DEFICIT IRRIGATION: A STRATEGY TO IMPROVE PROFITABILITY IN SUGARCANE IRRIGATION

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ABSTRACT

The purpose of this review was to gauge the potential to implement deficit irrigation strategies in the South African sugarcane industry. Deficit irrigation is a strategy aimed at maximising profitability as opposed to yields, and results in improvements in water use efficiency. This is because more frequent water applications result in increased losses, for example, from surface evaporation, runoff and deep percolation. Thus, yield increments are not linearly related to increasing water applications. In addition, incremental yield benefits decrease as watering increases. Reductions in applied water can allow deviations from design norms and translate to reduced capital and operating costs, which more than compensate for any reduction in crop yields.

The design and management strategies affecting the performance of conventional irrigation systems, in terms of uniformity and application efficiency are highlighted, as are irrigation scheduling methods and potential deficit irrigation planning tools. The recent progression in real time continuous monitoring tools may facilitate adoption of both deficit strategies and better scheduling practices. Analytical and decision support tools, which could be used to illustrate the benefits of moving from conventional to deficit irrigation include IRRIECON V2, an economic analysis tool which could be used in conjunction with water balance and crop yield models such as, ZIM*shed*, SA*shed*, CANESIM and *ACRU*cane.

Deficit irrigation implemented on sugarcane has the potential to be profitable. The resistance and recovery of sugarcane to water stress in the early growth stages, before full canopy development present water saving opportunities. In addition, benefits of “drying off” the crop to increase sucrose content during the later growth stages before harvest have been well documented. There is opportunity to research and apply decision support tools to facilitate the development and wider implementation of deficit irrigation strategies in the sugarcane industry from both a design and management perspective.

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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 worlds 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 average mean annual precipitationin 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). Recognising that water is a finite resource and to mitigate the imbalance between availability and demand, the Department of Water Affairs and Forestry (DWAF) have launched several campaigns to ensure water use is lawful, equitable, efficient and sustainable. These campaigns include 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 farmer'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 tariffs (English, 2002). Electricity largely 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. Similar to water, 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. Electricity tariff increases have also been proposed by the national service provider, ESKOM and, if approved, will contribute to the pressure on farmers, amongst others, to utilise resources more sparingly and efficiently (NERSA, 2007). Thus the potential for strategies such as deficit irrigation, which aim to optimise profits by decreasing water use and associated water and electricity tariffs, increase.

The specific focus of this document is on irrigation systems and strategies at the farm or field level in the sugarcane industry in South Africa with the objective of increasing profitability and optimising water use efficiency. The document consists of 8 chapters. In Chapter 2, the performance fundamentals and global trends in irrigation development are reviewed in order to track the movement from past to present towards higher water use efficiency. A management strategy to optimise water use efficiency, known as deficit irrigation, is introduced in Chapter 3. The concepts, principles, advantages and disadvantages of deficit irrigation are presented. In order to assist a farmer in moving from conventional to deficit irrigation, analytical and decision support tools to evaluate and demonstrate the potential benefits are required. A review of available decision support tools for deficit irrigation planning and management is presented in Chapter 4. The reviewed software allows for economic comparison of deficit/reduced irrigation strategies to full irrigation, taking agronomic practices into account. Furthermore, in-field continuous monitoring systems, such as soil moisture sensors, and their potential role in deficit irrigation are discussed. In Chapter 5, the physiology of sugarcane, in particular, critical growth stages in response to water stress are discussed. Chapter 6 consists of the conclusions and discussions. A project proposal to investigate the potential role of deficit irrigation with enhanced system designs and the use of continuous monitoring tools are presented in Chapter 7. Finally, Chapter 8 consists of a list of references cited in this document.

2. PERFORMANCE FUNDAMENTALS AND TRENDS

Not all irrigation water applied to crops is used effectively. Various fractions of water applied arrive at different destinations (Burt *et al.*, 1997). It is best to first understand the irrigation water balance before attempting to identify target areas to increase water use efficiency. The irrigation water balance traces the different flow paths of the water applied to a specified area. For a field application, the boundaries of the focus area are set as the top of the canopy and the bottom of the soil root zone (ASCE, 1978). The irrigation water balance then encompasses the destination or water use of the various fractions of water applied to the defined area.

2.1 Irrigation Water Balance

Water, amongst others, is a vital component of plant production. Water is absorbed by the roots of the crop and travels along a gradient to the leaves and through the stomata pores to meet the atmospheric evaporative demand. This process is beneficial to the plant as it keeps stomata pores open allowing for the intake of carbon dioxide that is necessary for photosynthesis and crop growth (ARC-ILI, 2004). However, due to the irregular and uneven distribution of rain, water is not always readily available to the roots resulting in crop stress and reduced growth. Thus, irrigation is warranted to ensure maximum growth rates (Hoffman *et al.*, 2007).

In the irrigation water balance, the inflows constitute precipitation, either as rain or irrigation. The outflows are made up of transpiration, evaporation, runoff and deep percolation (Burt *et al.*, 1997, Lecler, 2004a). Transpiration is the loss of water through the crop stomata into the atmosphere, as discussed above. Evaporation is the conversion of water from liquid to vapour that is then lost to the atmosphere. Transpiration is therefore a component of evaporation but has been separated out as it is related to crop growth and is often used to predict crop yield. Evaporation also occurs from water on the soil surface, intercepted on the leaf surface or droplets as they travel in the air. The remaining water fraction either infiltrates into the soil or flows away from the cropped area and can no longer be used for growth. The infiltrated water is either stored in the root zone and is readily available to the crop or drains below the root zone and is lost to the crop. Deep percolation is the process of water draining below the root zone. The rate of evaporation and transpiration is dependent on climatic factors such as solar radiation, wind, temperature and relative humidity and the soil water content (Burt *et al*, 1997). Infiltration, runoff and deep percolation are dependent on the intensity of precipitation, ground cover, slope of land and soil characteristics such as texture, structure and water holding capacity including antecedent water content amongst others (ARC-ILI, 2004).

By examining the irrigation water balance, the fraction of water used effectively by crops can be identified. Efficient irrigation aims to increase the effective use of applied water while minimising losses. Griffiths (2007) reported that irrigation efficiency meant different things to different people therefore, resulting in confusion. In an attempt to alleviate confusion amongst practitioners, Burt *et al.* (1997) presented terms such as consumptive, non-consumptive, beneficial and non-beneficial use to further describe the various fates of water use in the irrigation water balance. Griffiths (2007) stated that "Consumptive use was described as water lost to the atmosphere due to evaporation or transpiration, or water harvested in plant tissue that cannot be recovered. Non-consumptive use is water that was lost to the cropped area and can be reapplied in another area. Similarly beneficial use is water that supports crop production and is consumed to fulfil an agronomic need, while non beneficial water use is any use that is not beneficial as suggested by the name."

Considering a definition of water use efficiency/productivity to relate to more agricultural output for less water input, the above discussion suggests that this is best achieved by minimising non-beneficial uses such as: unnecessary evaporation from soil surfaces outside the cropped area; excess evaporation from bare soil surfaces due to, for example, too frequent wetting; spray evaporation and wind-drift beyond the field and excessive deep percolation beyond the needs of leaching unwanted and harmful salts from the root zone (Burt *et al.*, 1997). These issues will be discussed further in Section 2.2, where indicators of irrigation performance are introduced.

2.2 Irrigation Performance Indicators

Before presenting the attributes of irrigation systems and developments towards achieving higher water use efficiency, it is first necessary to define efficiency and other performance indicators that are used to measure the goodness of the systems.

Engineering efficiency is defined as the dimensionless ratio of output over input (Perry, 2007). Irrigation efficiency is defined as the ratio of the volume of water beneficially used to the total volume of irrigation water applied (ASCE, 1978). Continuing from the previous chapter, beneficial uses include: crop water use, salt leaching, frost protection, crop cooling, and pesticide and fertilizer applications. Non-beneficial uses that should be minimised to increase irrigation efficiency include: excessive deep percolation, surface runoff, transpiration from weeds, wind drift and spray evaporation (Hoffman *et al.*, 2007). Typically a high engineering efficiency implies a reduction of losses. Losses are considered a non-recoverable waste of resources and a reduction of losses will mean more input is available for alternative uses (Perry, 2007). This, however, does not hold true for irrigation efficiency and is the root of the confusion experienced in industry. Increasing irrigation efficiency by decreasing non-beneficial uses such as runoff and deep percolation does not necessarily make more water available for downstream users. Runoff and deep percolation in an inefficient irrigation system will enter back into the water balance as return flows thus becoming available to downstream users. Since the return flows may be of poorer water quality, it is ideal to have higher on-farm water use efficiencies in order to reduce the environmental impact on downstream users (English, 2002). Furthermore, it is in the interest of a farmer at farm or field level for irrigation efficiency to reflect an optimized and economical irrigation system. An optimised system reflects minimised water and electricity tariffs with high yields and optimum profits and therefore most beneficial to the farmer.

Application efficiency has been described as the “main farm irrigation efficiency indicator” and is defined as the ratio between the average low quarter depth of water added to the root zone storage and the average depth of water applied to the field based on a single event (Pereira *et al.*, 2002). Not only should an irrigation system reflect high irrigation and application efficiency with minimum non-beneficial uses, but the system should also ensure that the water application is distributed uniformly over the entire irrigated area. Non-uniform applications result in some areas within a field or block being under- or over-irrigated. Hence the first requirement of high irrigation efficiency is the uniform application of water (Griffiths, 2007). Pereira (1999) pointed out that the most common parameters used as indicators of uniformity are the coefficient of uniformity (CU), the distribution uniformity (DU) and the statistical uniformity (SU). The uniformity and efficiency parameters and methods of evaluating different systems were comprehensively reviewed by Griffiths (2007) and essentially involve the description, definition, relationship and application of field evaluations to measure the performance of various systems. As reported by Griffiths (2007), the CU value was developed for evaluating sprinkler systems and is a quantitative measure of the average deviation from the mean application depth. The DU gives an indication of the magnitude of uneven distribution and emphasis is placed on under watered areas. SU is usually used to represent the uniformity of micro systems accounts for the fact that water is not applied to the whole field area. It should also be noted that efficiency and uniformity indicators should be used in conjunction with each other to report the performance of a system. A highly uniform water application does not ensure high efficiency since water can be uniformly under or over applied.

In the next section, irrigation systems and trends towards achieving higher water use efficiency are discussed.

2.3 Irrigation Systems and Trends towards High Water Use Efficiency

Numerous developments and enhancements to irrigation system hardware and scheduling approaches have been made in order to improve performance. Furrow, overhead sprinkler and drip systems are the most widely used systems in sugarcane in SA (Olivier and Singels, 2004) and the developments and enhancements to these systems are discussed in this section.

2.3.1 Furrow Irrigation

Furrow irrigation has been the most commonly used method worldwide for many years (ARC-ILI, 2004). This is largely attributed to the low energy costs of the system. With surface irrigation it is often difficult to accurately place the correct amount of water at the plant roots at the right time. The even distribution of water is difficult due to varying soil infiltration and resistance influencing the movement of water over the soil surface (Hoffman *et al.*, 2007). The multi-dimensional variability of soil infiltration and resistance to flow over a soil surface contributes to the complexity of surface irrigation design and management. The efficiency and performance of surface irrigation has been limited by the inability to provide site-specific constraints, such as soil infiltration variability, without extensive field experiments. Development of simulation modelling, such as SIRMOD, has provided the opportunity to assess alternative field layouts, length and slope of furrows for example, and management strategies relating to cut-off and advance times which may result in more efficient irrigation practices (Raine and Walker, 1998). Furthermore, laser levelling and precision land preparation has been used to a large degree to decrease the variability of soil slope, unevenness and soil infiltration. The increase in performance and associated benefits justify the additional costs in land preparation (ARC-ILI, 2004). In the past, surface irrigation was synonymously linked to high labour requirements. Short furrow irrigation was also adopted in order to reduce the soil infiltration variability and increase performance and efficiency (ARC-ILI, 2004) Decreasing furrow dimensions and length allows for smaller more frequent applications which increases flexibility and robustness regarding soil characteristics. Labour was often used to control the discharge into furrows and resulted in large variations in the volume of water applied in each irrigation event. In modern systems, siphons, gated pipes and/or automated gates or valves are used to control the inflow (Pereira, 1999). Alternate furrow and surge irrigation were also developed as management strategies to use water more efficiently (Raine, 1999). In alternate furrow irrigation water is applied to every second furrow rather than every furrow. The benefits of alternative furrow irrigation are related to the reduction in losses due to evaporation from the soil surface (Raine, 1999). The application of water to alternative furrows in a series of relatively short on and off time periods is referred to as surge irrigation. Surge irrigation was used to cut back stream sizes and reduce runoff. Surge irrigation generally also reduces the soils infiltration thereby speeding up the advance front and improving the distribution uniformity (Hoffman and Martin, 1992).

2.3.2 Overhead Sprinkler Irrigation

Overhead sprinkler systems are usually pressurised systems utilising pumps and electrical energy to provide the pressure. Overhead sprinkler systems consists of permanent systems, portable systems such as quick coupling and dragline, and mobile systems such as centre pivots, linear move and travelling guns (ARC-ILI, 2004). Sprinkler discharge is mainly a function of pressure and the performance of sprinkler systems is often dependent on the operating pressure and reduced pressure variation in the system. Furthermore, the sprinkler water distribution pattern is affected by wind and results in reduced distribution uniformities in windy conditions (Zapata *et al.*, 2007). An optimised design matches soil infiltration, climate characteristics and crop needs with system layout, sprinkler discharge as a function of pressure and nozzle diameter and spacing between sprinklers and/or laterals, or towpaths of travelling guns taking into account labour and management considerations. The hydraulic design of sprinkler irrigation is generally well understood (Pereira, 1999). Parameters affecting the distribution uniformity are often fixed in the design phase, however, evaluation and maintenance is required to ensure issues such as leaking pipes and worn nozzles, which increase the pressure variation, are addressed. Improved methods include the use of pressure gauges and flow meters to monitor how well the system is operating in relation to the design specifications (Raine, 1999). Furthermore, emphasis has been placed on quality control of design and equipment selected in the design phase. Management parameters that impact on both the distribution uniformity and application efficiency include; intake characteristics of the soil, application rate of the sprinkler, duration of irrigation event and soil water deficit before an irrigation event. The infiltration characteristic of the soil, as pointed out earlier, varies spatially. Trashing in sugarcane is an example of one of the many ways with which the soil intake characteristics may be altered (Raine, 1999). In addition, developments in automation allow mobile systems such as centre pivots and linear move systems to vary the application rate by controlling the speed of the structure, matching it to the fluctuating soil infiltration rate, as the structure moves over different parts in the field (Hoffman and Martin, 1992).

Electricity tariffs contribute a large portion to the operating cost of pressurized systems. Selection of application rates affects the capacity of the system, and therefore the pump design and operating electricity costs. The introduction of low pressure floppy sprinklers was aimed at reducing electricity tariffs (Floppy Sprinkler (Pty) Ltd, 2003). Similarly lower - pressure, precision - application (LEPA) systems in centre pivots were introduced (Hoffman and Martin, 1992). The LEPA system comprised of spray devices dropped from the mainline pipe on a pivot to below canopy level. The system also reduced the fraction of soil wetted as compared to conventional centre pivot thereby reducing the non-beneficial evaporation from the soil surface.

2.3.3 Drip Irrigation

Drip systems are divided into surface and subsurface drip. Drip irrigation systems are fixed systems that use low pressure; low discharge emitters to apply water (Pereira, 1999). They are further characterized by the distribution of water in closely spaced pressurised conduits that apply the water frequently at low rates on or below the soil surface (Hoffman and Martin, 1992). The distribution uniformity of drip systems is dependent on system variables fixed in the design phase, similar to overhead sprinkler systems (Pereira, 2002). The pressure, discharge, emitter type, spacing and wetting volume, system layout and automation or control of flow and/or pressure all contributes to the design of the system. Other factors such as emitter susceptibility to clogging, type, location and cleaning capability of filters and equipment for fertiliser and chemical application also need to be considered in the design phase. The application efficiency is also dependent on the design variables as described above and, the management and scheduling of irrigation in terms of volume, frequency and timing of irrigation (Pereira, 1999). The subsurface drip system applies water near the centre of the root system replacing soil water loss frequently and in a precise manner. Issues such as variability in the soil surface that reduce infiltration rates and increase runoff are of no concern. Also, evaporation from the soil surface is limited as a result of wetting smaller fractions of soil (Hoffman and Martins, 1992). Drip systems have for the most part been associated with high irrigation efficiencies and uniformities. This is due to the fact that performance is mainly dependant on hydraulics and equipment design rather than management, soil differences and sprinkler overlapping patterns (Burt and Styles, 2007). Furthermore, developments in pressure compensating emitters contribute to negate the impacts of poor hydraulic design resulting in high pressure variation. Clogging of emitters as a result of poor water quality, mismanagement as well as a lack of maintenance is a serious problem which threatens the high performance associated with drip irrigation (Reinders and Koegelenberg, 2003). Filtration, flushing and chemical treatment of irrigation water are used to combat clogging.

In summary, distribution uniformity in drip and overhead sprinkler systems are determined to a large degree, by the design and correct selection of quality equipment. The farmer or irrigation manager can only impact on the performance of the system by ensuring that the system is performing according to design specifications through field evaluations and periodical maintenance. Application efficiency is dependent both on the design of the system and management of variables such as soil water depletion and the frequency, timing and volume of irrigation water applications which are all invariably linked to scheduling.

2.4 Irrigation Scheduling

Irrigation scheduling is the process of deciding when, where and how much water to apply (Pereira, 1999). Scheduling irrigation applications serves to ensure crop water requirements are met, whilst avoiding stress and minimising reductions in crop yields. In light of the increasing water scarcity, it is increasingly important to prevent over irrigation and wastage. Methods of scheduling irrigation include soil water balance calculations, estimating crop water requirements by determining crop transpiration rates as a function of climatic parameters, and monitoring plant responses in relation to water (Raine, 1999 and Stevens, 2006). The development and integration of these methods has, to a large extent, been driven by the need to determine the minimum amount of water required to maximise yield (Raine, 1999 and Jones, 2004).

Effective and accurate scheduling, 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, 1999). Unfortunately, only a part of the continuum is monitored in practise and the scheduling is based upon empirical relationships between the variable monitored and crop productivity (Hoffman and Martins, 1992). Stevens (2006) grouped irrigation scheduling methods and techniques in South Africa as follows; “Intuition, atmospheric based quantification of evapotranspiration, soil water measurement, plant based monitoring and integrated soil water balance approaches which includes pre-programmed irrigation methods as well as real time approaches.” Stevens (2006) also concluded that the majority of farmers do not measure soil water content and adoption of objective scheduling methods is below expectations. This was largely attributed to the perceived complexity of scheduling methods and models and the lack of advisory or support services to farmers. A few selected monitoring tools available to South African farmers are detailed in Section 4.3. Management of modernised or well-designed systems, with enhanced performance through accurate scheduling, is critical to optimising water use efficiency. In the next chapter a deficit irrigation strategy to optimise water use efficiency and profitability at the farm level is expanded on.

3. DEFICIT IRRIGATION

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, as opposed to a yield maximising strategy, derives more benefits in terms of water savings, food security and reduced environmental degradation. The relationship between crop yield and applied water and crop yield and transpiration is illustrated in Figure 3.1.

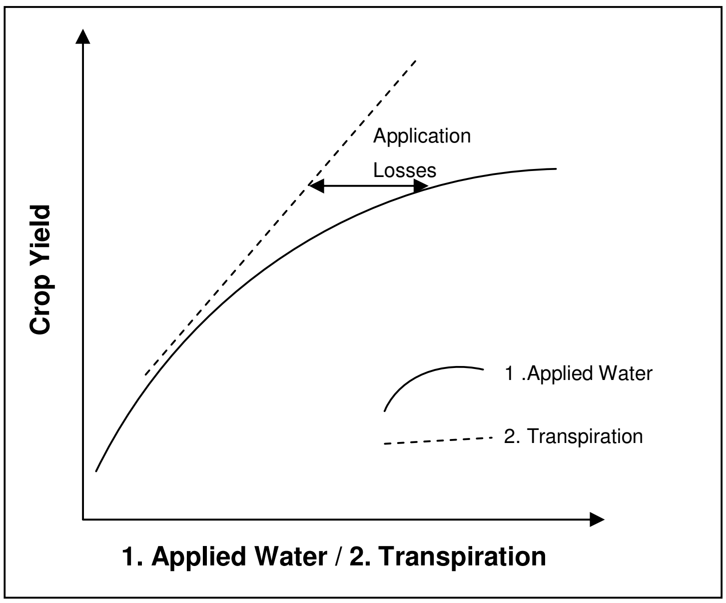

Figure 3.1 General form of crop production (Lecler 2004a, adopted from English, 1990)

As shown in Figure 3.1, 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 3.2 and is explained further, below.

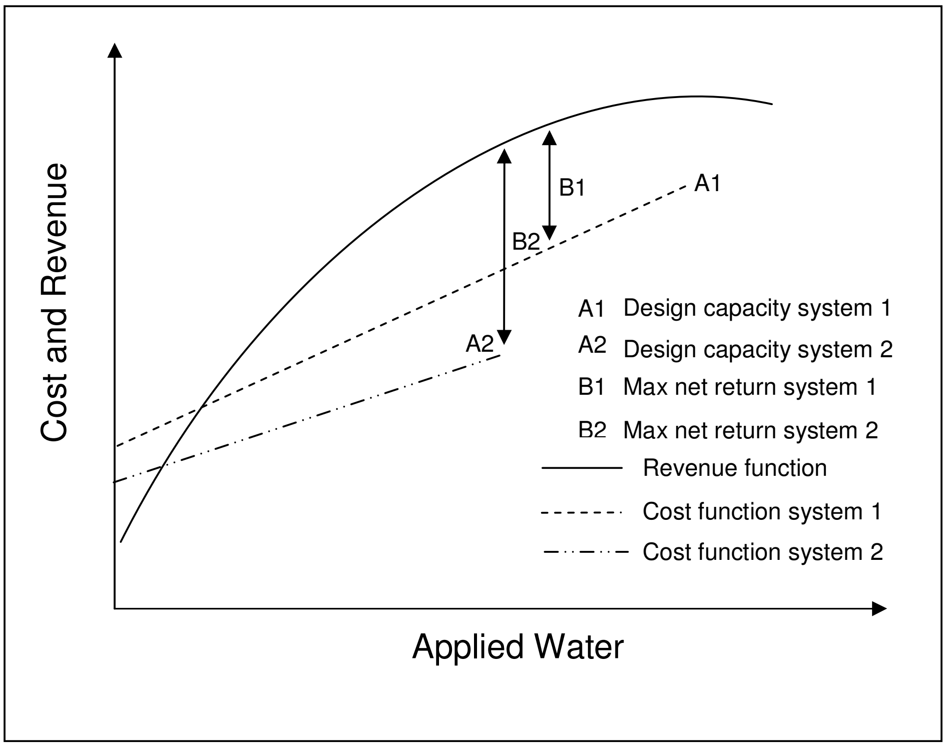

Figure 3.2 Cost and Revenue Functions (Lecler 2004a after English 1990)

In the cost and revenue functions shown in Figure 3.2, 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 3.1. 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 as shown by distances B1 or B2 in Figure 3.2. For the cost and revenue functions shown in Figure 3.2, 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).

4. DECISION SUPPORT 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 calculate the net margins for farms for varying scenarios of applied water and associated agronomic practices. Moreover, implementing deficit irrigation has implications on the accuracy of scheduling. Due to reduced volumes of irrigation, and a narrower margin for error, accurate monitoring of soil moisture, crop water intake and salinity will be needed. More accurate models for determining crop water requirements and yield forecasting will also play a major role (English, 2002). In this chapter, tools and models developed specifically for the sugarcane industry that could potentially play a role in implementing and managing deficit irrigation are presented.

4.1 Irrigation Scheduling and Yield Forecasting Models

The ZIM*shed* 2.0 *and* SA*shed,* developed by Lecler (2003 and 2004b, respectively) and CANESIM models, developed by Singels *et al.* (1998) have been developed to simulate the impact of irrigation on crop yield while also serving as an irrigation scheduling tool, and are in line with the analytical tools required to access deficit irrigation. *ACRU*cane, developed by Moult *et al* (2006) is an irrigation module integrated into the ACRU agrohydrological model. ACRUcane was developed specifically for sugarcane irrigation planning integrated with catchment runoff modelling. All of the models operate along the same fundamental principals but are not identical. A daily water budget, described as the irrigation water balance in Section 2.1, is used to account for the various fates of water. All models forecast the crop yield based on empirical relationships that have been developed and verified through intensive field experiments. The inputs into the models are not exhaustive and include the following; agronomics details such as plant date and length of season, irrigation system including irrigation frequency and depth, soil and climate characteristics such Class A-pan evaporation and rainfall, amongst others (Greaves, 2007). The outputs include the water use and corresponding yield or soil water deficit for irrigation scheduling purposes. Furthermore, the models have the ability to account for irrigation systems performing at different levels of uniformity. This is important when accounting for the impact of irrigation hardware and strategies on yield (Moult *et al.*, 2006). The yields and water use simulated by these models can then be used in economic models to assess the economic impact. This is discussed further the next section.

4.2 Analytical Tools to Assess Profitability

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). The specific costs associated with sugarcane farming practices such as the application of fertilizer and herbicide, planting, harvesting and haulage together with irrigation system, 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). 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 ZIM*sched* (Armitage *et al.* 2008). A similar irrigation economics model titled IREM was presented by Magwenzi (2002). These models are suitable tools 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. These agronomic models, however, need to be used in conjunction with yield and water use data, which may be simulated using the models presented in Section 4.2.

4.3 Continuous Monitoring Tools

The adoption of irrigation scheduling methods and techniques in South Africa is poor (Olivier and Singels, 2004). This is largely attributed to the perceived complexity of scheduling methods and/or the lack of support by extension and irrigation consultants. Developments in electronic communication in collaboration with monitoring tools allow for remote access to data. This is expected to improve the support available to farmers and enhance the adoption of better scheduling practices. The development and advancement of technology together with existing monitoring methods are presented in this section.

A comprehensive review of monitoring methods and techniques used for scheduling/irrigation water management in South Africa was presented by Stevens (2006). These included:

- atmospheric monitoring and direct measurement or indirect prediction of evapotranspiration;
- soil moisture monitoring including wetting front detectors, soil water potential with tensiometers and porous type instruments such as gypsum block and watermarks, and soil water content with neutron probes, capacitance sensors and time or frequency domain reflectometers amongst others;
- plant based monitoring through visual appearance, temperature and radiation measurements at the canopy, sap flow and trunk measurement to name a few.

Stevens's (2006) overview included a brief description of the advantages, short comings and suitable users or level of skill required for each method and/or instrument. A common trend amongst the methods and instruments reviewed was that the more accurate techniques required a higher level of skill (especially for calibration), are generally expensive, labour and management intensive and too time consuming if no data logger is used and, to a certain degree, are only representative of the site where the sensor was installed. This implies that a number of expensive sensors may be required to sufficiently reflect field conditions.

The development of economical, robust and accurate tools that are pre-calibrated with continuous logging capability and remote or less labour intensive communication of data from sensor in the field to user is forecasted to facilitate more accurate scheduling and possibly more efficient irrigation water use (Kennedy, 2008; Lecler, 2008 and Mercker, 2008). Continuous logging allows for events to be captured that would otherwise go unnoticed with conventional systems. Furthermore, communication of data via radio telemetry, GSM, GPRS and blue tooth to hand held devices or increasingly popular web based interfaces allows for real time monitoring and evaluation. Two examples of such systems includes capacitance probes developed and supplied by DFM Software Solutions (DFM, 2008), and crop growth stations, which are being developed to monitor soil water potential with watermarks, canopy temperature and stalk elongation in sugarcane, supplied by Kennedy (2008). The "*My*

Canesim System" also illustrates the effectiveness of a web based crop model using cellular technology to communicate scheduling advice to growers (Singels and Smith, 2006). These and other products are relatively unknown and progressively being developed. From the above, it is conclude that further investigation and research of newly available and progressive technology is required, especially in the context of deficit irrigation.

5. SUGARCANE AND 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 Chapter 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 5.1 was developed by Doorenbos and Kassam (1979) in order to quantify the impact of soil water stress on crop yields.

$$1 - Y_a/Y_m = K_y(1 - ET_a/ET_m) \quad \text{Eq 5.1}$$

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)
K_y	= yield response factor

In Equation 5.1, 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 value for sugarcane for different growth stages, as shown in Table 5.1, was 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 5.1 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 stage. Table 5.1 also illustrates that the yield response to water stress in the late maturation stage is insignificant.

Table 5.1 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 5.1 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 al* (1999) reported on past experiments conducted by Roberts *et al* (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, as described earlier in Chapter 2 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 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.

An issue with water deficits on sugarcane is that the crop appears stressed with a fair amount of leaf desiccation occurring (Inman-Bamber, 2003). To a farmer this appears to be detrimental and may force an irrigation event. The question to then pose is what means of measurement can a farmer use to detect if the water stress is detrimental to yield? Inman-Bamber (1995) reported that leaf and stalk extension rate are the best indicators of crop water status. 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 (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. In this chapter, it is clear that potential to implement deficit irrigation on a sugarcane crop, either within specific growth stages or over the total growing period is high.

6. DISCUSSION AND CONCLUSIONS

The irrigation water balance illustrates the complex interactions in the soil-plant-atmosphere continuum. Understanding the fate of various fractions of applied water is central to identifying target areas to reduce wastage of the valuable and scarce water resource. For this reason classification terms such as consumptive, non-consumptive, beneficial and non-beneficial uses have been introduced. The aim of increasing irrigation water use efficiency, often understood as 'more crop per drop' is, therefore, to minimise non-beneficial uses such as deep percolation in excess of leaching requirements, wind drift and spray evaporation and excessive evaporation losses from the soil surface. Uniform application of water over the field is also essential for efficient irrigation. The system design, correct selection of equipment and quality of equipment are important factors which impact on the uniformity of application. Application efficiency is a function of both design and management practices. The correct scheduling of irrigation applications is fundamental to achieving high application efficiency. This illustrates that both the design and management of irrigation systems are critical in attempting to use water more efficiently.

An optimising strategy called deficit irrigation has illustrated the potential to increase the beneficial and effective use of resources while producing optimum profits. Investigations and experiments have revealed that increments of yield gain are not linearly related to increased applications of water. This implies that increased water applications are not optimally beneficial or efficient. Deficit irrigation aims to increase profitability as opposed to yield. This is achieved by applying reduced volumes of water thereby reducing capital and operating costs which compensate for yield reduction. Furthermore, water savings may be used to irrigate additional land, if available, or stored in a dam for irrigation during dryer periods in the season. Deficit strategies also allow for deviation from design standards and norms which can further reduce capital and operating costs. Analytical and decision support tools are, however, required to determine and illustrate the benefits of deficit irrigation and facilitate decisions to move from conventional to deficit irrigation strategies. Smaller irrigation volumes and increased stress result in narrower margins for error. For this reason accurate real time continuous monitoring tools may be required to assist with scheduling.

In South Africa, especially in the sugarcane industry, the potential role of deficit irrigation to increase water use efficiency is promising. Analytical tools such as ACRUcane, CANESIM, ZIM*shed* 2.0, SA*shed* and IRRIECON V2 have been developed and are available to assess and quantify the benefits of deficit strategies. Continuous monitoring tools, in the form of soil moisture sensors and crop growth stations, are also progressively being developed and available to assist with implementation. Increasing the awareness and demonstrating the value of continuous monitoring tools is envisaged to increase adoption of such technology.

The resistance and recovery of sugarcane to water stress in the early growth stages before full canopy development and the benefits of 'drying-off' the crop to increase sucrose content before harvest have been well documented in the literature. Deficit irrigation implemented on sugarcane has the potential to take further advantage of these water saving opportunities. There is opportunity to research and apply decision support tools to facilitate the development and wider implementation of deficit irrigation strategies in the sugarcane industry.
In the South African context:

- the increasing pressure on water resources,
- the imbalance of electricity demand and supply,
- the increasing fuel prices that impact on cost of farm operations including cost of chemicals, and
- the increasing cost of labour

illustrate the need for innovative, accurate, improved and optimised methods of farming to remain profitable and sustainable. For this reason, there is opportunity to research and apply decision support tools to facilitate the development and wider implementation of deficit irrigation strategies in the sugarcane industry from both a design and management perspective.

7. PROJECT PROPOSAL

A project proposal to investigate the potential role of deficit irrigation in sugarcane with enhanced irrigation system designs and the use of continuous monitoring tools are presented in this chapter.

7.1 Problem Identification and Context

The agricultural sector is the largest water user in South Africa, mainly due to irrigation. Water scarcity and increasing demand has amplified pressure on agriculture to use water more efficiently. Furthermore, most irrigation systems are dependent on electricity to pressurise the system and/or pump water, which contributes to the operating costs. An energy crisis in South Africa has resulted in an increase in electricity tariffs to fund remedial programmes. Demand management strategies have been implemented to prevent wastage of the valuable resources. 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. For instance, from January 2007 to March 2008, the approximate price increases for LAN and Urea fertiliser were in the region of 65%, while the prices of Super phosphate and MAP increased by 250% (Omnia Nutriology, 2008). Strategies are thus required to assist farmers to cope with increasing costs by optimising and using limited resources more efficiently.

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 during a drier part of the season or to irrigate additional area thereby increasing water use efficiency. Furthermore, deficit irrigation allows a designer to depart from design standards and norms. Modernised irrigation designs appropriate for deficit irrigation may reduce capital and operating costs. In light of the energy crisis in South Africa, the flexibility of design may also allow farmers to take advantage of different electricity tariff structures and off-peak pumping.

A deficit strategy may allow smaller and less frequent applications that may reduce the pumping hours to within off peak hours thereby reducing the electricity tariffs further.

With the development of simulation and analytical tools in the sugarcane industry, evaluating the viability and performance of different strategies is simplified and relatively inexpensive compared to field experiments. These tools may prove useful in assessing and investigating the potential applicability of deficit strategies for the South African farmers in the current context. Furthermore, 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. A trend in the industry that has come to the fore has been continuous monitoring that allows for real time analysis and decision making.

7.2 Research Objectives

The overall project objective is to develop a strategy to increase profitability of irrigating sugarcane. The proposed research is broken down into the following sub objectives:

1. To research and present optimum combinations of irrigation design and scheduling strategies to maximise profitability and water and energy use efficiency.
2. To provide recommendations to improve design processes standards and norms.
3. Field test and refine a prototype continuous monitoring growth station in order to assess the potential value as a decision support mechanism for irrigation farmers.

7.3 Research Methodology

The SA*shed*, ZIM*shed* and/or CANESIM model will be used to simulate the yield and water use for various irrigation designs and management strategies. Runoff and deep percolation losses will also be estimated using these models. The yield and water use will then be used as input for the IRRIECON V2 model. Capital and operating cost of the irrigation system including the electricity and water tariffs as well as planting, fertilizer, herbicide, harvesting, haulage and transport costs are incorporated into the model to calculate the net margins. The net margins, electricity and water costs and water use, accounting for deep percolation and runoff, will then be used to analyse and assess the performance of the various strategies.

The irrigation systems to be considered are dragline sprinkler, drip and centre pivot systems as they are most prevalent in the South African sugarcane industry. Other systems such as automatic short furrow and the travelling big gun will also be considered due to increased popularity and potential role in the irrigation sector. The design and management strategies to be investigated are summarized in Table 7.3.1 below.

Table 7.3.1 Summary of design and management strategies to be investigated.

Management Strategies	
Deficit Strategies	• Test a number of deficit scheduling strategies that vary volume and frequency of applications as well as purposefully withholding water during specified periods in the season.
Design Strategies	
Sprinkler	• Nozzle diameter and sprinkler spacing selection: Impact on operating pressure, uniformity, watering capability, labour requirements, capital and operating costs. • Use of pumping hours in a day and practicality of not moving sprinklers in the dark.
Drip	• Spacing of laterals, emitters, emitter flow rates (in design context and implications of wetting patterns), clogging, surface versus subsurface drip, and cost of water treatment upstream of filters eg. for iron.
Pivot	• Minimising infiltration issues due to higher applications. Resulting from selecting length of pivots and cost optimisation. • Reducing evaporation from the soil surface in early crop stages.
Short Furrow	• Optimization of lateral length and pipe network.
Big Gun	• Travel lane spacing in relation to wind direction and speed, pipe sizing and impact on capital and operating costs.
All Systems	• Application volumes and frequency relating to capacity of system and therefore capital and operating costs. Including simulation for different electricity tariff structures to gauge economic benefit of using off-peak hours.

Different deficit strategies and potential for increasing profitability, water and energy use efficiency on sugarcane farms will be assessed. For all systems, the volume and frequency of application impacts on the capacity of the system. System capacity in turn is used to determine pipe and pump sizes which are directly correlated to the capital and operating costs. Furthermore, design capacity is interrelated with management practices and therefore has implications on the yield. Sample designs for the different irrigation systems and capacities will be assessed. Other issues relating specifically to a particular system are described in Table 7.3.1 and as above sample designs and strategies will be simulated and assessed in terms of profitability and water and energy use efficiency.

Selected continuous monitoring utilities, in the form of soil moisture monitoring tools and growth stations will be purchased from, for example, DFM Software Solutions and Eienaar Kennedy Besproeiing, respectively. The growth station monitors stalk elongation, temperature at canopy level and soil moisture status. These units will be installed in sugarcane fields, tested, potentially refined and assessed in terms of accuracy, appropriateness for sugarcane, ease of use, cost and value of data regarding increasing water and energy use efficiency and farm profitability.

7.4 Work Plan, Deliverables and Resources Required

Table 7.4.1 Milestones and timeframes for the project.

No	Milestone	Start Date	Completion Date
1	Installation of continuous monitoring systems.	30 May 2008	01 August 2008
2	Develop designs and obtain costs for the systems to be used for simulation.	15 July 2008	1 November 2008
3	Establish what deficit strategies are to be simulated.	15 July 2008	1 November 2008
4	Gather weather data for different climatic regions in SA.	15 July 2008	1 November 2008
5	Input all data into models and run simulations	1 November 2008	28 February 2009
6	Analysis and interpretation of simulation results	1 March 2009	31 May 2009

7	Adjustment and modification of designs and management strategy and re-simulate if necessary	1 May 2008	30 June 2009
8	Final analysis and interpretation of simulation results	30 June 2009	30 October 2009
9	On going analysis and interpretation of data from monitoring systems on weekly basis	30 May 2008	30 October 2009
10	Final MSc. Thesis Document	1 October 2009	20 December 2009

The milestones and timeframes for the project are outlined in Table 7.4.1. It is perceived that designers do not have the time to explore deviations from design norms in order to optimise irrigation designs. This is largely due to time and budget constraints established in the tender or contract. Attempts will be made to evaluate the standard design procedures and identify areas for improvements in the context of this project. If possible, recommendations for improved design procedures and thought processes in designing irrigation systems will be produced. The analysis and interpretation of simulation results is envisaged to reveal strategies both in irrigation systems design and irrigation deficit management which could increase the profitability and water and energy use efficiency on sugarcane farms. The success or failures of these strategies will also be documented and discussed. Furthermore, the degree of value added by the continuous monitoring systems in the context of a deficit strategy and improving water and energy use efficiency will be investigated.

In the summary the three main deliverables of the project are:

1. Presentation of optimum combinations of design and deficit strategies to maximise profitability and water and energy use efficiency.
2. Recommendations to improve design processes and design standards and norms.
3. Report on the value of continuous monitoring as a decision support mechanism for irrigation farmers.

The resources required to complete this project are listed in Table 7.4.2.

Table 7.4.2 Resources required to complete the project.

No.	Required Resources	Total Costs	Source
1	Simulation Software	-	SASRI / UKZN
2	Input Data – Weather records, irrigation, agronomic and mechanization costs	-	SASRI / UKZN / Irrigation Consultants / Farmers
3	Growth Stations	R 30 000	NRF via SASRI
4	Soil Water Monitoring Systems	R 30 000	SASRI
5	Operating Capital: Software utilities, subscriptions…	R 30 000	SASRI
6	Travel and Sundry Expenses	R10 000	SASRI

7.5 Ethical Considerations

Due to the nature of the work, the South African Sugarcane Research Institute (SASRI) has bound the author via a confidentiality agreement to prevent the exhibition of sensitive information to the public.

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