieved to remove rocky material, leaves and grass and mixed with water to obtain a thick slurry. The slurry mixture was then poured into the hole, approximately 5 cm deep, to create a seat for the deepest Watermark sensor. A PVC pipe was fitted around the collar of the Watermark sensor and used to locate the sensor snugly into the slurry at the correct depth. The slurry mixture first and the soil later were then backfilled into the hole in layers until the required depth for the next sensor was attained. The backfill was firmly tapped in using the handle of an old broomstick to ensure good contact between the sensor and the soil. The remaining 2 sensors were placed in the same hole in the same manner at 30 cm and 15 cm depths. The Soil Temperature Probes were placed in the same hole just above the 30 cm Watermark sensor. The cables were then threaded through the hole in the housing unit and connected to the Onset Hobo logger. Silicone was used to fix the cables in place and seal any gaps in order to protect the logger from water. Finally, the lid of the housing unit was screwed on and the box was placed on the ground in between the sugarcane, out of harm’s way.

Results

The Watermark soil water potential sensors were used to record measurements from August 2007 to July 2008. This period coincided with the growing season of the sugarcane crop. The time series for the Watermark data for two sites, namely 1A and 1B, from two different fields are shown in Figure 3 and Figure 4. The time series for sites 2A and 2B which were in different parts of the same field showed no significant differences or new information, except a drier trend, and are, therefore not presented in this paper. In Figures 3 and 4, the water potential is represented in kPa on the Y-Axis, were a higher kPa value indicates a drier soil.

In Figure 3, it can be observed that in the early season (September to November), the soil at site 1B reflects a wetter pattern at all depths of the profile compared to site 1A shown in Figure 4. The 15 cm and 30 cm graphs, in Figure 4, illustrate more root extraction activity. The crop response to water, at site 1A and 1B, in terms of root activity after the dry winter was expected to be similar, even though the crops were of slightly different ages. Both sites are in close vicinity to each other and would have received similar amounts of rainfall. Site 1B, however, is located on land which is relatively flat, and poor drainage coupled with irrigation and high rainfall in September and October may have resulted in anaerobic conditions. Soil conditions at site 1B were therefore not as conducive to root growth and activity compared to site 1A.

Furthermore, during November and December the root extraction activity at the 15 cm and 30 cm depths was fairly high at 1B and even though the shallower layers had been depleted, there was relatively little activity at the deeper depth, indicating limited root growth. Extraction at the deeper depth only started in mid December even though water was available earlier in the season. At site 1A, the roots at the 60 – 80cm depth began extracting water early in November much sooner than at site 1B and the shallower layers were not as dry. This indicates that soil conditions at site 1A were more conducive to root growth/activity and this may have contributed to less stress compared to site 1B.

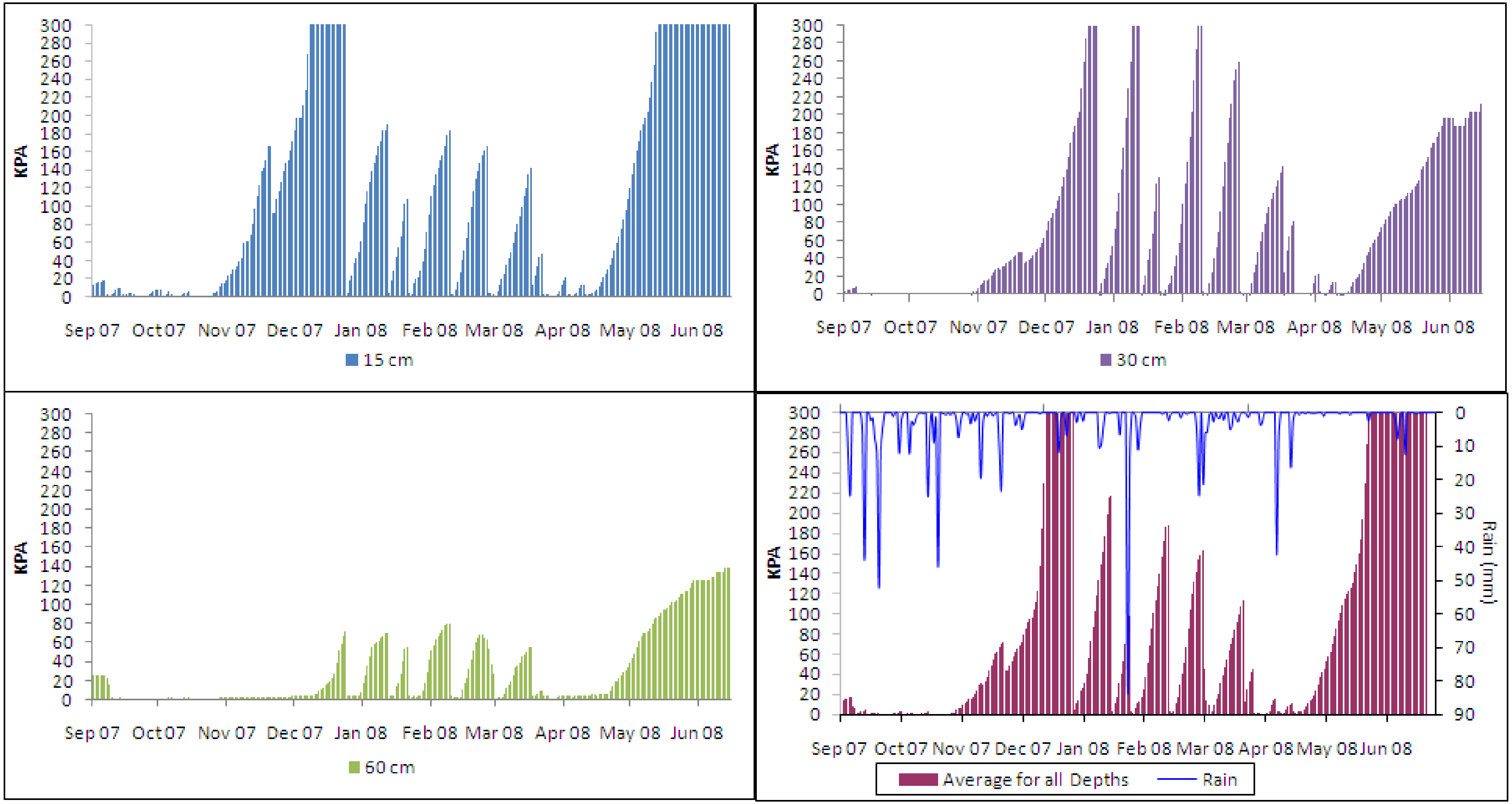

Figure 3 Time series of soil water potentials for each depth and average of all depths for Site 1B

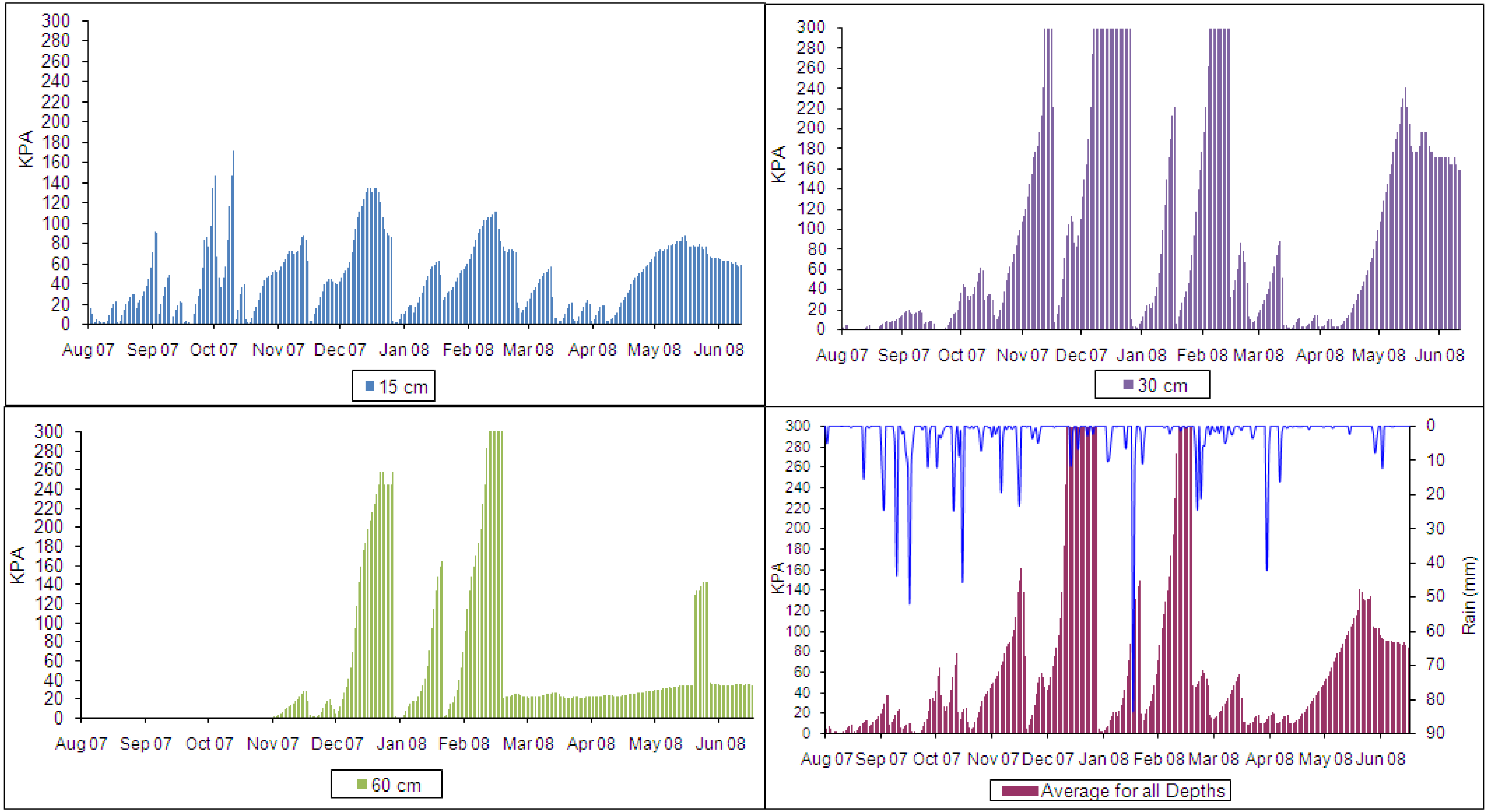

Figure 4 Time series of soil water potentials for each depth and average of all depths for Site 1A

Inman-Bamber (2002) reported that the threshold water potential for stress in sugarcane is approximately 100 kPa. Studying Figures 3 and 4, it can be seen that the stress threshold of 100 kPa is exceeded for large periods of time between November and February and again between May and July. This also holds true for sites 2A and 2B. The "stress" during May to July is not as critical as during November to February because during the winter period the temperatures are generally too low to drive major growth. Furthermore, the crop at site 1A was harvested in July. Hence, no irrigation occurred after April in order to dry-off the crop for harvesting and potentially increase the sucrose content.

In the summer months between November 2007 and February 2008, the average soil water potential over the profile often exceeded the 100 kPa stress threshold. Growth over this period is rapid due to the availability of ample radiant energy and, water stress over this period has a substantial impact on the final crop yield (Doorenbos and Kassam 1979). To illustrate the timing of water stress experienced by the crop on the participating farms, the percentage distribution of the average soil water potential for different growth stages is shown in Figure 5.

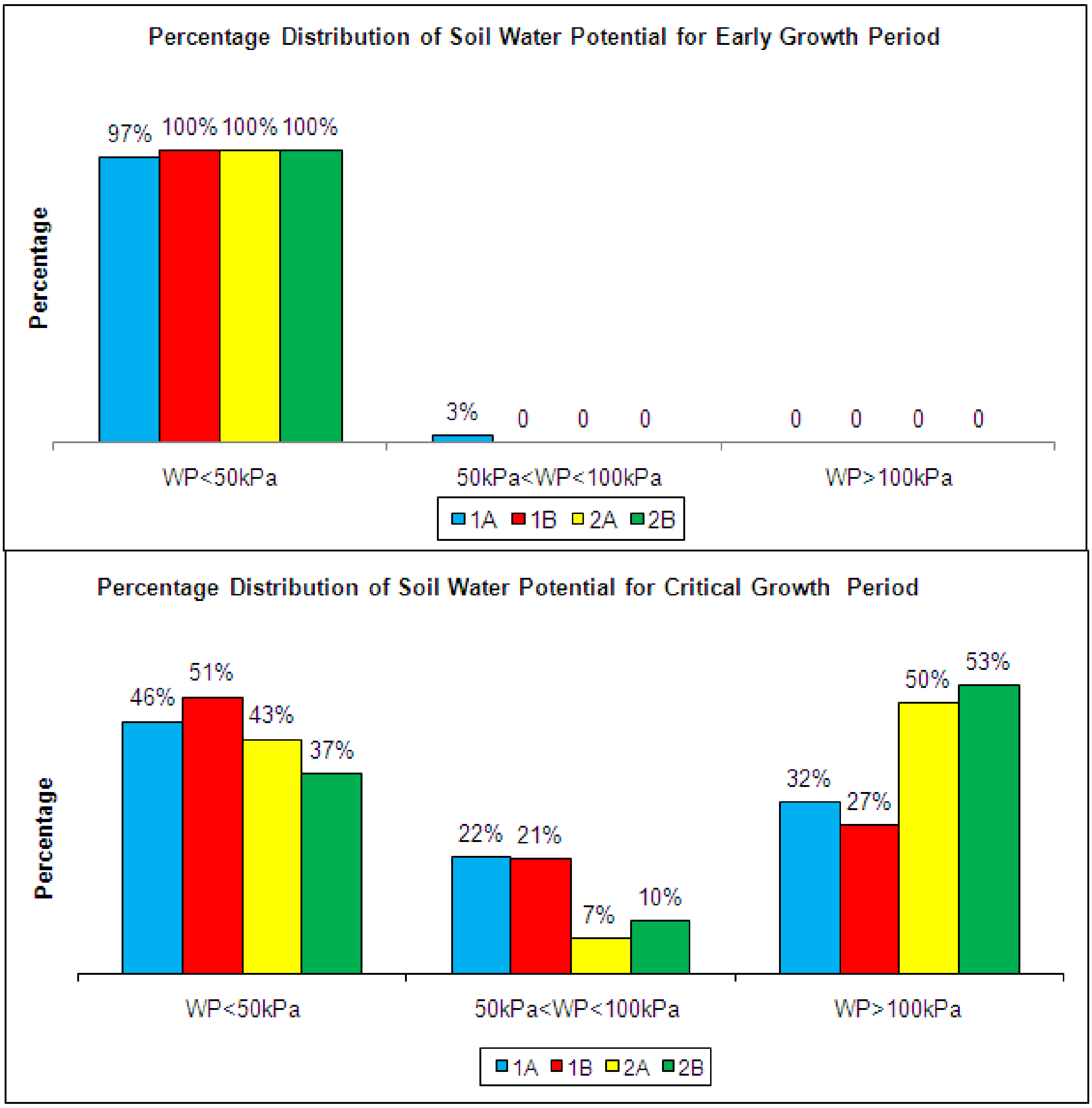

Figure 5 Percentage Distribution of average soil water potential

For the sites on both farms the soil is very wet in the early growth stage, between August and November, and the opportunity does exist for saving water by reducing irrigation. However, a large amount of water stress was experienced during the critical growth period of the year, particularly on the farm where sites 2A and 2B were located. At sites 2A and 2B, the crop experiences water stress for as much as 50% of the critical summer growth period between November and February. This information substantiates Greave's (2007) hypothesis that farmers within the irrigation scheme were under-irrigating and that there is potential to improve crop yields by increasing irrigation water applications. In general the Watermark soil water potential sensors only represent a small area on the farm and spatial variation of irrigation performance may be questioned. However, the selection of sites for this project was done in collaboration with the farmers and was purportedly representative of the typical conditions on the farm as a whole.

Conclusions and Recommendations

The Watermark soil water potential sensors proved to be a valuable tool in substantiating Greaves's (2007) hypothesis of under-irrigation. The data provided evidence of substantial water stress during critical growth periods but also provided evidence that there was potential to save water early in the growing season. Availability of soil water potential data should, therefore, assist farmers to monitor the performance of their irrigation strategies and make improvements. Furthermore, near-real-time soil water potential data could be utilized to trigger the timing of irrigation applications.

The Watermark sensor and Onset Hobo data-logger combination provided a relatively cheap and robust system to capture valuable soil water potential data. Downloading data can, however, be tedious and time consuming if data is required on a frequent basis, as required, for example, to make irrigation application decisions. Remote access to data, via GPRS, for example, is an area which should be explored. Nevertheless, monitoring systems such as the one described, can add value in providing relatively inexpensive information to inform irrigation management decisions and contribute to optimising the use of water for crop production. This will be of great benefit to individual farmers and the wider community.

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- Professor S. Lorentz and Mr. JJ Pretorius from the School of Bioresources Engineering and Environmental Hydrology at the University of KwaZulu-Natal for their great work in calibrating the Watermark sensors in the pressure plate apparatus.
- The participating farmers for their valuable time, effort and assistance on site. Due to the sensitivity of the work, a confidentiality agreement was signed that prevents publishing the names of the farmers.
- Water Research Commission (WRC) for providing funding for the project.

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APPENDIX F: ELECTRCITY TARIFF INCREASES: THE IMPACT ON IRRIGATORS? (Jumman and Lecler, 2010)

SHORT COMMUNICATION

ELECTRCITY TARIFF INCREASES: THE IMPACT ON IRRIGATORS?

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Abstract

Until recently the cost of electricity in South Africa was arguably rated amongst the cheapest in the world. However, there have been recent tariff increases, including: 14.2% effective from 1st April 2008, 34.4% effective from 1st July 2008 and finally a further 33.6% increase on 1st July 2009. In addition, a 25% increase each year over the next three years starting on 1st April 2010 was approved subsequent to this study. The hypothesis investigated in this communication was that the increase in electricity tariffs has impacted substantially on the profitability of farmers and poses a serious threat to irrigators. The *Irriecon V2* decision support tool was used to quantify the impact of the electricity tariff increases. A semi-permanent sprinkler irrigation system, capable of delivering 48 mm on a 10 day cycle, was designed for 60 ha block. Heatonville weather data, for the 1998/99 cropping season, were used in the *ZIMsched 2.0* model to generate a soil water balance with realistic irrigation applications. The cost of electricity for the simulated irrigation applications was then determined for the past three electricity tariff increases for the Landrate, Ruraflex and Nightsave Rural options. The electricity bill for the 60 ha field would have increased from R 74 889 to R 134 971 on the Landrate option. Similar increases were obtained for the Ruraflex and Nightsave Rural options.

Keywords: Irrigation, electricity tariffs, irrigation operating expenses

Introduction

In previous years, the cost of electricity in South Africa was arguably rated amongst the cheapest in the world. This has changed in recent times. The countries energy supplier, Eskom, has struggled to meet the electricity demands. As a result, a number of increases in the electricity tariffs have been affected to mitigate the situation. Increases in tariffs included: 14.2% effective from 1st April 2008, 34.4% effective from 1st July 2008 and finally a further 33.6% increase on 1st July 2009. In addition, Eskom submitted a Multi Year Price Determination (MYPD) proposal to the National Energy Regulator of South Africa (NERSA), requesting for a 45 % tariff increase per annum for the next three years (www.eskom.co.za/tariffs). Subsequent to this study, a 25% tariff increase, each year for the next three years, effective from 1st April 2010, has been approved. In light of the economic climate, the past and pending increase in electricity tariffs are expected to impact, substantially, on farm profitability. This study was aimed at quantifying, for a specific scenario, the increase in the electricity bill over the last three tariff increases.

Materials and Method

A hypothetical semi-permanent irrigation system was designed for a 60 hectare field in the Heatonville area in Northern KwaZulu-Natal. The irrigation system was capable of delivering 48 mm of water on a 10 day cycle and was fairly representative of the Heatonville area. For the designed 60 hectares and 1000 m main line, the pumping system was required to pump a flow of 116.42 m^3/hr at a head of 90.74 m which requires a power rating of 45.7 KW. It was assumed that a 50 kVA, 3 phase transformer was installed on the farm. Irrigation applications occurred in two 12 hours sets per a day.

ZIMsched 2.0, a daily soil water balance model was used to determine seasonal irrigation amounts (Lecler, 2004) assuming a soil with a total available water content (TAW) of 76 mm was refilled when 45.6 mm was depleted (60% of TAW). A gross irrigation application of 48 mm was reduced by 10% to account for wind drift and evaporative spray losses. In this case, weather data for the 1998/99 cropping season was obtained from the Pogela weather station in Heatonville. The combination of the system pumping specifications and annual irrigation demand was then used in the *Irriecon V2* (Armitage *et al.*, 2008) model to determine the cost of electricity for the prescribed irrigation applications as determined by *ZIMsched 2.0*. The annual electricity costs were determined with tariff prices for the 2007/08, 2008/09 and 2009/10 years in order demonstrate the impact of increasing electricity tariffs on farmers. In addition, electricity costs were determined for the Landrate, Ruraflex and Nightsave options.

Results

755 mm of rainfall was recorded for the 2004/05 crop season. The *ZIMsched 2.0* model predicted that the annual irrigation demand, taking into account rainfall, was an additional 998 mm. A management factor of 0.7 was applied to the simulated yields and the resultant cane yield was predicted to be 89.6 tons/ha. Applying 807.84 mm of irrigation water over 60 ha translated into the pumping of 589 671 m^3 of water per annum which consumed 231 472 Kilowatt hours. The fixed, variable and total cost of electricity for this system within the specified conditions is shown in Table 1. The variable costs refers to the Rands charged per Kilowatt hour for the energy actually consumed while fixed costs is a levy charged for the use of infrastructure. It should be noted that fixed costs are payable irrespective of whether electricity was consumed or not.

Table 1 Break down of model predicted electricity costs for irrigation on 60 ha in the Heatonville area based on weather data from the 1998/1999 cropping season

Ruraflex					
Fixed Costs[1]					
	Service	Admin.	Network		**Total**
2007/2008	R 1,507	R 2,205	R 2,490		**R 6,202**
2008/2009	R 2,022	R 2,960	R 3,336		**R 8,318**
2009/2010	R 2,683	R 767	R 4,560		**R 8,009**
Variable Costs[2]					
	Reactive Energy	Active Energy	Voltage Surcharge	Transmission Surcharge	**Total**
2007/2008	R 896	R 47,636	R 8,277	R 570	**R 57,380**
2008/2009	R 1,203	R 63,925	R 11,107	R 765	**R 77,000**
2009/2010	R 1,532	R 103,517	R 17,974	R 1,234	**R 124,257**
Ruraflex					
Total costs[3]					
2007/2008					R 63,582
2008/2009					R 85,318
2009/2010					R 132,266

Landrate			
	Fixed Costs[1]		
	Service	Network	**Total**
2007/2008	R 2,340	R 2,460	**R 4,800**
2008/2009	R 3,096	R 3,254	**R 6,350**
2009/2010	R 3,449	R 4,212	**R 7,661**
	Variable Costs[2]		
	Active Energy		**Total**
2007/2008	R 70,090		**R 70,090**
2008/2009	R 93,978		**R 93,978**
2009/2010	R 123,310		**R 123,310**
Landrate			
Total costs[3]			
2007/2008			R 74,889
2008/2009			R 100,329
2009/2010			R 134,971

Nightsave Rural					
	Fixed Costs[1]				
	Service	Admin	Network		**Total**
2007/2008	R 1,507	R 2,157	R 1,890		**R 5,555**
2008/2009	R 2,022	R 2,891	R 2,532		**R 7,445**
2009/2010	R 2,683	R 767	R 3,258		**R 6,707**
	Variable Costs[2]				
	Energy Demand	Active Energy	Voltage Surcharge	Transmission Surcharge	**Total**
2007/2008	R 22,231	R 25,791	R 8, 635	R 499	**R 57,156**
2008/2009	R 29,836	R 34,637	R 11, 592	R 670	**R 76,736**
2009/2010	R 42, 327	R 60,952	R 18, 431	R 1, 065	**R 122,775**
Nightsave Rural					
Total costs[3]					
2007/2008					R 62,710
2008/2009					R 84,181
2009/2010					R 129,483

1 Fixed costs – Infrastructure costs that are charged irrespective of whether electricity is consumed or not.

2 Variable costs – Cost of actual energy consumed charged in Rand per Kilowatt hour

3 Total costs – Sum of fixed and variable costs

As shown in Table 1, the electricity bill for the 60 ha block would have increased from R 63 582 to R 132 266 on the Ruraflex option. Similarly the increase for the Landrate and Nightsave Rural options were R 74 889 to R 134 971 and R 62 710 to R 129 483, respectively. On average, the cost of electricity was increased from R 0.32 per Kilowatt hour to R 0.58 per Kilowatt hour. The results indicate that under these constraints, the electricity bill for a 60 ha farm would have almost doubled in a space of three years.

Conclusion

In light of the above findings, and in the context of the further increases in electricity tariffs in the near future, the profitability of irrigated farms with low margins is under threat These preliminary findings highlight the need to develop and implement strategies to assist growers to overcome these difficult times.

References

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