PERFORMANCE OF IRRIGATION AND WATER MANAGEMENT SYSTEMS IN THE LOWVELD OF ZIMBABWE

Neil Louis Lecler

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School of Bioresources Engineering and Environmental Hydrology
University of KwaZulu-Natal
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DISCLAIMER

I wish to certify that the work reported in this thesis is my own original and unaided work except where specific acknowledgement is made.

Signed:

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ABSTRACT

In order to assess the performance of water management approaches and irrigation systems used by the sugar industry in the Lowveld of Zimbabwe, a sugarcane yield and irrigation systems simulation model was developed. The model, named *ZIMsched 2.0*, was used to predict how field derived indices of irrigation systems performance, such as the coefficient of uniformity, CU, impacted on estimated recoverable crystal, ERC, yields and the water balance. This was done across a range of soil conditions, seasonal climates, irrigation system types and existing and refined irrigation scheduling strategies. Results of a verification study of the model showed an index of agreement, 'd', equal to 0.96 and a Pearson's correlation coefficient equal to 0.94, between observed and simulated yields of ERC, relative to a reference treatment. Application of the model showed the actual and also the potential performance of the different irrigation system hardware. Additional applications of the tools and information which were developed as a result of this research included an integrated economic assessment of peak irrigation system design specifications and associated deficit irrigation watering strategies. In an effort to translate theoretical water savings into practical realities a range of novel water management tools was also developed.

Most of the drip irrigation systems in the Lowveld were performing below potential due to excessive infield variations in applied water. The performance of furrow irrigation systems was limited by the large variations in water applied to individual furrows, and water applications that were, on average, excessively high relative to soil water holding characteristics. Simulations showed that sub-surface drip irrigation systems have a slight edge on other irrigation systems in terms of *potential* efficiency. Average water savings for drip irrigation systems ranged from approximately 2.2 to 1.5 Ml/ha relative to floppy irrigation systems, and 3.5 to 2.3 Ml/ha relative to typical furrow irrigation systems, depending on how water applications were scheduled. A major finding was that there was potential for the Lowveld sugar industry to use up to 30% less water per hectare on an annual basis if *ZIMsched*, a specialist spreadsheet-based irrigation scheduling tool developed during the course of the project, was used to derive more appropriate and system specific water management guidelines. However, simulations showed that with the more precise irrigation scheduling there could be a slight crop yield penalty when the distribution uniformity of applied water was poor.

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1. INTRODUCTION

One of the severe consequences of the 1991/2 drought in the south east Lowveld of Zimbabwe[1] was the near closure of the sugar industry there (Kaseke, 1998). The drought highlighted the importance of investigating the performance of the irrigation systems and water management strategies which were being used in the sugar industry. Building more dams to increase the level of available water storage may help to mitigate risk; however, water supply and demand interactions still remain and questions as to the optimal level of land development for the increased water storage would still need to be addressed. Therefore, whether or not more dams are, or can be, built, there is a need for increased insight into water supply and demand interactions, the selection and proper design, operation and maintenance of suitable types of irrigation systems, together with the implementation of well matched water management strategies, in order to ensure the long term viability of the Lowveld sugar industry. The Lowveld sugar industry is not unique in terms of these requirements. Most irrigated agricultural industries in southern Africa operate in a climate characterised by recurring droughts and increasing competition for limited water supplies. The need to assess irrigation and water management systems and strive for continuous improvement is, therefore, wide ranging.

The Lowveld sugar industry, which was the focus of this study, is situated around latitude 21°S, and has an average altitude of approximately 420 m.a.s.l. It is in a semi-arid region, with a climate characterised by very hot summers and short cold winters. Average annual rainfall is 561 mm. The rain falls mainly over the summer months of November to March and seasonal deviations from the mean are high, ranging from 467 mm below the long term average in 1991/2 to 481 mm above the long term mean in 1977/78. Annual A-pan equivalent evaporation averages 1990 mm and therefore a secure supply of irrigation water is essential for crops to flourish on the fertile paragneiss and basalt derived soils which cover much of the area. The Lowveld would not have been developed to its present state, including approximately 45 000 hectares of irrigated sugarcane, had it not been for the development of vast water resources, mainly on the Runde river and its major tributaries, the Chiredzi, Mutirikwi and Tokwe rivers. These rivers rise in the Highveld of Zimbabwe and pass through granite escarpments, which offer excellent dam sites. Water is conveyed from

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[1] Hereafter the south east Lowveld of Zimbabwe is referred to as 'the Lowveld'

these dams to the farming areas via a complex network of weirs, natural channels, gravity fed canals and pipelines, as well as inter-basin transfers (Clowes and Breakwell, 1998).

Many different types of irrigation and water management systems are being used by growers of sugarcane in the Lowveld. While traditionally the majority of sugarcane was grown using furrow irrigation or hand-moved overhead sprinkler irrigation, other types of irrigation systems, including centre pivots, floppy and drip irrigation systems were also attracting increasing interest and were being increasingly adopted. Descriptions of the various irrigation systems, in the context of the Lowveld, are given in the Zimbabwe Sugarcane Production Manual (Clowes and Breakwell, 1998). What is important to note is that each type of irrigation system has different characteristics which make it more or less suitable for application under different circumstances. Apart from manufacturer claims and informal anecdotes there has been little, if any, scientifically valid and/or verified information to date on the comparative performance of these different types of irrigation systems in the Lowveld environment. The water management approaches which were being used were also not necessarily well suited to all the different types of irrigation hardware or circumstances. Therefore, in order to improve performance and make rational decisions regarding the selection, upgrading and management of different types of irrigation systems, the following questions require objective answers:

- how effectively are the different types of irrigation systems being implemented and used?
- how effectively could the different systems be used? and
- under what circumstances would a change to another type of irrigation system, or water management approach, result in more effective use of resources and gains in productivity?

The research described in this thesis has been undertaken with the aim of developing the methods, tools and information to provide answers to these questions.

A purely experimental approach, whereby appropriate experiments and an intensive irrigation systems monitoring exercise is used to evaluate the performance of irrigation systems and water management approaches, was considered initially. However, such an approach was deemed inappropriate because the experiments and monitoring needed to evaluate a representative sample of the various irrigation systems, for different soils and water management strategies and over a range of relatively wet and dry seasons, would have been too time consuming, costly and disruptive to be practically feasible. In addition, there was a high risk that results from such experiments and monitoring would be significantly biased by extraneous factors (such as soil compaction, nematodes or diseases), operational problems and inconsistent management and baseline conditions over time. Therefore, an alternative and supplementary irrigation systems evaluation strategy was sought.

An extensive international literature exists on irrigation systems performance assessment and measurement. For example, Burt *et al.* (1997) and Purcell and Currey (2003) provide good syntheses of relevant literature and the vast array of irrigation system performance definitions. Those authors have also attempted to provide working frameworks for irrigation performance assessments. They highlight the premise that one of the most important aspects of the in-field performance of irrigation systems is the uniformity with which water is applied; however, they do not show how to relate irrigation uniformity to crop yields. De Juan *et al.* (1996) and Li (1998) have proposed approaches to relate the uniformity with which irrigation water is applied to crop yields. Their approaches are mathematically explicit representations which substantiate the premise that the uniformity of seasonal, or growth stage specific, applications of water affects crop yields. However, what was needed for this study was a process-based evaluation tool which accounts for the uniformity with which water is applied, but within the wider context of both the intra- and inter-seasonal dynamics of the soil, plant, atmosphere, continuum and the associated irrigation system and water management interactions.

Available process-based simulation tools for estimating irrigation crop water demand and associated sugarcane yield impacts are historically derived mainly from South African and Australian initiatives. In South Africa, these initiatives have resulted in the development of the *ACRU* agrohydrological model (Schulze, 1995; Lecler and Schulze, 1995), the CANEGRO model (Inman-Bamber, 1991; Inman-Bamber, 2000) and the CANESIM model (Singels *et al.*, 1998; Bezuidenhout and Singels, 2003). Australian initiatives have resulted in, for example, the development of APSIM-Sugarcane (McCown *et al.*, 1996; O'Leary, 2000). In the context of this study all these models, despite their respective strengths, also included substantial limitations. These limitations were related primarily to their representation of different types of irrigation systems, especially those regarding evaporation from a differentially wetted soil surface. This factor is important when comparing different types of irrigation systems, for example, overhead sprinkler irrigation to furrow irrigation. Furthermore, none of the models contained algorithms to account for non-uniform irrigation water applications. The APSIM, CANEGRO and CANESIM models were also reportedly weak in terms of adequately accounting for water stress effects (Singels *et al.*, 1998; Van Antwerpen, 2000; O'Leary, 2000). This was a major concern with regard to their potential for evaluating the effects of water management strategies. Work on relating water stress to sucrose yields as opposed to cane yields was also not well established and is still largely in the developmental phase (O'Leary, 2000; Singels and Bezuidenhout, 2002). Furthermore, access and support for most of these models was also a practical constraint to their development and application in the Lowveld.

The Food and Agricultural Organisation Paper No. 56 (FAO 56; Allen *et al.*, 1998) provides an additional well founded basis for estimating irrigation crop water requirements and associated crop yield impacts. It is also being promoted as an international standard. Furthermore, FAO 56 provides algorithms which specifically differentiate between the water budgets pertaining to different irrigation system (hardware) characteristics. However, the FAO 56 water budget is somewhat too simplified in terms of accounting for effective rainfall and deep percolation and it also does not distinguish between uniform and non-uniform irrigation water applications. Kassam and Smith (2001) have also reported that the relationships between water stress and crop yield, which are referred to in FAO 56 and are described in detail by Doorenbos and Kassam (1979), in many cases need to be adapted and refined.

Thus, in the author's view, there existed no wholly appropriate method with associated tools for evaluating the in-field performance of irrigation systems in the Lowveld of Zimbabwe. As discussed previously, a solely experimental approach, whilst theoretically possible, would have been impractical and would probably have yielded unreliable results. Typical irrigation performance indices such as those described, for example, by Burt *et al.* (1997) need to be translated into associated impacts on yield and water budgets (and hence profitability), and existing models and approaches had limitations in their ability to do this.

With this background, the hypothesis for this research was that new techniques and tools were needed in order to assess the in-field performance of the various irrigation and water management systems in the Lowveld. These did not necessarily have to be developed *ab initio,* but could be based on an appropriate synthesis and development/refinement of existing options/approaches. The overall approach which was proposed for the evaluation of irrigation and water management systems in the Lowveld is described as follows:

- Develop and/or apply tools and methods to record in-field irrigation systems performance data, such as the typical depth and distribution uniformity of applied water.
- Use the in-field performance data/information recorded or measured to calculate 'Irrigation Engineering Performance Indices' (IEPIs) of irrigation systems performance. An example of an IEPI is the coefficient of uniformity, CU, which gives an indication of the distribution uniformity of applied water (Burt *et al.*, 1997).
- Develop a sugarcane yield and irrigation systems simulation model to predict how the field-derived IEPIs impacted potential crop yields and water budgets, taking into consideration the characteristics of different irrigation systems and water management strategies prevailing in the Lowveld, in relation to various soil and climatic conditions.
- Verify and apply the sugarcane yield and irrigation systems simulation model in order to assess the typical performance of irrigation and water management systems prevalent in the Lowveld. Compare performance of the various systems under typical conditions in practice to the performance of the various irrigation systems if more optimal but achievable IEPIs and water management strategies were used.

This irrigation systems performance evaluation methodology was, in itself, unique. Furthermore, the research resulted in the synthesis and development of appropriate algorithms into an irrigation systems and crop yield simulation modelling tool with distinctive capabilities. Verification and subsequent application of this tool resulted in new information pertinent to the Lowveld and a systematic and scientific basis for assessing the performance of irrigation and water management systems. In addition, the research provided the basis for other developments and applications including, for example, a range of new and improved irrigation scheduling tools, methods and models for the assessment of irrigation system design and management strategies, and an assessment of alternative reference evaporation estimation and measurement options.

This study is structured as follows: In Chapter 2, factors which affect irrigation system performance are reviewed in order to provide a background to the description of methodologies, tools and data collection described in Chapter 3. The primary focus of Chapter 3 is to provide a description of the methods and model developed to translate in-field measurements of irrigation systems performance, such as the distribution and depth of applied water, into associated impacts on crop yields, water budgets and irrigation performance indices. In Chapter 4, results of a verification study of the simulation model are presented together with results from the application of the methodologies, in order to assess the performance of irrigation and water management systems prevalent in the Lowveld sugar industry. Other tools and applications developed in this study, for example, those for determining optimal irrigation system capacities and water management strategies and tailored irrigation scheduling charts as well as a spreadsheet-based, 'farmer friendly' irrigation scheduling tool, are presented in Chapter 5. Key implications to the sugar industry arising from information derived during this study together with appropriate recommendations are given in Chapter 6. The layout of the thesis is illustrated diagrammatically in Figure 1.1.

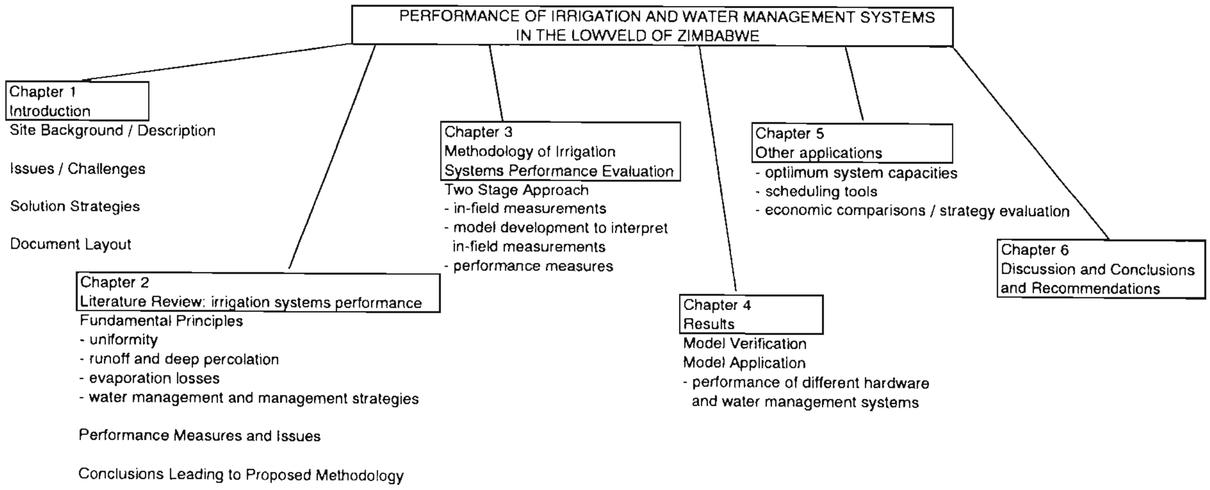


Figure 1.1 Thesis layout

2. IRRIGATION SYSTEMS PERFORMANCE: A PERSPECTIVE

With increasing demand and competition for finite water resources, the efficiency of water used in agriculture and the performance of irrigation and water management systems is coming under ever closer scrutiny. This was especially so in Zimbabwe, where irrigated agriculture has been reported to "*consume 80 % of the recorded water use*" at an average efficiency of only 60 % (GoZ, 1999). Often statements such as these can be grossly misinterpreted, leading to the widespread belief that much of the nation's future water requirements can be obtained by improving the efficiency with which water is used in irrigated agriculture. Judging by statements such as the one quoted below from Australia, such perceptions on irrigation efficiency are widespread.

> *"the use of the term 'irrigation efficiency' has caused an absolute dichotomy between the physical situation of the hydrologic system and the public's and government's perception of the physical nature of water management. These incorrect views are so pervasive and strongly held that billions of dollars have been proposed for investment to correct for low irrigation efficiencies with the general public actually believing that their water problems will be solved"* (Allen and Willardson, 1997, cited by Fairweather *et al.*, 2003)

One of the issues with irrigation efficiency is that unlike more traditional definitions of efficiency, for example, in thermodynamics, water which is not used efficiently is not necessarily lost or 'consumed', but often becomes available downstream. In addition, efficiencies are often quoted somewhat casually without losses being measured or defined accurately. All this contributes to a situation where there is much misunderstanding and misconception regarding irrigation systems performance (Clemmens, 2000). Part of this lack of understanding could be addressed if the fates of applied water at the field, farm and watershed scales could be better determined and understood. The concepts of irrigation efficiency and the goal of achieving sufficient water for the future are more complex than what is often perceived.

A perspective of irrigation systems performance is provided in this Chapter. This includes the water balance, irrigation uniformity, water management and a summary of various irrigation performance measures and frameworks. The information given provides the basis for the approach proposed to assess the in-field performance of irrigation and water management systems in the Lowveld, which is described in Chapter 3.

2.1 The Water Balance

At the heart of any consideration of irrigation systems performance is an irrigation water balance and the determination of the fate of the various fractions of the total irrigation water applied (Burt *et al.,* 1997; Clemmens, 2000; Fairweather *et al.*, 2003). In order to apply a water balance, the boundaries of the system need to be defined and the potential fates of different fractions need to be identified so that the various components can be measured or estimated. Once the components of the water balance are quantified, and the boundaries of the system defined, various performance indicators can be estimated. Performance will also vary depending on the spatial and time scale. The spatial scale can vary from a single irrigation application device (a syphon tube, a sprinkler, or a micro irrigation emitter) to an irrigation set (a single sprinkler lateral) to broader land scales (field, farm district, watershed). The time scale can vary from a single irrigation application, a part of the crop season, the irrigation season, a year or a period of years (Howell, 2003). In Figure 2.1 the various fractions of water applied which are involved in defining irrigation performance at the field level are illustrated.

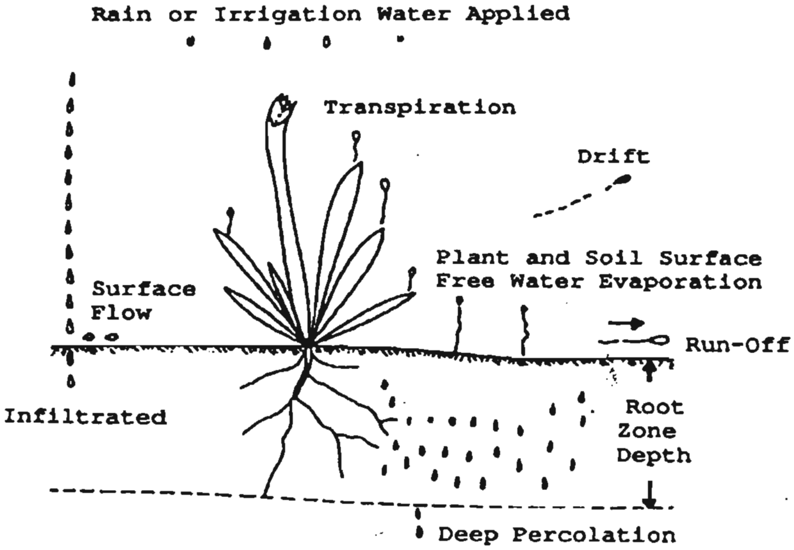


Figure 2.1 Various fates of water in the soil-plant-atmosphere system (ASCE, 1978)

The definitions of the components of the water balance, as indicated in Figure 2.1 are introduced in this section, based mainly on the paper of Burt *et al.* (1997). Details of methods and approaches which have been formulated to quantify these components of the water balance are provided in Chapter 3.

2.1.1 Evaporation

Evaporation is the conversion of water from liquid form to vapour form. In the context of this sub-section, only evaporation from free surfaces of water in transit, from plant surfaces that have intercepted irrigation water and from the soil surface interface are considered. Evaporation of any water that has passed through the plant, i.e. transpiration, is dealt with separately. Examples of water in transit are sprinkler droplets, surface ponding, puddles and surface runoff. The rate of evaporation is dependent on climatic conditions, water surface area and soil properties. Changing the frequency of application, the irrigation method used, or the amount of mulching and shading can modify the amount of evaporation that takes place. The amount of evaporation can also be influenced by advection. For example, a flowing canal can have higher evaporation per unit area than a large open body of water (Burt *et al.*, 1997). Losses of water due to evaporation are unlike losses of water due to runoff, deep percolation, seepage from canals and pipe leaks, all of which potentially feed back to downstream areas.

2.1.1.1 Spray evaporation, wind drift and plant interception

Evaporation of plant intercepted water together with evaporation of water sprayed from irrigation emitters and wind drift losses depend to a large degree on the irrigation system, the type of emitter and also the prevailing weather conditions. The contributions that spray evaporation and wind drift make towards water which is lost from the system are very difficult to assess accurately. The reason for this is that spray evaporation is accompanied by a largely compensating reduction in evaporation of water from the soil and plant because, after the evaporation of the irrigation spray, less energy is available to evaporate water from the soil and plant surfaces (Heermann *et al.*, 1990; Thompson *et al.,* 1993). In addition, it is reasonable to assume that the contribution of spray evaporation to the micro-climate during very hot conditions, namely a reduced vapour pressure deficit and lower temperature, may also result in enhanced photosynthesis, relative to a non-sprinkler irrigated crop (Tolk *et al.*, 1995). For these reasons, some daytime spray evaporation "loss" should actually be considered a beneficial water use.

In similar vein it is apparent that evaporation of water intercepted by crop canopies is not a major loss as it can contribute beneficially to evapotranspiration (Schnieder, 2000). Reported measurements of net water losses from spray evaporation and canopy intercepted water are typically less than 10% (McNaughton, 1981; Tolk *et al.*, 1995 and Thompson *et al.*, 1997).

2.1.1.2 Evaporation from the soil surface

Evaporation of water from exposed soil surfaces is the most significant component of "wasted" water in irrigation. This is so even though there are some small compensatory feedbacks to transpiration, whereby the relative contribution by transpiration is reduced when the soil surface is wet and increased when the soil surface is dry (Ritchie, 1971; Adams, *et al.*, 1976; Ritchie and Johnson, 1990). Overall total evaporation from the cropped surface increases when the soil surface is wetted (Burt *et al.*, 1997; Allen *et al.*, 1998).

Evaporation of water from the soil surface is dependent on the following factors.

- Agronomic practices: these can either inhibit or encourage evaporation from the soil surface. For example, surface mulching and narrower row spacing can reduce the component of water evaporated from the soil surface significantly.
- The type of irrigation system and its management: systems that apply water to a large proportion of the field's surface area will have large amounts of that applied water lost due to evaporation from the soil surface, especially if the system is managed such that the water is applied to the soil surface frequently in relatively small amounts, prior to the development of a full crop canopy. In the report by Allen *et al.* (1998), the evaporation from the soil surface when water is applied at intervals of four days, is shown to be nearly four times greater than the corresponding evaporation if the interval between irrigations is extended to 20 days. The fraction of the soil surface wetted by irrigation can vary significantly depending on the type of irrigation system and these variations can also have significant impacts on evaporation losses prior to the development of a full crop canopy. Typical values for the fraction of the soil surface wetted for different types of irrigation systems are given in Table 2.1.

Table 2.1 Common values of the fraction, f_w, of soil surface wetted by irrigation applications (after Allen *et al.*, 1998)

Irrigation System	**f_w**
Centre Pivot	1
Drip	0.0 - 0.4
Sprinkler, Floppy	1
Furrow	0.4...0.7

2.1.2 Transpiration

Transpiration is the evaporation process of liquid water within a plant through the stomata and plant surfaces into the air (Pereira and Allen, 1999). Transpiration takes place within the soil-plant-atmosphere continuum and, therefore, for transpiration to proceed at potential rates, the atmospheric demand for water must be balanced by the flow of water to the plant roots and from the root surfaces to the leaves. Crops predominantly lose water through their leaves, as a result of stomata which facilitate exchange of gases and water vapour. The vapour exchange with the atmosphere is controlled by stomatal aperture. Nearly all water taken up by a plant's root system is lost by transpiration and only a small fraction is used by the plant (Allen *et al.*, 1998). Transpiration is normally considered to be a beneficial water loss.

The rate of transpiration, like that of direct evaporation, depends on available energy supply, the vapour pressure gradient and wind. Transpiration is also dependent on soil water content, both excess and deficient, soil water salinity, crop management, plant physiology and growth stage (Burt *et al.*, 1997; Allen *et al.*, 1998; Pereira and Allen, 1999).

2.1.3 Evapotranspiration

Evapotranspiration (ET) is the combined process of evaporation from the soil and wet plant surfaces as well as the transpiration from the plant. Evaporation and transpiration occur simultaneously and there is no easy way to distinguish between the two processes. Normally the combined ET is estimated by soil water balance or aboveground energy balance methods (Burt *et al.*, 1997). When the crop is small, water is predominantly lost by soil water evaporation, but once the crop develops and especially when it completely covers the soil, transpiration becomes the dominant process (Allen *et al.*, 1998)

Soil, crop, irrigation (management) and atmospheric factors influence the ET process. Differences in resistance to transpiration, crop height, crop roughness, reflection, ground cover and rooting characteristics result in different ET levels in different crops under identical environmental conditions. Factors such as poor land fertility, poor fertilization, soil compaction, pests and diseases and poor soil management may also impact on crop development, and hence ET. The effect of the soil water content on ET is determined primarily by the water deficit and type of soil. On the other hand, too much water, which results in water logging, can also damage the roots and inhibit root water uptake by inhibiting respiration. Management decisions such as maintaining wet or dry soils, or stressed versus unstressed crops, will influence ET. For most irrigated crops part of ET is supplied by rainfall and part supplied by irrigation water (Burt *et al.*, 1997; Allen *et al.*,1998).

2.1.4 Infiltration

Infiltration is the process whereby rainfall, or irrigated water, enters the soil profile (Lorentz *et al.*, 1995). All the water that enters the soil surface is in transit. Some enters the plant through the root system immediately while another fraction, *viz.* that up to and even exceeding the so-called drained upper limit or field capacity, is temporarily stored as soil water in the root zone. This stored water may also enter the plant, be drawn to the soil surface and evaporate, or eventually move down below the root zone (Burt *et al.*, 1997).

2.1.5 Deep percolation

Deep percolation is the fraction of applied water that moves through the soil to below the root zone, at which stage it is then unavailable to the crop (Burt *et al.*, 1997). It can result from excess application of irrigation water and the non-uniformity of irrigation water over a field area. Some deep percolation is required to remove salts that are concentrated by evapotranspired irrigation water. Dependent on project or defined boundaries, deep percolation has the potential to be re-used downstream. However, it is often of much poorer quality than the original irrigation water (Clemmens, 2000).

2.1.6 Runoff

Runoff may be defined as the surface water that leaves an area's boundary in liquid form. For a given field, runoff is not usually considered a beneficial water use. However, runoff is often captured and re-used elsewhere, or even on the same field. Runoff does, however, often pick up sediments and agricultural chemicals and can become degraded in quality (Clemmens, 2000). Surface water that is collected from an area's boundary and is reapplied within the region is not considered as runoff in water balance and efficiency considerations (Burt *et al.*, 1997).

2.1.7 Diverted water versus consumed water

There is a vast difference between water diverted for use by irrigation and the amount of water actually "used", "consumed" or removed from the system by irrigation.

2.1.7.1 Diverted water

Diverted water includes all water that is diverted from a river or pumped from a well for use in irrigation. Many references to irrigation efficiencies imply a relationship between water stored in the crop's root zone and *diverted* water. With diverted water in the denominator, quoted efficiencies in the order of 50% or lower are common. However, with these so-called "*inefficient*" irrigation schemes, a large proportion of the diverted water returns to the system as return flows. The reason for this is that the greatest causes of irrigation inefficiencies are water leaving/"lost" from the root zone due to deep percolation and/or surface runoff (Schulze and Dunsmore, 1984; Heerman *et al.*, 1990). Thus, although a great proportion of a catchment's water may be *diverted* for use in irrigation, the amount of water actually consumed, or lost from the system, may be far less. Often improvements in field-level irrigation application efficiency result in only small changes to the amount of water available in the system as a whole. This is so because the amount of water consumed remains little changed between efficient and inefficient irrigations. Nevertheless, although non-consumptive fractions of diverted water can often be re-applied elsewhere, this water will likely be degraded in terms of quality (Burt *et al.*, 1997)

2.1.7.2 Consumed water

In irrigated agriculture, water *consumed* or lost from the system is the water that evaporates into the atmosphere from:

- the plant,
- the soil, and
- the supply system, or
- water which is removed in harvested plant tissues, for example, in watermelon or tomatoes (Burt *et al.*, 1997).

This evaporated (or removed) water is far less variable than diverted water and has relatively little effect on the irrigation efficiencies that are so often reported.

An understanding of the hydrological water balance is fundamental to assessing irrigation performance. If the components of the water balance can be quantified, various performance indices can be derived. Also rational decisions can be made regarding the appropriateness of water uses and their effects on crop production and the environment (Clemmens and Burt, 1997). The variability of water applications at the field scale can impact on the overall field water balance. Therefore, the uniformity of irrigation water applications plays an important role in irrigation systems performance.

2.2 Uniformity of Irrigation Water Applications

Irrigation uniformity refers to the evenness of irrigation water applications. The uniformity of the applied water can have a significant effect on the performance of irrigation systems (Pitts *et al.*, 1996; Clemmens, 2000; Howell, 2003). Irrigation uniformity is a characteristic of the type of irrigation system, and also the standard to which a given system has been designed, and is operated and maintained. It can also be affected by soil infiltration characteristics and land preparation. It can have significant effects on irrigation performance because even if the timing and average magnitude of water applications is well matched to crop water demand and soil water storage capacity, non-uniformity results in some areas receiving relatively higher water applications and other areas receiving relatively lower water applications. Excessive runoff and deep percolation losses are likely on the areas receiving the relatively higher water applications and reductions in crop yield can be expected on the areas receiving the relatively lower water applications. Depending on how well an area is drained, reductions in crop yields can also occur on the areas receiving excess water. The influence that irrigation uniformity can have on crop yields is highlighted by the results shown in Table 2.2.

Table 2.2 Crop sensitivity to irrigation application uniformities, where a coefficient of uniformity, CU, equal to 100 indicates perfect uniformity (after Reinders, 1996)

Coefficient of Uniformity (CU)	**Yield (t/ha)**	
	Maize	**Bananas**
60	4.2	23.4
72	6.0	33.6
80	6.8	38.3

A planning model to determine optimal irrigation strategies which takes into account the effect of the non-uniformity of irrigation water applications on crop yield has been described by de Juan *et al.* (1996). However, a major constraint of de Juan *et al.*'s (1996) model in terms of potential application for evaluating irrigation and water management systems performance in a given environment, is that the water balance was somewhat over-simplified.

In de Juan *et al.*'s (1996) approach, an initial sub-model was used to estimate irrigation water requirements associated with a given (inputed) ET deficit. Using a simple water budget in this sub-model, application of irrigation water was assumed to return the soil to field capacity at the selected ET deficit. The sub-model thus determined an irrigation schedule and translated the selected ET deficit into an associated seasonal irrigation application requirement. The ET deficit was related to a yield impact using the production function of Stewart *et al.* (1977) and yield response factors proposed by Doorenbos and Kassam (1979). Next, a deficit coefficient (C_d) was defined as the ratio between the average deficit depth and the required depth, as illustrated in Figure 2.2. Then, assuming the reduction in ET equates to the soil water deficit (an example of the over-simplification of the water balance), C_d was related to yield, dependent on the proportion of the crop's water requirement which was supplied by irrigation, as opposed to rainfall. C_d was determined from the mathematical properties of an assumed distribution function describing the application of irrigation water. This enabled C_d to be determined for a given uniformity and depth of irrigation application relative to the deficit depth. Thus de Juan *et al.* (1996) were able to investigate relationships between a theoretical seasonal crop water requirement, the amount of water applied relative to this theoretical requirement, the uniformity of the applied water and an associated crop yield.

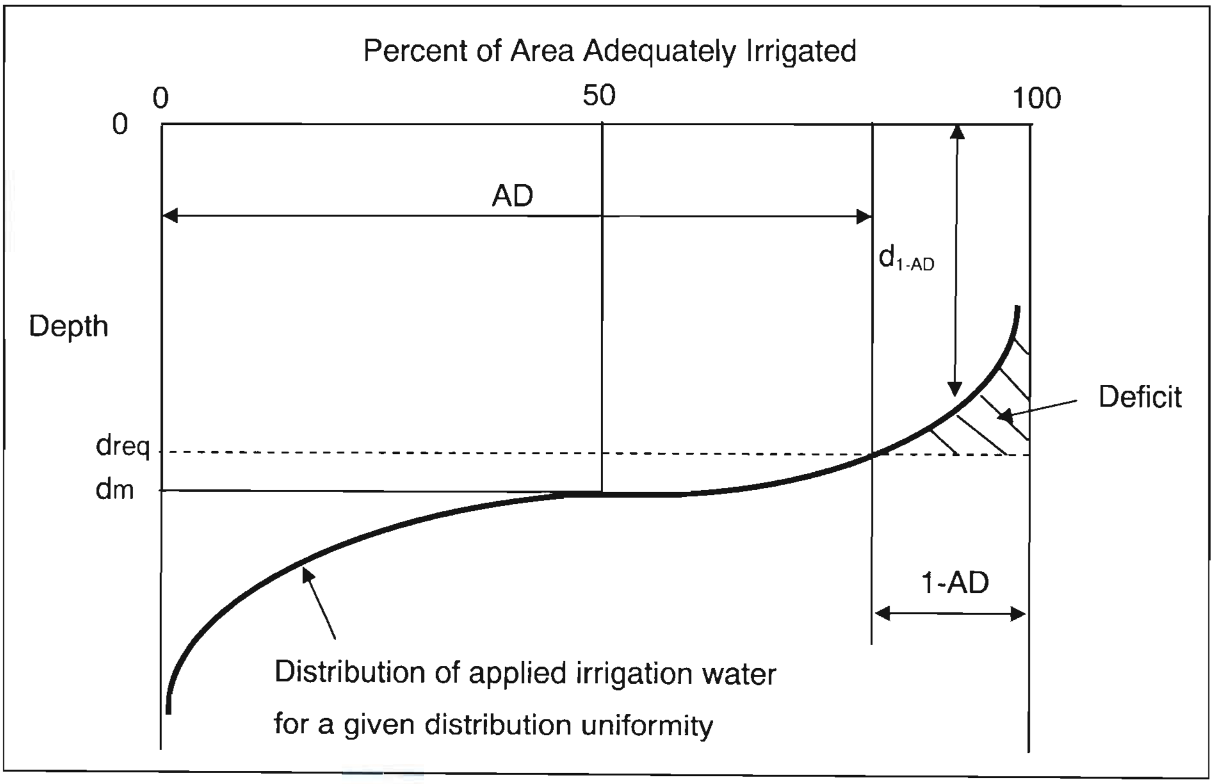


Figure 2.2 A normal distribution for applied irrigation depths with a certain distribution uniformity. The variable d_{req}, is the depth required to replace the water deficit in the soil, d_m is the average depth of infiltrated water, AD represents the area receiving adequate water, $d_{1\text{-}AD}$ is the average deficit depth of water in the under-irrigated area (1-AD), the shaded 'Deficit' area is the total soil water deficit (after de Juan *et al.*, 1996)

Li (1998) presented a similar approach of relating crop yield to irrigation uniformity. However, Li (1998) used the model proposed by Jensen (1968) to relate crop yield to water deficits at particular growth stages to try and better represent water stress effects. The water budget of Li's (1998) is also simplified, especially with regard to the relationship of the soil water deficit to the ET deficit and the proportion of the crop water requirements which are satisfied by rainfall.

Mantovani *et al.* (1995) not only described the development of a model to relate yield to irrigation amount and uniformity, which is apparently the foundation of the approaches of both de Juan *et al.* (1996) and Li (1998), but also compared this approach to results obtained by running a more process-representative, but data intensive crop growth model, namely CERES-Maize (Jones and Kiniry, 1986). The inclusion of irrigation application uniformity in the growth model simulations was achieved by running the CERES-Maize simulation model to simulate multiple units, with each unit receiving a different irrigation application amount dependent on irrigation uniformity. A comparison between the simple model and the CERES-Maize model adapted to simulate spatial variability in applied water showed similar trends but differences in absolute values (Mantovani *et al.*, 1995). The multiple water budgets approach has the advantage of better representing the dynamics of the soil water balance.

Whilst the importance of irrigation uniformity in determining the optimal irrigation application amount has been widely recognised (see also, Solomon, 1984; Letey, 1985; Clemmens, 1991; Burt *et al.*, 1997; Ascough, 2001), in a review of literature related to sugarcane and irrigation (including Inman-Bamber *et al.*, 1993; McGlinchey and Inman-Bamber, 1996; Robertson *et al.*, 1997; Singels *et al.*, 1999; Magwenzi, 2000; Inman-Bamber *et al.*, 2001; Ascough and Kiker, 2002) no explicit relationship between irrigation uniformity and crop yields was found.

2.3 Water Management

Managers of irrigation systems, by the appropriateness of their actions and/or instructions often contribute the most to poor or good irrigation systems performance. Two very important performance characteristics of an irrigation system which are largely determined by management and/or design decisions are the amount of water applied at each irrigation application and the rate at which water is applied.

2.3.1 Amount and rate of water applied

For most types of irrigation system the amount of water applied at each irrigation application can be varied between reasonable limits in relation to soil and crop characteristics. However, for most furrow irrigation systems, application amounts are relatively inflexible, being largely dictated by layouts and soil infiltration characteristics (Kruger, 1998). With many furrow irrigation systems it can be very difficult to control the magnitude and the evenness of water applications, especially when trying to apply relatively small amounts of water per application, e.g. < 40 mm. When the amount of water applied per irrigation application is not well matched to soil water holding characteristics, performance will be poor because of either:

- excessive crop stressing if the soil is depleted to a level coinciding with larger irrigation applications, or
- inefficient irrigation with excessive runoff and deep percolation losses and associated drainage problems if large irrigation applications are applied at relatively low soil water depletion levels in order to avoid excessive drying of the soil and crop water stress.

The effects of irrigation uniformity on system performance also depend on the average amount of water applied at an irrigation application. Poor application uniformities may not result in large reductions in crop yields if the average amount of water applied, d_m, is so large that even the areas receiving relative lower amounts of water, (1-AD), receive water sufficient to prevent crop water stress (cf Figure 2.2). However, depending on the drainage characteristics of a field, there will likely be problems on the areas receiving excess irrigation water. Problems likely to arise include: poor root aeration, excessive runoff and deep percolation, a raised water table and the associated development of salinity problems.

If the rate of water applied is not well matched to soil water infiltration characteristics, excessive runoff and possibly erosion will occur. Poorly designed centre pivots are prone to having excessive runoff problems towards the outer towers because of high application rates at the outer ends. Some soils, especially those with high silt content, are very prone to surface capping, exacerbated by the impact of water droplets. As a result of this potential runoff issue, specialist apparatus, *viz.* the Reinders infiltration meter (Reinders and Louw, 1984) has been developed to assess soil infiltration rates under sprinkler irrigation and it is important for designers to utilise such apparatus for determining centre pivot specifications.

2.3.2 Runoff and deep percolation

Excessive runoff and deep percolation losses are often the greatest contributors to low field-level irrigation application efficiencies, and result largely from poor water management and/or system design. A major problem is incorrect matching of irrigation water applications to crop water demands. Runoff and deep percolation can be reduced considerably by appropriate irrigation scheduling, i.e. ensuring that water is applied in quantities not exceeding the soil water storage capacity at a time before undesirable crop stress occurs. The type of irrigation system, its uniformity and the irrigation strategy being followed can also have a significant impact on these losses. Runoff and deep percolation losses from a field do, however, return to the system as return flows, and can become available for re-use, especially to areas downstream of the field. However, to reiterate, the impacts of the return flows on *water quality* needs to be carefully monitored and can be a cause of major salinity problems.

2.3.3 Irrigation strategy

The irrigation *strategy* adopted by management can also have a major effect on irrigation systems performance. Irrigation water losses, including those due to spray evaporation, wind drift, evaporation from the soil surface, surface runoff and deep percolation (especially if uniformities are poor) increase with increasing irrigation water application. In addition, with increasing water application, the effective use of rainfall is likely to diminish as the probability of rain falling on an already wet soil is high. The net result is that if a plot of crop yield versus actual transpiration and applied irrigation water is drawn, the yield versus applied irrigation water line will curve away from the yield versus transpiration line as shown in Figure 2.3. This is one of the reasons why the application of the large amounts of irrigation water needed to maximise yield seldom results in optimum system performance and may not realise maximum economic return. Adjusting the irrigation strategy is often the best way of ensuring gains in irrigation systems performance and overall profitability (English and Raja, 1996; Boggess and Ritchie, 1988; MacRobert and Savage, 1998; Lecler, 2001).

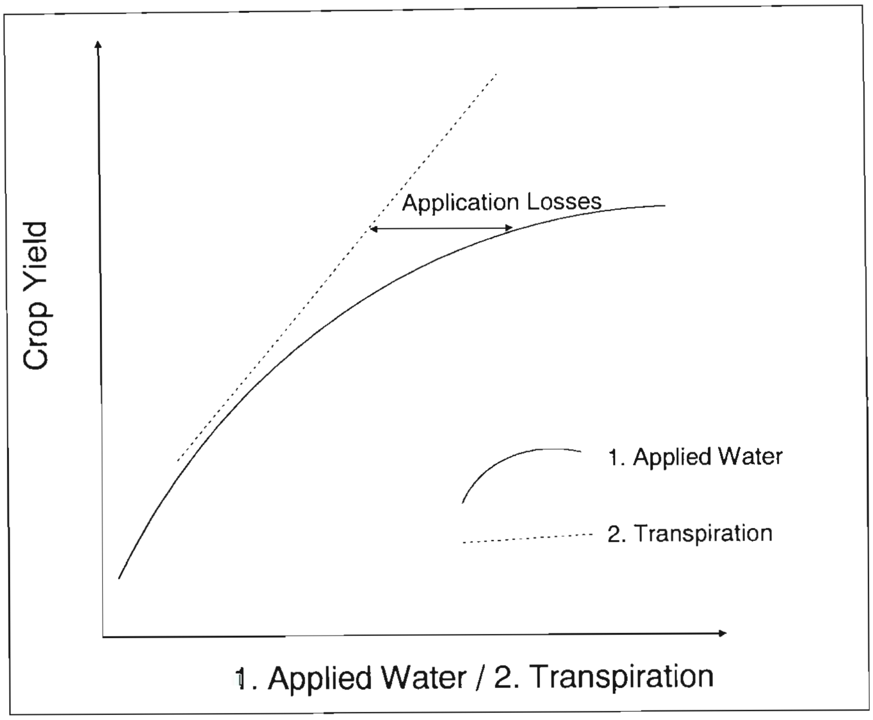


Figure 2.3 General form of a crop production function (after English, 1990)

2.3.4 Deficit irrigation: some concepts (after English, 1990; Lecler, 1998)

Deficit irrigation is an optimising strategy whereby *net returns*, as opposed to crop yields, are maximised. This is often achieved by reducing the amount of irrigation water applied to a crop to a level that results in some yield reduction caused by water stress, i.e. deliberate under-irrigation. The fundamental goals of deficit irrigation are:

- to reduce water losses, and
- maximise profits through a reduction in capital and operating costs.

Recognition of the following points is fundamental to an understanding of deficit irrigation, *viz.*

- that water losses increase as the number and the magnitude of irrigation water applications increase,
- that the application of irrigation water is costly, in terms of both direct costs but more importantly in terms of *lost opportunities*, and
- that the determination of an optimal irrigation strategy is very dependent on water supply and demand interactions, particularly on whether a shortage of water or a shortage of land is the factor limiting production.

Irrigation water application costs are related to actual costs of water, interest on capital equipment, energy, labour and also opportunity costs, especially if water is limited. When water, as opposed to land, is limited the water saved by reducing irrigation applications per hectare may be used to irrigate additional land either immediately or during droughts after having been saved or "banked" in storage works. Whilst per hectare yields may be lower, the potential to irrigate additional land can result in a significant increase in total income over a given production period. The potential income from the irrigation of the additional land is an opportunity cost of water which can be substantial. If land is limited, the question is then simplified to what irrigation application amount results in the maximum difference between irrigation application costs and yield related returns.

In Figure 2.4, two cost functions and a revenue function are shown. The revenue function has the same shape as the yield versus applied water curve (cf. Figure 2.3), as revenue is simply the product of yield and crop price. The lower limit of the cost functions represents fixed field costs, for example, capital costs, crop insurance, fixed costs of irrigation, planting, tillage, chemical use and harvesting. The slope of the cost functions represents the marginal variable field costs of production, for example, pumping costs, water costs and yield related costs, for example harvesting and haulage. The upper limit of the cost functions represents the maximum water delivery capacity of the two different irrigation systems. The maximum water delivery capacity of an irrigation system is a hardware limitation that can have very significant cost and flexibility implications. For example, for the two systems shown in Figure 2.4, the system with the smaller capacity, i.e. System 2, does not have sufficient capacity to irrigate for maximum crop yields. However, the implications of lower capital and operating costs are such that the net returns are nearly double those attainable with the larger system, i.e. System 1, even though the attained crop yields are lower.

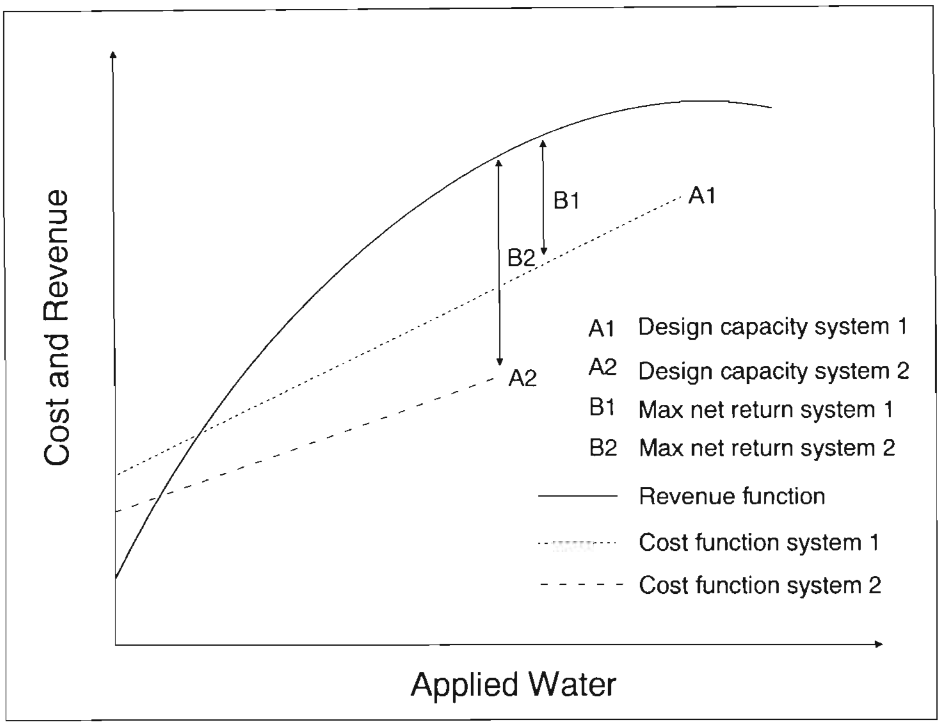


Figure 2.4 Cost and revenue functions (after English, 1990)

Given that the relationships given in Figure 2.4 were known precisely, the selection of an optimum strategy for either land- or water-limited production could be achieved. The analytical framework for such an exercise has been well documented by English (1990). However, whilst it is fairly easy to determine the cost function, the following two questions remain.

- Is water limiting production or is land limiting production, and does this change over time, *viz.* within a season or over a period of years?
- How can the information relating yield to irrigation applications be determined?

Therefore, the adoption of deficit irrigation requires, at minimum, knowledge of crop ET, crop response to water deficits, including critical growth periods and the economic impact of yield reduction strategies (Perreira *et al.*, 2002). In addition, knowledge of the associated interaction of irrigation water demand and supply is critical (Lecler, 1998).

2.4 Irrigation Performance Measures

A plethora of irrigation performance indicators, usually termed efficiencies, have been defined in the literature. A comprehensive overview of the evolution of efficiency and irrigation performance concepts is given by Fairweather *et al.* (2003), who referred mainly to Solomon (1984), Bos and Wolters (1989) and Clemmens and Solomon (1997). Often the same term, for example, 'irrigation efficiency', has meant different things to different researchers or different segments of the irrigation profession. In an attempt to contribute to some order to the profusion of terms and concepts, the *American Society of Civil Engineers Task Committee on Defining Irrigation Efficiency and Uniformity* (ASCE-TC) undertook to standardise the definitions. This collaborative effort is contained in Burt *et al.* (1997) and was proposed as the new industry standard on the correct definitions of irrigation performance criteria, relating primarily to engineering aspects of performance. There have also been other initiatives which were more inclusive and included, *inter alia*, crop productivity impacts. For example, a four-stage project, titled "*Determining a Framework, Terms and Definitions for Water Use Efficiency in Irrigation*", was undertaken to make progress on the development of consistent irrigation standards throughout Australia (Purcell and Currey, 2003). A framework for water use efficiency and water productivity was also proposed by Smith (2000). Taken together, these initiatives provide incisive perspectives of irrigation performance assessment, measures and indices and they are, therefore, summarised and discussed in the section which follows.

2.4.1 Irrigation efficiency

Efficiency is generally associated with a transformation of inputs to outputs and can be expressed as follows (Smith, 2000):

$$\text{Efficiency} = \frac{\text{output}}{\text{input}} \text{ x } 100\% \qquad \text{Eq. 2.1}$$

With reference to defined system boundaries, Burt *et al.* (1997) define irrigation efficiency, IE, according to the following relationship:

$$\mathrm{IE} = \frac{\text{volume of irrigation water beneficially used}}{(\text{volume of irrigation water applied} - \Delta \text{ storage of irrigation water})} \text{ x } 100\% \qquad \text{Eq. 2.2}$$

The concept of beneficial water use is not straightforward. It can have many different interpretations and these different interpretations influence seasonal irrigation efficiency. A common mistake, for example, is the double counting of beneficial uses. An example of double counting is water that is applied for frost protection, which is later available to the crop for evapotranspiration (Burt *et al.*, 1997). Typically, beneficial water use may include the required evapotranspiration and the leaching water required for salinity management (Howell, 2003). However, evaporation from the soil surface is not necessarily beneficial and a field that requires a relatively higher leaching fraction in comparison to another field will only be differentiated from the field requiring a lower leaching fraction, if the leaching fraction is excluded from the so-called beneficial water used.

2.4.2 Irrigation consumptive use coefficient

It was noted by Solomon and Burt (1999) that IE is often misinterpreted from the point of view that (100 - IE)% of applied irrigation water can be conserved or reallocated. This misconception is what, more likely than not, prompted Burt *et al.* (1997) to include the concept of the irrigation consumptive use coefficient (ICUC). The ICUC is defined as follows:

$$\mathrm{ICUC} = \frac{\text{volume of irrigation water consumptively used}}{(\text{volume of irrigation water applied} - \Delta \text{ storage of irrigation water})} \text{ x } 100\% \qquad \text{Eq. 2.3}$$

The ICUC can be applied at a field, project, district or farm scale and has sometimes been incorrectly used to estimate IE. Burt *et al.* (1997) also stress that while water used for salt removal or drainage water may have quality problems that make them unusable, this does not, however, mean that they have been consumed, as they could be re-used after treatment. The relationship between ICUC and IE, as defined by Burt *et al.* (1997), is shown in Figure 2.5.

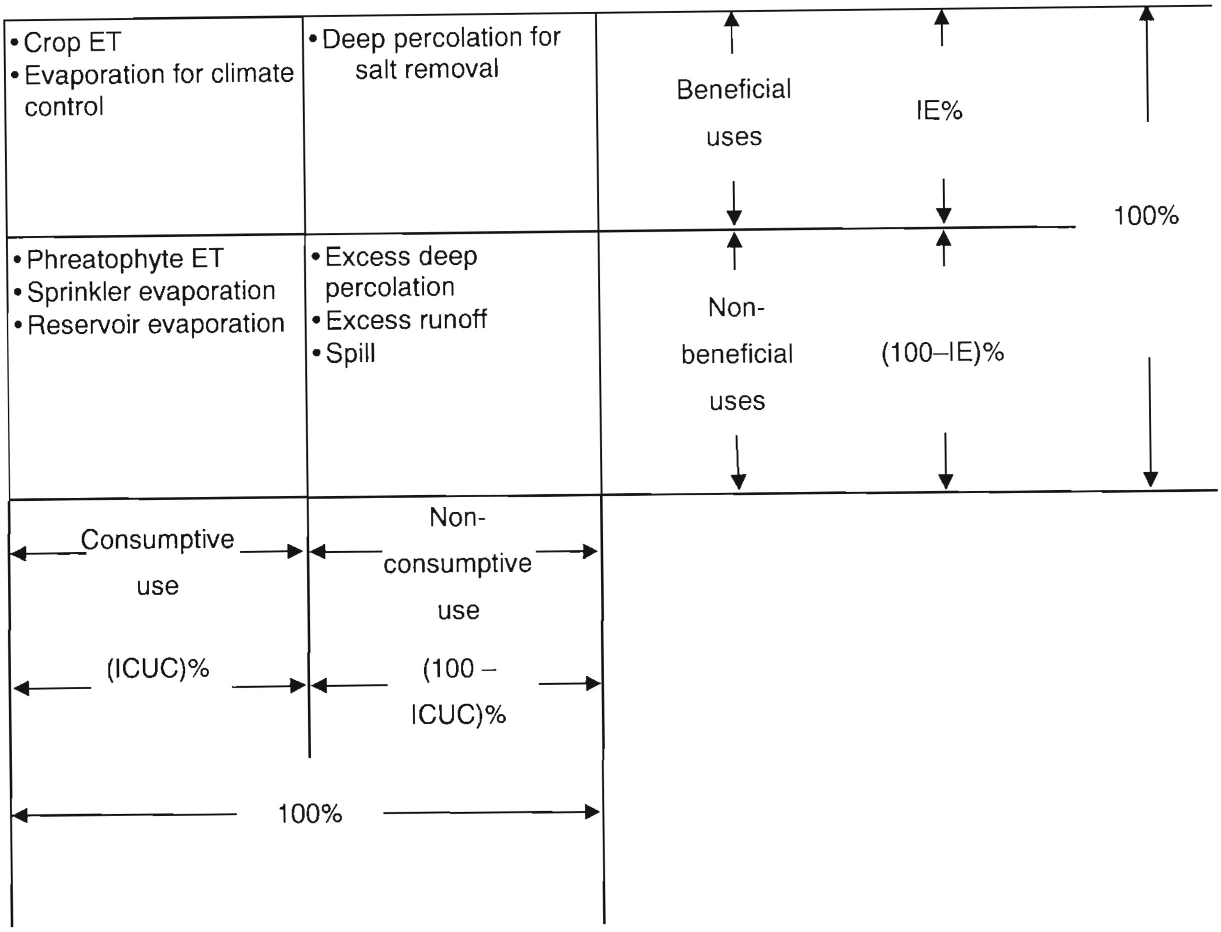


Figure 2.5 The relationship between IE and ICUC which highlights the division between consumptive and non-consumptive uses as distinct from the division between beneficial and non-beneficial uses (after Burt *et al.*, 1997)

2.4.3 Irrigation sagacity

Whilst irrigation efficiency (IE) can be a useful term for comparison of irrigation water use, from a societal and grower's perspective it can be incomplete. The reason for this is that other benefits may accrue to society or to the environment from water used for irrigation and hence reasonable uses need to be included in the numerator (Burt *et al.*, 1997). These concepts for reasonable use resulted in a new term, *viz.* the irrigation sagacity (IS), this being defined as a better measure of prudent water use. Irrigation sagacity, IS, is defined as follows (Burt *et al.*, 1997):

$$IS = \frac{\text{volume of irrigation water beneficially and / or reasonably used}}{(\text{volume of irrigation water applied} - \Delta \text{ storage of irrigation water})} \times 100\% \qquad \text{Eq. 2.4}$$

Burt *et al.* (1997) do not suggest that IS be used in place of IE, but that the two should be given with clear definitions so that the appropriateness of the ratio can be judged.

The relationship between IE and IS, with examples of various reasonable but non-beneficial water uses as defined by Burt *et al.*(1997), is shown in Figure 2.6.

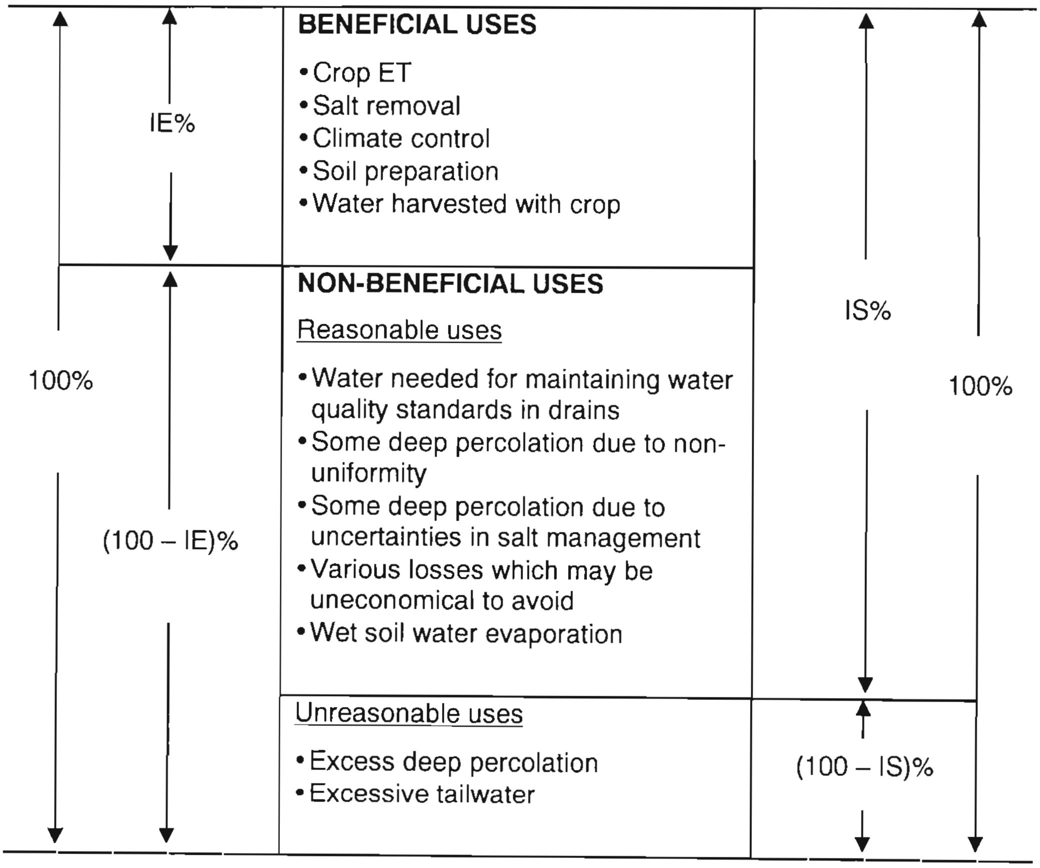


Figure 2.6 The relationship between irrigation efficiency (IE) and irrigation sagacity (IS). IS was introduced as a better measure of prudent water use (after Burt *et al.*, 1997)

2.4.4 Application efficiency

The efficiency terms IE, IS and ICUC are difficult to evaluate rapidly and require a detailed quantification of the water balance components. Application efficiency, AE, is based on the concept of meeting a target application depth for an irrigation event. This allows judgmental decisions, such as beneficial or reasonable uses, to be separated from how well the irrigation system is able to meet a target depth of application. The AE term applies only to a single irrigation event. The target depth chosen can be the soil moisture deficit, SMD, or a smaller amount to supplement potential rainfall, or it could contain a desired depth of reclamation water, or it may be a requirement for leaching of salts (Burt *et al.*, 1997). The definition of AE for a single event is thus:

$$AE = \frac{\text{average depth of irrigation water contributing to target}}{\text{average depth of irrigation water applied}} \times 100\% \qquad \text{Eq. 2.5}$$

Equation 2.5 replaces an earlier definition of AE given in Equation 2.6.

$$AE = \frac{\text{average depth of irrigation water stored in the root zone}}{\text{average depth of irrigation water applied}} \times 100\% \qquad \text{Eq. 2.6}$$

The main difference between Equations 2.5 and 2.6 is that Equation 2.5 allows for multiple beneficial uses, for example, a portion of spray evaporation and plant intercepted water which can contribute beneficially to ET (Schneider, 2000).

Implicit in the definition of AE is the assumption that the target depth is uniform across the field and that no time period needs to be specified, as it accounts for a single event only. If the requirement is just equal to all the expected beneficial uses, AE can be used to approximate IE (Burt *et al.*, 1997).

2.4.5 Irrigation uniformity measures

Depending on the type of irrigation system, different indices have become routinely used as the standard means of describing irrigation uniformity. The indices used in the Standards of the American Society of Agricultural Engineers (ASAE EP419.1, 1998a; ASAE S436.1, 1998b; ASAE EP458, 1998c) are described here together with the recommendations of the ASCE-TC (Burt *et al.*, 1997).

2.4.5.1 Christiansen's coefficient of uniformity (CU)

Christiansen (1942) proposed a coefficient of uniformity mainly intended for sprinkler systems. The coefficient of uniformity is, therefore, most often used to describe the uniformity of overhead sprinkler, floppy and centre pivot irrigation systems (e.g. Pitts *et al.* 1996; Magwenzi, 2000; Ascough and Kiker, 2002). Coefficients of uniformity are defined according to Equations 2.7 and 2.8.

$$CU = 100(1-\sum|D_s - D_m|/\sum D_s) \qquad \text{Eq. 2.7}$$

$$CU_{cp} = 100(1 - \sum S_s|D_s-(\sum(D_sS_s) / \sum S_s)| / \sum(D_sS_s)) \qquad \text{Eq. 2.8}$$

where

CU = Christiansen's coefficient of uniformity

CU_{cp} = Heermann and Hein coefficient of uniformity for centre pivots

D_s = catch can depth of application (mm)

D_m = mean catch can depth (mm)

S_s = distance from centre of pivot to catch can (m).

The numerical significance of the CU is illustrated in Figure 2.5, where the cumulative water application distributions for CU values of 80 and 88 for two floppy irrigation systems are shown. By definition, half of the field area receives less than the average application depth and half of the field area receives more than the average application depth. Lower CU values result in greater deviations from the average application depth as illustrated by the greater extremes in water application depth for a CU of 80 versus a CU of 88.

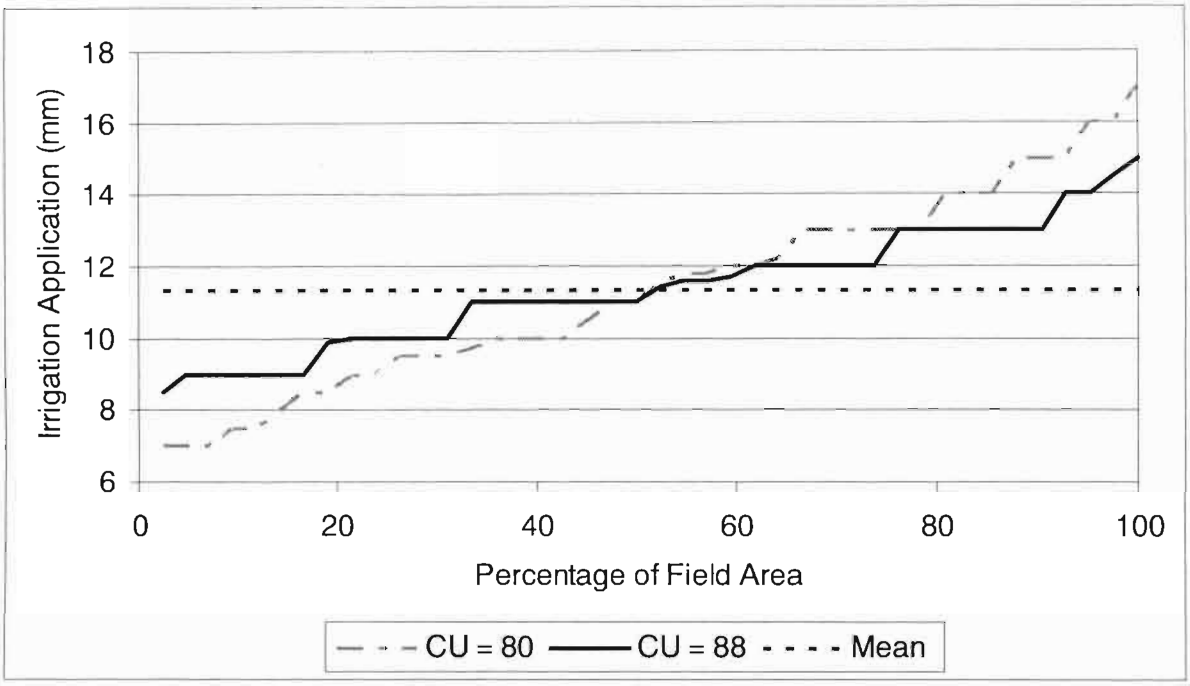


Figure 2.7 Comparison of different CU values for floppy irrigation systems evaluated by the Zimbabwe Sugar Associations's Mobile Irrigation Performance Evaluation Unit, MIPU (after Griffiths, 2002)

2.4.5.2 Statistical uniformity (SU)

The statistical uniformity, SU, is usually used to represent 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). It is defined according to Equation 2.9, *viz.*

$$SU = 100(1-CV) \qquad \text{Eq. 2.9}$$

where

SU = statistical uniformity

CV = coefficient of variation of applied water in a representative sample

= standard deviation of the sample divided by the sample mean.

2.4.5.3 Distribution uniformity (DU)

Low quarter distribution uniformity, DU_{lq}, is the term most often used to describe the uniformity of surface irrigation systems (Howell, 2003). The low quarter distribution uniformity is defined according to Equation 2.10, *viz.*

$DU_{lq} = (D_{zq} / D_z) \times 100$ Eq. 2.10

where

DU_{lq} = low quarter distribution uniformity

D_{zq} = average depth of water infiltrated in the quarter of the area which received the least infiltrated depth (mm)

D_z = average depth of water infiltrated (mm).

The DU_{lq} and CU coefficients are mathematically interrelated. Warrick (1983) has presented relationships between different uniformity terms for normal, log-normal, uniform, specialised power, beta and gamma-distributions of applied irrigation water. Assuming a normal distribution, the relationships between CU, SU and DU_{lq} are:

$DU_{lq} = 100 - 1.59\,(100\text{-}CU)$ Eq. 2.11

$DU_{lq} = 100 - 1.27\,(100\text{-}SU)$ Eq. 2.12

These relationships are shown quantitatively for a range of CU values in Table 2.3. It is clear that of the three performance measures, DU_{lq} is the most stringent. Clemmens and Solomon (1997) note that the normal distribution represents many irrigation component distributions.

Table 2.3 Relationships between uniformity measurements for normally distributed irrigation water applications derived using Equations 2.11 and 2.12.

Christiansen's Coefficient of Uniformity (CU)	**Statistical Uniformity (SU)**	**Distribution Uniformity (DU_{lq})**
97	96	95
90	88	84
83	80	74
80	76	69
73	67	59
67	59	48

2.4.5.4 Global distribution uniformity

Burt *et al.* (1997) note that from the perspective of the crop it is the field-wide uniformity of irrigation water applications which is important. In surface irrigated fields, variations in soil-infiltration characteristics along the length of run, but also transversely from furrow to furrow, influence the global uniformity, as do variations in inflow from furrow to furrow. Similarly, non-uniformity in the distribution of water applied in a sprinkler field is not only dependent on the wetting pattern of adjacent sprinklers, but also on the overall pressure variation in the field laterals as well as the variation in nozzle wear and sizes throughout the field. Thus there are, in principle, many causes of non-uniformity. Furthermore, the scale of measurement is also important.

Burt *et al.* (1997) propose that while it is not practical to measure field-wide uniformity distribution of applied irrigation water, it is feasible to study the uniformity of the individual components and then to combine effects in such a way as to get a good estimate of the global uniformity. Component distribution uniformities (DUs) should only be combined through proper statistically valid techniques. Burt *el al.* (1997) thus maintain that the lack of a statistical basis for CU, precludes combining results for sprinkler overlap, with some description of the pressure variation in the laterals. This supports their rationale for proposing wider adoption of DU in favour of CU as a standard uniformity descriptor.

In order for DU to be applied universally to all crops, the concepts of the totality of field elements and elements of scale need to be incorporated. An element is defined as the smallest area in the field that requires water and within which the variation in distributed water is not important. The concept of element scale is crucial for the generic use of DU. For example, in an orchard a DU = 100 does not imply that the whole field receives the same amount of water, but that the elemental areas receive the same amount. On the other hand, in a wheat field with plant coverage everywhere, a DU = 100 would imply that the whole field receives the same water application (Burt *et al.*, 1997).

Distribution uniformity is not an efficiency term. To re-iterate, an irrigation event can have a high DU, but if excessive water has been applied then the application efficiency, AE, will be low. However, a high AE with minimal under-irrigation is only possible if the DU is also high. The above concept of distribution uniformity assumes that a uniform target is desired within the irrigated field (Burt *et al.*, 1997).

2.4.6 Potential application efficiency

Potential application efficiency, PAE, is based on the concept that the irrigation event could be terminated when the target depth would just be met by the average of the lowest values in the irrigation infiltration distribution. In this way deep percolation losses would be kept to a minimum, due only to the non-uniformity of application, while the AE would be at a maximum with minimal under-irrigation (Burt *et al.*, 1997).

As with DU, PAE cannot be quantified until the lowest values in the distribution have been characterised over a specified fraction of the field area. Here again the norm is to use the lower quarter, and hence the definition for PAE_{lq} follows (Burt *et al.*, 1997):

$$PAE_{lq} = \frac{\text{average depth of irrigation water contributing to target}}{\text{average depth of irrigation water applied such that } d_{lq} = \text{target}} \times 100\% \qquad \text{Eq. 2.13}$$

where

d_{lq} = average of depths accumulated in that quarter of the field area receiving the smallest depths (cf. Figure 2.2)

Thus, PAE_{lq} can be used to estimate the gross amount of water to apply. The denominators of DU_{lq} and PAE_{lq} differ by the amount of surface losses, such as runoff and evaporation, and therefore PAE_{lq} can be accurately estimated as (after Burt *et al.*, 1997):

$$PAE_{lq} \approx (DU_{lq} \ / \ 100) \times (100 - \%\ \text{surface losses}) \qquad \text{Eq. 2.14}$$

where surface losses include evaporation during an irrigation event, spray drift and surface runoff. Note DU_{lq} is a percentage in Eq 2.14.

From the above, the gross irrigation water required for an irrigation event can be estimated as (Burt *et al.*, 1997):

$$\text{Gross average depth to apply} = \text{Target depth} \times \frac{100}{PAE_{lq}} \qquad \text{Eq. 2.15}$$

2.4.7 Low-quarter adequacy

The degree to which the target, or required depth, is met is termed adequacy. In keeping with the definition of AE based on the requirement for all beneficial uses, the low-quarter adequacy (AD_{lq}) is given by (Burt *et al.*, 1997):

$$AD_{lq} = \frac{d_{lq}}{d_{req}} \qquad \text{Eq. 2.16}$$

where

d_{req} = the required depth for all beneficial uses (mm).

With this definition, an $AD_{lq} < 1$ indicates under-irrigation and $AD_{lq} > 1$ indicates over-irrigation. When $AD_{lq} = 1$, then $AE = PAE_{lq}$ and the surface losses match potential values. This definition of adequacy differs from other definitions that are based on the percentage of area adequately irrigated (Burt *et al.*, 1997).

It should be highlighted, however, that the rationale for the relationships given in Equations 2.14, 2.15 and 2.16 for PAE_{lq}, the gross average depth to apply and AD_{lq} are based on the assumption that applying water such that d_{lq} is equivalent to the target application depth is best. This may not necessarily be the case. For example, if irrigation is largely supplementary to rainfall on a drought tolerant crop, application of a relatively lower amount of irrigation water, such that a greater proportion of the field is under-irrigated, may be much more efficient, have a minimal effect on crop yields, and result in increased profitability. The need for a fundamental shift in emphasis away from maximising crop yields to rather maximising benefits, especially economic benefits, is well motivated by English *et al.* (2002).

2.4.8 Alternative water use efficiency and water productivity frameworks and definitions

Land and Water Australia have completed a two stage, four year project to develop a framework and gain acceptance on efficiency, uniformity and water use efficiency terms. The framework was developed to include all aspects of an irrigation system that affect irrigation water use efficiency. The framework is summarised in Figure 2.8 (Purcell and Currey, 2003). The most commonly accepted water use efficiency terms, their derivation and relationships are also shown in Figure 2.8.

An issue addressed by the Australian initiative was the mixture of units in 'efficiency' terms. For example, water use efficiency defined as:

Total crop production (kg) / Irrigation Water Applied (Ml) Eq. 2.17

In strict terms, efficiencies should be dimensionless. Therefore a proposed solution was to refer to specific performance indicators as 'indices', and not efficiencies. It also became necessary to define more and more performance indices depending on the purpose at hand. Thus the concept of a 'water use efficiency toolbox' was proposed, with each tool a specific performance index which fitted under the general label of 'water use efficiency'. Any performance indicator could, therefore, be tailor-made to suit the purpose of a particular study, provided it was clearly defined with units specified (Purcell and Associates, 1999)

Another water use efficiency and productivity framework which was proposed by Smith (2000) is shown in Figure 2.9. With reference to Figure 2.9, Smith (2000) distinguishes three levels of water use efficiency and productivity. Combining the different levels he defines 'water use efficiency' as the fraction of the total water available by both rainfall and irrigation that is used by the crop for transpiration. Thus in his definition, water use efficiency integrates the total pathway of water both from irrigation and rainfall, each with their own typical pathway efficiencies and evaporation patterns, which will be different for rain and irrigation.

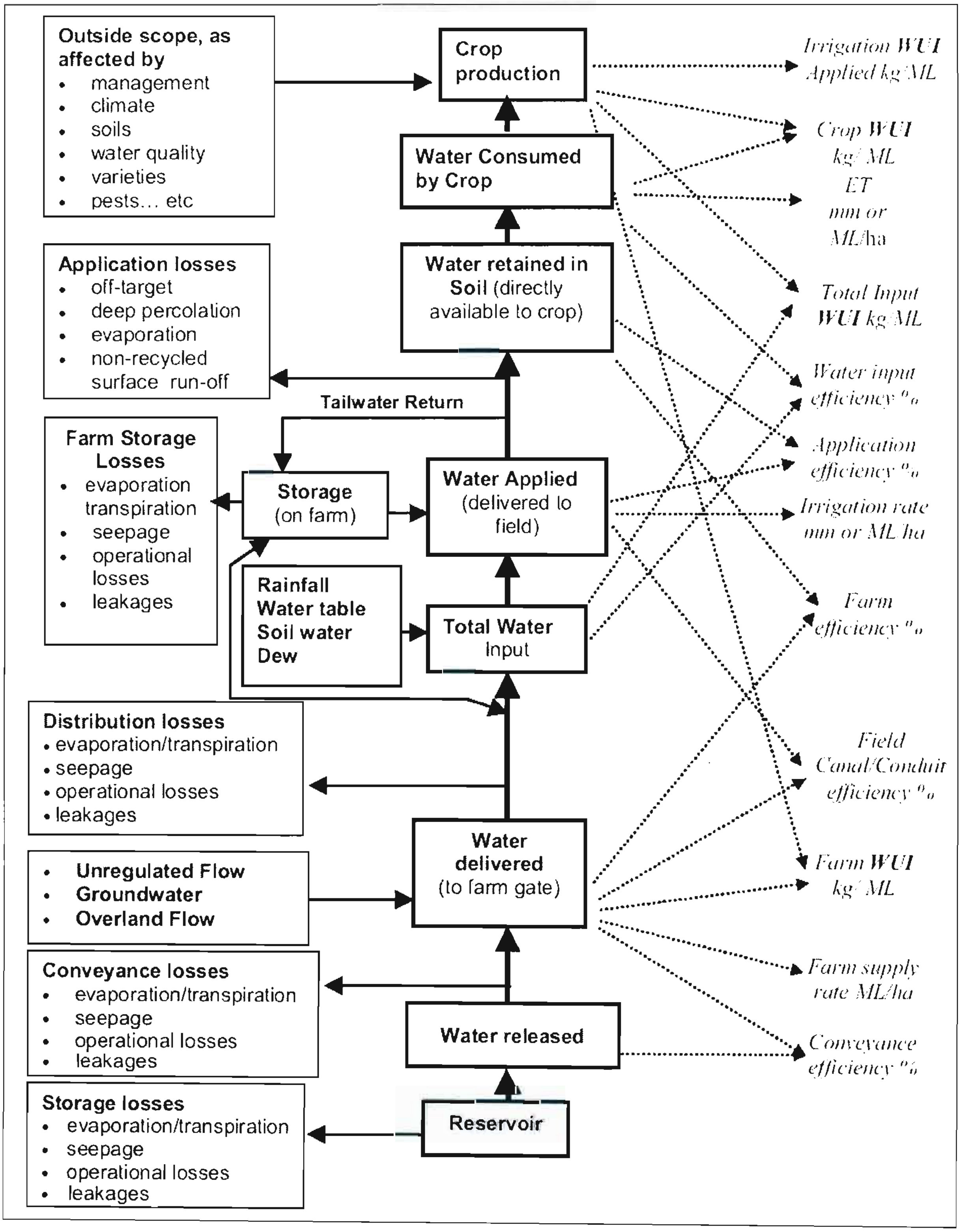
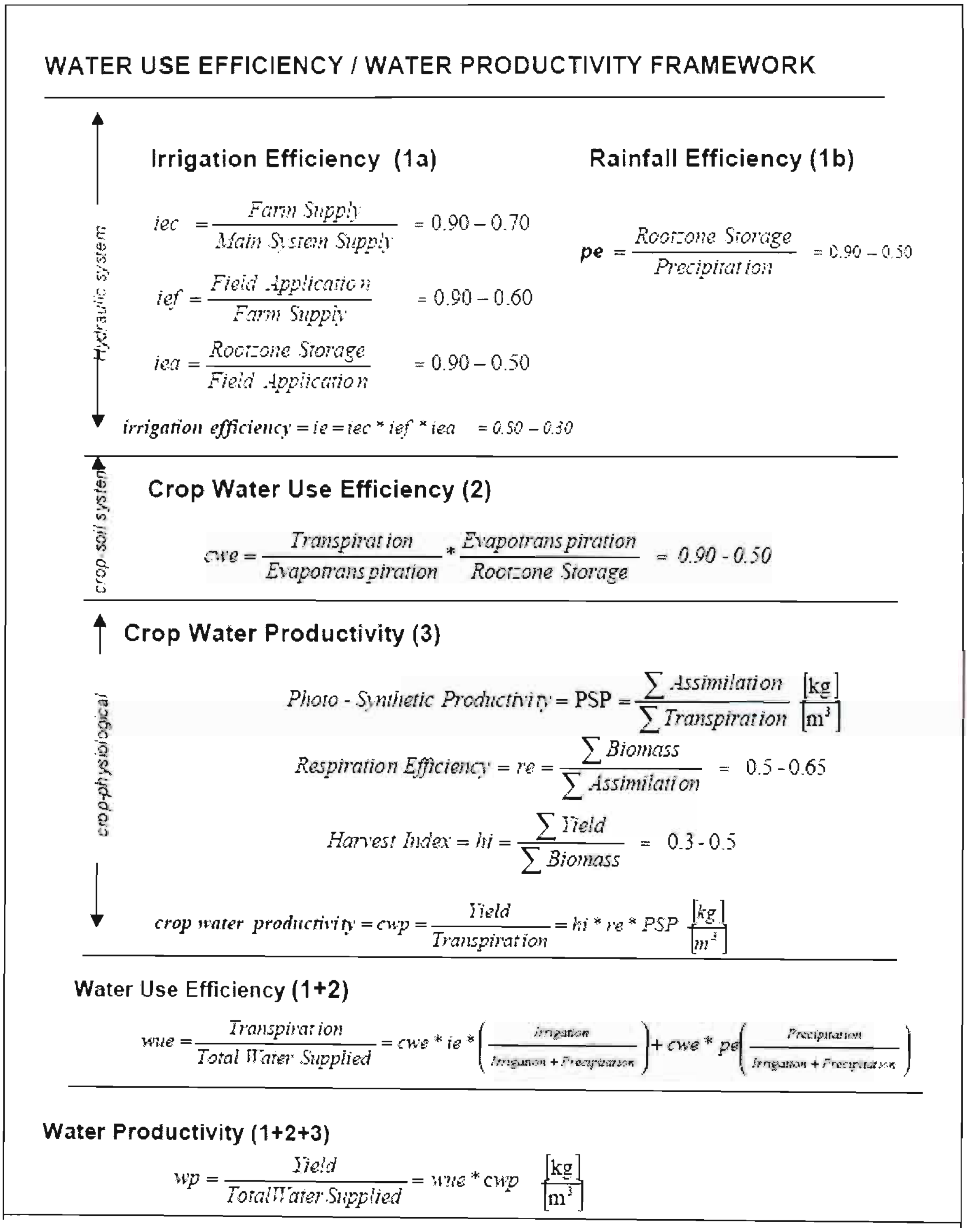


Figure 2.8 Proposed Australian framework for Water Use Efficiency (Purcell and Currey, 2003)



WATER USE EFFICIENCY / WATER PRODUCTIVITY FRAMEWORK

Irrigation Efficiency (1a)

$$iec = \frac{Farm\ Supply}{Main\ System\ Supply} = 0.90 - 0.70$$

$$ief = \frac{Field\ Application}{Farm\ Supply} = 0.90 - 0.60$$

$$iea = \frac{Rootzone\ Storage}{Field\ Application} = 0.90 - 0.50$$

$$irrigation\ efficiency = ie = iec * ief * iea = 0.50 - 0.30$$

Rainfall Efficiency (1b)

$$pe = \frac{Rootzone\ Storage}{Precipitation} = 0.90 - 0.50$$

Crop Water Use Efficiency (2)

$$cwe = \frac{Transpiration}{Evapotranspiration} * \frac{Evapotranspiration}{Rootzone\ Storage} = 0.90 - 0.50$$

Crop Water Productivity (3)

$$Photo\text{-}Synthetic\ Productivity = \mathrm{PSP} = \frac{\sum Assimilation}{\sum Transpiration} \left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right]$$

$$Respiration\ Efficiency = re = \frac{\sum Biomass}{\sum Assimilation} = 0.5 - 0.65$$

$$Harvest\ Index = hi = \frac{\sum Yield}{\sum Biomass} = 0.3 - 0.5$$

$$crop\ water\ productivity = cwp = \frac{Yield}{Transpiration} = hi * re * PSP \left[\frac{kg}{m^3}\right]$$

Water Use Efficiency (1+2)

$$wue = \frac{Transpiration}{Total\ Water\ Supplied} = cwe * ie * \left(\frac{Irrigation}{Irrigation + Precipitation}\right) + cwe * pe\left(\frac{Precipitation}{Irrigation + Precipitation}\right)$$

Water Productivity (1+2+3)

$$wp = \frac{Yield}{Total\ Water\ Supplied} = wue * cwp \left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right]$$

Figure 2.9 Water use efficiency and productivity framework (Smith, 2000)

Water productivity is then defined as the yield produced per unit of water for a given crop – water supply system. Smith (2000) also includes a relationship for assessing the economic benefits of water productivity investments, according to the following relationship:

$$\text{Rate of return}_{\text{Water productivity investments}} = \frac{\text{Yield x Market price}}{\text{Water investments + Agricultural investments}} \qquad \text{Eq. 2.17}$$

****

In this chapter, key determinants of irrigation systems performance have been reviewed. The uniformity with which water is applied can have a significant effect on the performance of irrigation systems and is related to the type of irrigation system and the standard to which it has been designed, operated and maintained. There is strong evidence that while losses due to plant intercepted water, spray evaporation and wind drift vary for different types of irrigation system and weather, there is a degree of compensation resulting from associated reductions in transpiration and evaporation of water from the soil surface, and possibly also enhanced relative growth rates associated with modified micro-climates during extremely hot weather. The amount of irrigation water applied in relation to the available soil water storage capacity is largely determined by management, but it can also be constrained by the type and design of the irrigation system, particularly with furrow irrigation. Management through the selection and implementation of irrigation watering schedules, or scheduling methodologies, can have significant effects on overall system performance, especially if the irrigation hardware is well designed. If the irrigation hardware is poorly designed and has a low inherent irrigation uniformity, overall performance is likely to be poor, even with appropriate watering schedules and good water management.

The most significant losses from a field are due to evaporation from the exposed soil surface, runoff and deep percolation. These losses depend on both the type of irrigation system and its management. Runoff and deep percolation both return to the system as return flows and can potentially be re-used, however, the impact of the return flows on *water quality* needs to be carefully monitored.

For a given type of irrigation system, which is performing at a certain level, the management strategy (e.g. a deficit irrigation management strategy) can also have significant impacts on overall system performance. In order to determine an appropriate deficit irrigation strategy, a prediction tool to relate the estimated recoverable crystal (ERC) yields of sugarcane to various watering strategies, types of irrigation system, measures of irrigation application uniformity, soils, seasonal weather patterns and water supply is needed.

In order to quantify irrigation systems performance, a range of indices and methods has been proposed. While there have been efforts to standardise performance terms and definitions, the Australian experience shows that such standards do not necessarily meet the constraints or requirements of all particular circumstance or situations. Since performance comparisons are important it is, therefore, very important that any proposed performance indices are well specified. Thus the associated units, calculation procedures and assumptions, including the system boundaries and the time scale, should be explicit. Also, since the primary role of irrigation is to facilitate improved productivity, some indication of the impact of the performance of the irrigation and water management system on crop yields and associated returns on investment is important. The determination of appropriate values for the numerators and denominators used in the indices is difficult and open to varied interpretations.

It may be concluded that the rational quantification of the water balance in relation to the uniformity of applied water, the environment and the water management approach forms the basis of assessing the performance of irrigation and water management systems at the field scale. Methodologies proposed and adopted to achieve this 'rational quantification' of the water balance are described in Chapter 3.

3. METHODOLOGY

The methodology formulated to evaluate the performance of both the irrigation and water management systems prevalent in the Lowveld, is described and discussed in this Chapter.

3.1 Background

In theory, the performance of irrigation and water management systems in the Lowveld could have been assessed by taking a range of appropriate measurements. However, the experiments and monitoring needed to evaluate a representative sample of all the various irrigation systems and associated irrigation application uniformities, for all the different soils present and water management strategies being applied, and that over a range of relatively wet and dry seasons, would have been too time consuming, costly and disruptive to be practically feasible. In addition, there was a high risk that results from such experiments and monitoring would be significantly biassed by extraneous factors (such as soil compaction and/or pest and disease impacts), operational hiccups and inconsistent management and baseline conditions. Therefore an alternative to a purely experimental evaluation approach to evaluating the performance of irrigation and water management systems in the Lowveld was needed.

A modelling approach, although relying on relatively few well designed experiments for the development and verification of appropriate algorithms, involves the integration of numerous and complex procedures and knowledge into a system which, in contrast to a purely experimental approach, can be used to evaluate a wide range of irrigation systems, performance measures and water management strategies relatively efficiently. Depending on the structure of the model, the effects of a wide range of conditions, such as wet and dry seasons and /or deep or shallow soils can also be examined. Such evaluations can be objective and relatively cost effective to undertake.

Available process-based simulation models for estimating irrigation crop water demand and associated sugarcane yield impacts have included mainly South African and Australian initiatives. In South Africa, these initiatives have resulted in the development of the *ACRU* agrohydrological model (Schulze, 1995; Lecler and Schulze, 1995), the CANEGRO model

(Inman-Bamber, 1991; Inman-Bamber, 2000) and the CANESIM model (Singels *et al.*, 1998; Bezuidenhout and Singels, 2003). Australian initiatives have resulted in the development of APSIM-Sugarcane (McCown *et al.*, 1996; O'Leary, 2000). In the context of this study, all these models had limitations. These limitations related primarily to their representation of different types of irrigation systems, especially regarding evaporation from a differentially wetted soil surface, which is important, for example, when comparing overhead sprinkler irrigation to sub-surface drip irrigation, and none of the models had algorithms to account for non-uniform irrigation water applications. The APSIM, CANEGRO and CANESIM models have also been identified to be weak in terms of accounting for water stress effects (Singels *et al.*, 1998; Van Antwerpen, 2000; O'Leary, 2000). This was a major concern with regard to their potential for evaluating various water management/irrigation scheduling strategies. Research on relating water stress to sucrose, as opposed to cane yields was also not well established and in a largely developmental phase (O'Leary, 2000; Singels and Bezuidenhout, 2002). Furthermore, access and support for most of these models was a practical constraint to their development and application in the Lowveld.

The Food and Agricultural Organisation's Irrigation and Drainage Paper No. 56 (FAO 56), is being promoted as an international standard for estimating irrigation crop water requirements (Allen *et al.*, 1998). Furthermore FAO 56 provides algorithms which specifically distinguish between the water budgets pertaining to different irrigation system (hardware) characteristics, which was very important in the context of this study. However, the FAO 56 water budget is somewhat simplified, for example, in terms of accounting for runoff, deep percolation and effective rainfall and also in not differentiating between uniform and non-uniform irrigation water applications. Furthermore, Kassam and Smith (2001) reported that the relationships between water stress and crop yield which are referred to in FAO 56, and which are described in detail by Doorenbos and Kassam (1979) need, in many cases, to be adapted and refined.

Therefore, it may be concluded that at the start of this study, there existed no wholly appropriate method and associated tools for evaluating the in-field performance of irrigation and water management systems for sugarcane in the Lowveld of Zimbabwe. A solely experimental approach while theoretically possible would have been impractical. Typical irrigation performance indices, for example, those described in Chapter 2 by Burt *et al.* (1997), have limitations. Primarily there is a need to relate uniformity and adequacy of irrigation water applications to associated impacts on crop yields, water budgets and hence profitability. The existing models and approaches reviewed have limitations in their ability to do this.

Thus, in the context of the perspectives given in Chapter 2, the following multi-faceted approach was formulated and executed in order to assess the in-field performance of irrigation and water management systems with specific reference to the irrigation of sugarcane in the Lowveld.

- Tools and methods to record in-field operating characteristics of various irrigation systems in the Lowveld environment were developed and/or acquired by a Mobile Irrigation Performance Evaluation Unit (MIPU). The MIPU was initiated by the author but much of the work was carried out by a candidate MSc Engineering student, Brent Griffiths, who worked under the author's supervision.
- The data and information acquired using the tools and methods from the MIPU were used to calculate 'Irrigation Engineering Performance Indices' (IEPIs) such as the coefficient of uniformity, CU, which gives an indication of how uniformly irrigation water was being applied.
- A sugarcane yield and irrigation systems simulation model was developed to predict how these IEPIs impacted on crop yields and the water budget, for different soils, seasonal weather conditions, irrigation systems and water management strategies.
- The sugarcane yield and irrigation systems simulation model was verified against experimental trial data and applied to assess the typical performance of irrigation and water management systems prevalent in the Lowveld. The performances of the various irrigation and water management systems under typical conditions in practice, as reported by the MIPU were compared to the performances of the various irrigation systems assuming more optimal but achievable IEPIs and water management strategies.

This approach is illustrated diagrammatically in Figure 3.1.

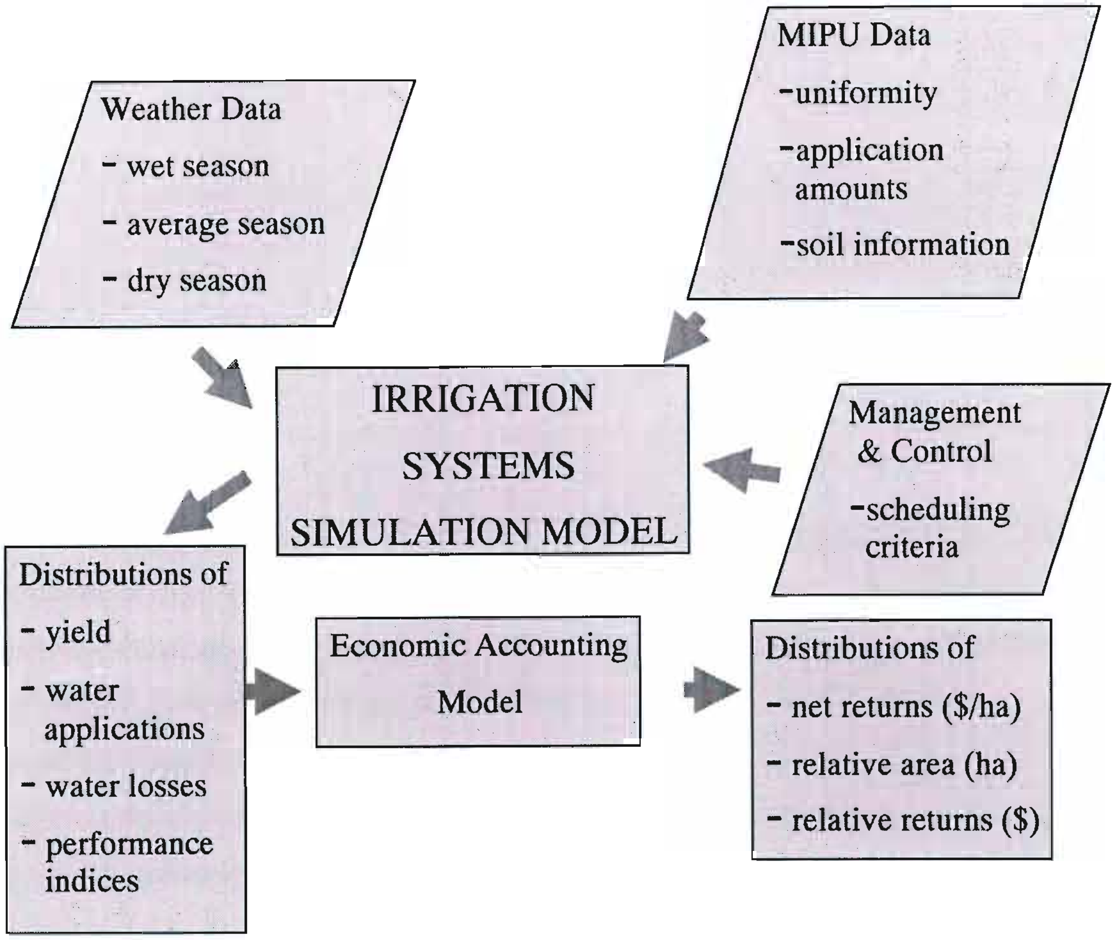


Figure 3.1 Diagrammatic depiction of the methodology used in this study for the evaluation of irrigation hardware and water management systems in the Lowveld of Zimbabwe

The focus in this Chapter is on the development of the irrigation systems simulation model. While the MIPU was an integral part of the methodology (which the author had formulated and initiated), the day-to-day operations of the MIPU were largely the responsibility of Brent Griffiths and are, therefore, only given brief mention in this thesis.

3.2 Collection of In-field Data and Information on Irrigation Systems Operating Characteristics

The Mobile Irrigation Performance Evaluation Unit (MIPU) was initiated by the author under the auspices of the Water Management Project (WMP) of the Zimbabwe Sugar Association Experiment Station (ZSAES). Brent Griffiths, a graduate student under the author's supervision, was employed to acquire and/or develop the necessary measuring equipment, computer software and methodologies for assessing the in-field operational characteristics of the various irrigation systems. The main focus of the evaluations was on the assessment of equipment wear, water application uniformities and causes of poor application uniformities. The equipment and the various procedures used by the MIPU for evaluations are summarised in Griffiths and Lecler (2001).

3.3 Interpretation of In-field Irrigation Systems Performance Data and Information

In terms of the water balance and crop yield impacts, the evenness or uniformity with which water is applied, and the amount of water applied at each irrigation application, are two of the most important performance characteristics of a given type of irrigation system. This information was captured by the MIPU and reported in the form of Engineering Performance Indices, such as the coefficient of uniformity, CU. However, whilst the engineering indices reported by the MIPU to describe irrigation uniformity and water applications (cf. Chapter 2) were vitally important, and provided some basis for systems comparisons, additional interpretation was required in order for them to be translated to associated impacts on potential sugar yields (i.e. estimated recoverable crystal, ERC) and the water balance. This additional interpretation required the development of the irrigation systems simulation model.

A model of a system can be described as a set of equations or rules that quantitatively describe the operation of the system through time. Simulation is the process of solving these equations within the rules with changing time, i.e. mimicking the performance of the system over time by calculating the values of the variables at each series of time steps (Peart and Curry, 1998). A deterministic crop and irrigation systems simulation model, *ZIMsched 2.0* was developed by the author in order estimate how water management, different irrigation system characteristics and the in-field measures of irrigation systems operating characteristics derived by the MIPU, impacted on potential crop yields and the water balance.

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), so that the following processes were accounted for, as illustrated in Figure 3.2:

- evaporation from the soil surface and transpiration in relation to:

  - atmospheric evaporative demand,
  - available soil water, including excess and/or deficient conditions,
  - crop and rooting characteristics (the development of which were related to temperature),
  - irrigation system type,
- stormflow (surface runoff), and
- deep percolation, all of which relate to
- rainfall effectiveness, and are impacted by
- the uniformity or non-uniformity of irrigation water applications.

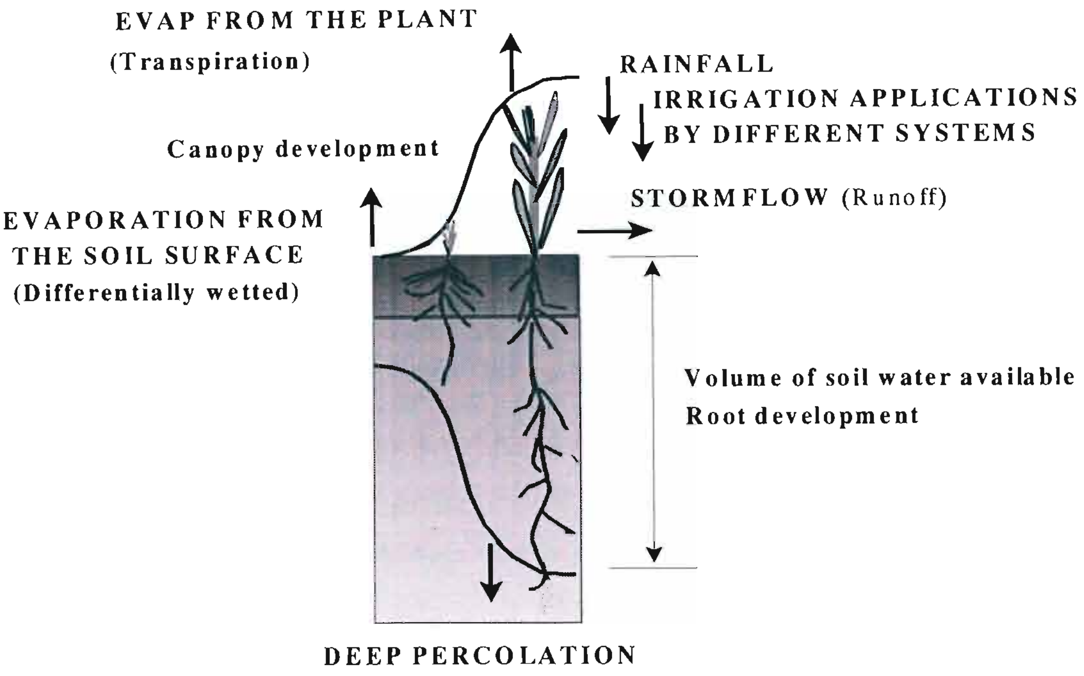


Figure 3.2 Components of the water balance which impact on crop yields as represented in *ZIMsched 2.0*

ZIMsched 2.0 is considered unique in terms of not only its synthesis and integration of the water budgeting and crop yield algorithms which were developed, but also because this translates into the unique capability of differentiating between different types of irrigation system and accounting for different levels of irrigation system performance (in terms of uniformity of water applications), while also predicting yields of estimated recoverable crystal (ERC).

In this section *ZIMsched 2.0* is presented and the concepts and algorithms which were integrated and/or developed and refined and used in *ZIMsched 2.0* are described. The validity of *ZIMsched 2.0* is also discussed. Verification of *ZIMsched 2.0* against experimental trial data is discussed in Chapter 4.

3.3.1 Total evaporation

In *ZIMsched 2.0,* total evaporation from the cropped surface (i.e. evapotranspiration) is dependent on climatic conditions, soil water status, crop canopy status and rooting characteristics.

3.3.1.1 Crop coefficient

The crop coefficient is used to relate evaporation from the cropped surface to atmospheric evaporative demand, AED. Evaporation from the soil and the crop are determined separately, based on the internationally accepted algorithms described in the FAO Irrigation and Drainage Paper No. 56 (Allen *et al.,* 1998). It is very important to separate these processes because prior to the development of significant canopy cover, water losses are dominated by evaporation from the soil surface. This evaporative loss can be highly variable because different types of irrigation systems wet different fractions of the soil and there are also variations in wetting frequencies. Thus, effective early season crop coefficients can vary significantly dependent on the type and operation of irrigation system (cf. Chapter 2). The solution proposed by the FAO (Allen *et al.,*1998) was to use a dual crop coefficient, i.e. the basal crop coefficient (K_{cb}) to control potential transpiration from the plant and a coefficient (K_e) to control evaporation from the soil. The evaporative losses from the cropped surface may thus be expressed as follows:

$$ET_c = (K_{cb} + K_e).\ E_{ref} \qquad \text{Eq 3.1}$$

where

ET_c = evaporation losses from the cropped surface (evapotranspiration) (mm)

K_{cb} = basal crop coefficient

K_e = coefficient controlling evaporation from the soil

E_{ref} = reference evaporation to represent atmospheric evaporative demand, AED (mm)

3.3.1.1.1 Basal crop coefficient, K_{cb}

The basal crop coefficient, K_{cb}, is defined as the ratio of the crop evapotranspiration to the reference evaporation (ET_c/E_{ref}) when the soil surface is dry but with transpiration occurring at the potential rate, i.e. soil water is not limiting transpiration. The value of $K_{cb}.E_{ref}$ does include a residual diffusive evaporation component supplied by soil water below the dry surface and by soil water beneath dense vegetation (Allen *et al.*, 1998).

Guidelines for sugarcane basal crop coefficients are as follows:

- 0.15 during the initial stages, i.e. the residual diffusive evaporation component, and
- (K_c - 0.05) for a full canopy crop, where K_c is the crop coefficient used for a full canopy crop grown under conditions were the soil surface is wetted (Allen *et al.*, 1998).

The variation of crop coefficients with time, or the rate of canopy development, is very dependent on temperature and therefore the concept of relating crop coefficients to thermal time is better than relating them to calendar days. The reason for this is that variations in the rate of canopy development, which are associated with different planting/ratooning times (early, mid, late season) and seasonal temperature variations, can be automatically accounted for. Hughes (1992) used lysimeter data collected at Pongola in northern KwaZulu-Natal, South Africa and reported on by Thompson (1986) to develop a relationship between thermal time and crop coefficients for the period from germination to establishment of full canopy. Thermal time was determined using the following relationship:

$$TT = (T_{max} + T_{min})/2 - 12^{\circ}C \qquad \text{Eq 3.2}$$

where

TT = thermal time (degree days)

T_{max} = daily maximum temperature (°C)

T_{min} = daily minimum temperature (°C).

The equation for crop coefficients that best fitted Pongola data from one plant crop and four ratoon crops was as follows (Hughes, 1992):

$$K_c = 0.2977 + (1.32\text{x}10^{-6}\text{x}TT_A^2) + (-6.83\text{x}10^{-10}\text{x}TT_A^3) \qquad \text{Eq 3.3}$$

where

K_c = average crop coefficient, (i.e. it includes effects of evaporation from the soil surface and from the plant in one lumped coefficient)

TT_A = accumulated thermal time (degree days).

Note that this relationship is only valid for TT_A accumulated until the maximum K_c value is reached.

Using linear interpolation, the basal crop coefficient, K_{cb}, (i.e. representing evaporation from the plant only) can be derived from K_c (i.e. soil and plant lumped together) as follows:

$$K_{cb} = K_c/0.4 \text{ x } 0.15 \qquad \text{for } K_c < 0.4 \qquad \text{Eq 3.4}$$
$$K_{cb} = K_c - (0.25 - (K_c - 0.4) \text{ x } 0.2/0.45) \qquad \text{for } 0.4 < K_c < 0.85$$
$$K_{cb} = K_c - 0.05 \qquad \text{for } K_c > 0.85.$$

This procedure for deriving K_{cb} (Equation 3.4) was assessed for conditions in the Lowveld by analysis of sugarcane crop growth data recorded by Mr Haslem at the Zimbabwe Sugar Association Experiment Station. Haslem (-) collected leaf area index (LAI) data that included data for four crops planted in different years and during the early, mid and late part of the season. In order to compare the rate of canopy (and hence K_c) development, a plot of the Haslem's (-) LAI data versus thermal time, together with the K_c relationship derived by Hughes (1992) is shown in Figure 3.3. With reference to Figure 3.3 it can be seen that there was a very close correspondence between the development of K_c and the development of LAI, up to a LAI = 3. A LAI = 3 is the typical LAI value at which ET reaches a maximum (Ritchie, 1972; Kristensen, 1974).

Furthermore, using Haslem's data a relationship between thermal time and LAI was derived, *viz.*

$$LAI = -0.57356 + 0.003084\, TT_A \qquad \text{for } TT > 185 \text{ and } LAI \leq 3 \qquad \text{Eq 3.5}$$

where

LAI = leaf area index

TT_A = accumulated thermal time (degree days, cf. Equation 3.2).

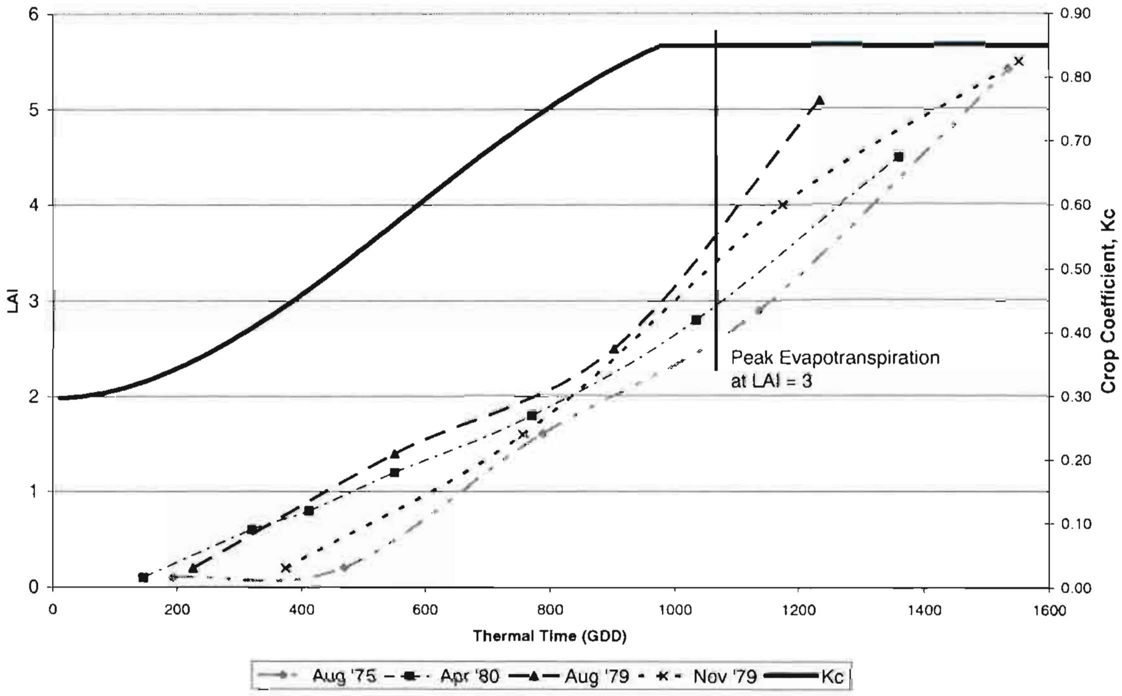


Figure 3.3 Leaf Area Index (LAI) for an August 1975 plant crop, April 1980 ratoon crop, November 1979 ratoon crop and an August 1979 ratoon crop vs thermal time. LAI data were collected by Haslem (-) at ZSAES. The graph also shows the crop coefficient, K_c, vs thermal time relationship which determines the rate of canopy development in *ZIMsched*.

This relationship in Equation 3.5 was then used together with a relationship between K_{cb} and LAI (Equation 3.6), reported by Ritchie (1972) as an alternative independent means of deriving K_{cb}, *viz*.

K_{cb} = $(0.71.LAI^{0.5} - 0.21)\ K_{pan}$ for $LAI \leq 3$ Eq 3.6

K_{cb} = $1.0\ K_{pan}$ for $LAI \geq 3$

where

K_{cb} = basal crop coefficient

K_{pan} = coefficient used to adjust Ritchie's original relationship which used a short grass $E_{ref,}$ to an A-pan based E_{ref}

= 0.85 as an average for conditions in the Lowveld of Zimbabwe.

As shown in Figure 3.4 there was very close agreement between:

- the K_{cb} values derived using the Hughes (1992) K_{cm} vs TT relationship and linear interpolation (Equations 3.3 and 3.4), and
- K_{cb} values derived using the TT vs LAI relationship derived using data collected in Zimbabwe and converted to K_{cb} using Ritchie's (1972) relationship between K_{cb} and LAI (Equations 3.5 and 3.6).

Through the use of Equations 3.3 and 3.4 in *ZIMsched 2.0,* the effects of planting/ratooning in different months and the effects intra-seasonal temperature variations on the rate of canopy development and associated water use for different types of irrigation systems was, therefore, considered to be well represented.

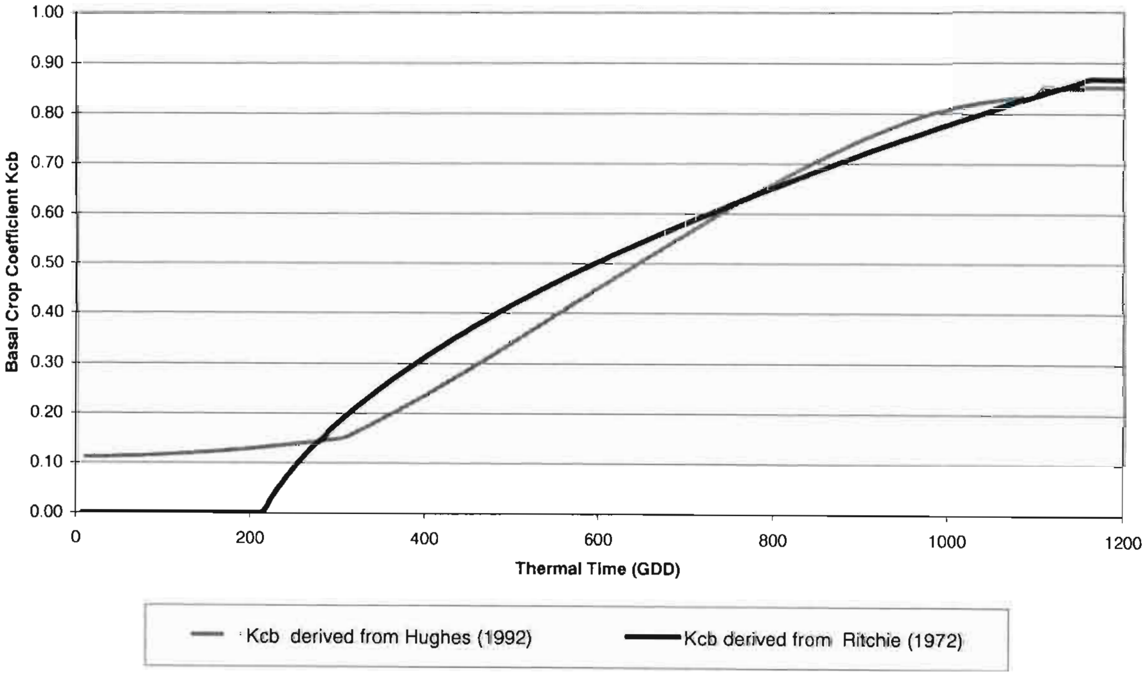


Figure 3.4 The basal crop coefficient, K_{cb} calculated using the values derived from Hughes's (1992) K_c vs TT relationship and linear interpolation (Equations 3.3 and 3.4), and K_{cb} values derived using the thermal time (TT) vs leaf area index (LAI) relationship derived using data collected in Zimbabwe and converted to K_{cb} using Ritchie's (1972) relationship between K_{cb} and LAI (Equations 3.5 and 3.6)

In *ZIMsched 2.0* the maximum value for K_c was limited to 0.9 when using evaporation from a class A-pan as a reference to represent atmospheric evaporative demand, AED. Thus the corresponding limit for K_{cb} , was 0.85. These limits were based on an analysis of irrigation trial data from the Zimbabwe Sugar Association Experiment Station (ZSAES) and an analysis of A-pan data and data from an Automatic Weather Station (Lecler, 2001a; Appendix A). Analysis of data from trials where full canopy sugarcane was irrigated using various fractions of evaporation from a class A-pan to determine irrigation intervals (so-called "pan factor" trials) showed that there was little benefit in irrigating full canopy sugarcane assuming a K_c greater than 0.9 (Lecler 2001a), an observation also supported by Ellis *et al.* (1985) and Nyati (1996). Data from these 'pan factor' irrigation trials also served as an indirect verification for evaporation losses from sugarcane in relation to the evaporation measured from an A-pan, i.e. assuming estimated recoverable crystal (ERC) t/ha as the dependent variable instead of soil water, which in many ways is more integrated and meaningful.

3.3.1.1.2 Soil surface water evaporation coefficient, K_e (after Allen *et al.*, 1998)

The coefficient K_e describes the potential evaporation of water from the soil surface, which is assumed to take place in two stages. In the first stage, when the topsoil is wet following irrigation application or rainfall, K_e is maximal. In the second stage, after a certain amount of water has evaporated, the soil surface is drier and K_e reduces, eventually reaching zero when there is minimal water near the soil surface for evaporation. The limit to evaporation from a wet surface relative to evaporation from an A-pan is set to 1.0 in *ZIMsched 2.0* when evaporation from an A-pan is used as the reference evaporation, E_{ref}, i.e. $K_{cb} + K_e = 1.0$ or $K_e = 1.0 - K_{cb}$,

The two stages are modelled using Equation 3.7, *viz.*

$$K_e = K_r(1.0 - K_{cb}).\ f_{ew}\ 1.0 \qquad \text{Eq 3.7}$$

where

K_e = coefficient controlling evaporation from the soil surface

K_{cb} = basal crop coefficient

K_r = evaporation reduction coefficient dependent on cumulative depth of water depleted (evaporated) from the topsoil,

f_{ew} = fraction of soil that is both exposed and wetted, i.e. from which evaporation takes place.

Following rain or an irrigation water application $K_r = 1$, and evaporation is determined by the energy available for evaporation. As the soil surface dries, K_r becomes less than 1 and evaporation is reduced. K_r becomes zero when no water is left for evaporation from the surface layer. The amount of water that can be depleted by evaporation from the soil surface during a complete drying cycle is estimated as:

$$TEW = 1000(\Theta_{dul} - 0.5\Theta_{pwp})\, Z_e \qquad \text{Eq 3.8}$$

where

TEW = total evaporable water from the top soil (mm)

Θ_{dul} = soil water content at the drained upper limit (field capacity) (m^3/m^3)

Θ_{pwp} = soil water content at permanent wilting point (m^3/m^3)

Z_e = thickness of the surface soil layer that is subject to drying by way of evaporation, taken as 0.1 m in ZIMsched 2.0.

Stage 1 evaporation from the soil surface ($K_r = 1$) holds until the cumulative depth of evaporation, D_e, is such that hydraulic properties of the upper soil become limiting and water cannot be transported to the surface at a rate to match potential demand. D_e is the readily evaporable water (REW) and typical values range from 5 to 12 mm, with values generally highest for fine and medium textured soils. Default values based on soil texture that are used in *ZIMsched 2.0* are given in Appendix B.

Stage 2 evaporation from the soil surface ($K_r < 1$) starts when $D_e > REW$. At this point the soil surface is visibly dry and evaporation from the exposed soil decreases in proportion to the amount of water remaining in the surface soil layer.

3.3.1.1.3 Exposed and wetted fraction, f_{ew}

Where the entire soil surface is wetted, as by sprinkler irrigation or rainfall, the fraction of soil surface from which most evaporation occurs, f_{ew}, is essentially defined as ($1-f_c$), where f_c, is the fraction of soil surface covered by vegetation. However, for wetting events which only wet part of the soil surface, e.g. a water application with furrow irrigation or sub-surface drip irrigation, f_{ew} must be limited to f_w, which is the fraction of soil surface wetted by irrigation, i.e.

$$f_{ew} \quad = \quad \min(1-f_c\ , f_w) \qquad \text{Eq 3.9}$$

where the 'min' function selects the lowest value of '$1-f_c$' or 'f_w'.

The limitation imposed by Equation 3.9 assumes that the fraction of soil which is wetted occurs within the fraction of soil which is exposed to sunlight and ventilation. This is generally the case, except for subsurface drip irrigation and in-row furrow irrigation. In these cases where the wetted fraction is largely shaded, f_w is reduced by multiplying by $((1-(2/3)f_c)$ (Allen *et al.*, 1998).

3.3.1.1.4 The exposed soil fraction, 1 - f_c

The fraction of the soil surface covered by vegetation, f_c , is determined in *ZIMsched 2.0* using the relationship between thermal time (TT) and K_{cm} as the basis for a relationship between TT and f_c, given in Equation 3.10, *viz.*

$$\begin{array}{llll} f_c = Grd_{ini} & \text{for} & TT < 340 & \text{Eq 3.10} \\ f_c = \max(Grd_{ini}\ , \min(0.99,((TT-340)/(1000-340))0.99)) & \text{for} & TT > 340 & \end{array}$$

where

Grdini = initial ground cover, e.g. due to surface mulching (fraction ≥ 0 ; ≤ 0.99).

where 'max' and 'min' select the maximum or minimum of the terms in brackets. The numerical values, '340' and '1000' are based on the LAI vs TT data collected by Haslem (-) at ZSAES (cf. Figure 3.2).

3.3.1.1.5 Daily calculation of K_e

Determination of K_e requires a daily water balance computation in order to calculate the cumulative depletion, D_e , for the surface layer from a wet condition. The daily soil water balance equation for the exposed and wetted fraction, f_{ew} , of the surface soil layer is given as

$D_{e,i} = D_{e,i-1} - (P_i - RO_i) - I_i/f_w + E_i/f_{ew} + T_{ew,i} + DP_{e,i}$ Eq 3.11

where

$D_{e,i-1}$ = cumulative depth of evaporation following complete wetting from the exposed and wetted fraction of the topsoil at the end of day i-1 (mm)

$D_{e\,i}$ = cumulative depth of evaporation following complete wetting from the exposed and wetted fraction of the topsoil at the end of day i (mm)

P_i = rainfall on day i (mm)

RO_i = stormflow/runoff from the soil surface on day i (mm)

I_i = irrigation depth on day i that infiltrates the soil (mm)

E_i = evaporation from the soil surface day i (mm)

$T_{ew\,i}$ = depth of transpiration from the exposed and wetted soil surface layer on day i (mm)

$DP_{e,i}$ = deep percolation from the topsoil layer on day i if soil water content exceeds the drained upper limit, i.e. field capacity (mm) (Note: $DP_{e,i}$ is always assumed equal to zero as although the surface layer may be draining, in such a state the surface will likely be wet and evaporation from the surface uninhibited)

f_w = fraction of soil surface wetted by irrigation (0.01 - 1)

f_{ew} = exposed and wetted soil fraction (0.01 - 1)

with limits, $0 \leq D_{e,i} \leq TEW$.

Equation 3.11 is simplified in the FAO 56 calculations (Allen *et al.*, 1998) which assume that all water infiltrates, i.e. RO is zero, and that transpiration from the surface layer that contributes to E_i is negligible. In *ZIMsched 2.0* :

- stormflow/runoff (RO) is not assumed to be zero, but is calculated using the modified SCS stormflow equation (Schulze, 1995), and
- transpiration, T_{ew} , from the soil layer contributing to E_i is not assumed to be zero.

The proportion of the actual transpiration for a day that is extracted from the topsoil layer is related to the total rooting depth and the soil water content in this layer, according to Equation 3.12, such that

$F_{T,i} = \max(0, 0.1/(R_{fac}.S_{dep}).(TAM_{10} - D_{e,i-1})/TAM_{10})$ Eq 3.12

where

$F_{T,i}$ = fraction of actual transpiration on day i that is extracted from the topsoil layer

R_{fac} = proportion of maximum effective soil rooting depth that is penetrated by roots, always has a value such that the depth from which water uptake can occur is ≥ 0.4 m

= $0.4/S_{dep}$ for $TT_A < 340$

= $\min(1, (1 - 0.4/S_{dep}).(TT_A-340)/(980-340) + 0.4/S_{dep}))$ for $TT_A \geq 340$

with the limit $S_{dep} \geq 0.4$ m

(Note: it is assumed that maximum rooting depth coincides with the development of full canopy cover (Jensen *et al.*, 1990))

TT_A = accumulated thermal time (degree days)

S_{dep} = the maximum potential effective rooting depth for a fully grown crop (m)

$TAM_{0.1}$ = total available water in the topsoil layer of 0.1 m, viz. $(\Theta_{dul} - \Theta_{pwp}) \times 0.1$

Θ_{dul} = soil water content at the drained upper limit, i.e. field capacity (m^3/m^3)

Θ_{pwp} = soil water content at permanent wilting point (m^3/m^3)

$D_{e,i-1}$ = cumulative depth of evaporation following complete wetting from the exposed and wetted fraction of the topsoil at the end of day i-1 (mm).

3.3.1.2 Atmospheric evaporative demand, AED

The evaporation measured using a class A-pan is used to represent AED in *ZIMsched 2.0*. The reason for this is that in Zimbabwe most of the research involving sugarcane crop water use has been undertaken using the evaporation from A-pans as the reference evaporation (Ellis *et al.*, 1985; Nyati, 1996). Nevertheless, the correlation between the evaporation from an A-pan and the evaporation from a cropped surface can be markedly different in summer and winter and also under advective conditions, or when there are wide variations in wind and humidity (Allen *et al.*, 1998). The following two alternatives to the A-pan were therefore investigated:

- the Food and Agricultural Organisation, version of the Penman-Monteith reference evaporation (Allen *et al.*, 1998), and
- the evaporation measured using an ETgage, a relatively simple atmometer device (Asbell, 1999) that may better represent a plant.

However, in a report on the investigation (Appendix A), Lecler (2001a) showed that there was very little difference between using A-pan data with appropriate pan factors and the

Penman- Monteith equation with data from an automatic weather station, especially when the data were averaged over a five day period, which was less than a typical sprinkler irrigation cycle. An additional reason for selecting A-pan data as the default reference evaporation option in *ZIMsched 2.0* was that the data from the AWS and ETgage at ZSAES were only collected from 1998 and 2000 respectively. Therefore, the records were relatively short and less adequate for investigating inter-seasonal differences between wet, dry and normal seasons.

3.3.1.3 Rooting characteristics

In *ZIMsched 2.0* the root zone which delimits the depth of soil from which water is available to the crop is dynamic, in order to account for root growth and associated soil water stress effects. The depth of the zone from which water uptake can occur, R_z , was calculated by assuming that maximum rooting depth coincides with the development of full canopy (Jensen *et al.*,1990), which in *ZIMsched 2.0* is predicted from a relationship with thermal time, *viz.*

$$R_z = R_{fac} \cdot TAM \qquad \text{Eq 3.13}$$

where

R_z = depth of the zone from which water uptake can occur (m)

R_{fac} = proportion of maximum effective soil rooting depth that is penetrated by roots, and which always has a value such that the depth from which water uptake can occur is ≥ 0.4 m

= $0.4/S_{dep}$ for $TT_A < 340$

= $\min(1, (1- 0.4/ S_{dep}).(TT_A-340)/(980-340) + 0.4/ S_{dep}))$ for $TT_A \geq 340$

with the limit $S_{dep} \geq 0.4$ m

(Note: it is assumed that maximum rooting depth coincides with the development of full canopy cover (Jensen *et al.*, 1990))

TT_A = accumulated thermal time (degree days)

S_{dep} = the maximum potential effective rooting depth for a fully grown crop (m).

3.3.1.4 Transpiration under conditions of soil water stress

Transpiration (T) is reduced below its maximum value (i.e. “potential”) if soils are too dry relative to AED, according to a relationship derived by Slabbers (1980). Based on first principles, Slabbers (1980) developed a relationship which accounts for the fact that the soil water content at which actual transpiration (T_a) is less than potential (T_p) is dependent on:

- the critical leaf water potential of the crop, (ψ_{cl}) and
- the evaporative demand of the atmosphere (AED),

such that if it is very hot, plant stress will start to occur at relatively high soil water contents, whereas when it is cooler and more humid, plant stressing will only start to occur at relatively lower soil water contents. This relationship is discussed in more detail in Lecler and Schulze (1995).

To express the effects of soil water stress in terms of soil water contents is not wholly correct because the rate of water uptake is influenced more directly by the energy level of the soil water (soil matric potential and associated hydraulic conductivity) than by the water content. The energy level of soil water corresponds to different soil water contents for different soil types, and therefore the soil water content at which a crop starts to experience stress is also a function of soil type (Allen *et al.*, 1998). For example, the energy levels of the water in a clay and a sand will be different if the water contents are the same. The fraction of total available water (TAM) at which stress starts, 'f' is given in Equation 3.14 (after Slabbers, 1980):

$$f = \max(0.2\ ,\ 0.94+0.0026(\psi_{cl}/AED)) \qquad \text{Eq 3.14}$$

where

f = fraction of TAM at which stress starts

ψ_{cl} = critical leaf water potential (kPa), which for sugarcane is defaulted to -1200 kPa in *ZIMsched 2.0*, after Inman-Bamber (1986)

AED = atmospheric evaporative demand, represented in *ZIMsched 2.0* by the evaporation from an A-pan (mm).

In order to account for the effects of soil type on the amount of depletion required before a soil water content is reached at which stress starts, Equation 3.15 is used:

$$D_{str} = TAM.R_{fac}((1-f) + F_{text}/100(1-f)) \qquad \text{Eq 3.15}$$

where

D_{str} = depletion required before transpiration is reduced below potential due to a shortage of soil water (mm)

f = fraction of TAM at which soil water stress starts

TAM = total available water (mm)

F_{text} = soil texture dependent percentage increase or decrease in the fraction of TAM that is depleted before stress starts (%), with default values for F_{text} given in Allen *et al.*, (1998; cf. also Appendix B).

Evaporation from the plant is also reduced below potential if soils are above field capacity due to poor aeration. This is accounted for in *ZIMsched 2.0* using an equation from the *ACRU* model (Schulze, 1995), which was based on research reported by Dijkhuis and Berliner (1988). The interrelationships used in *ZIMsched 2.0* between soil water content and the ratio of actual to potential transpiration (T_{actual} : $T_{potential}$) are illustrated diagrammatically in Figure 3.5.

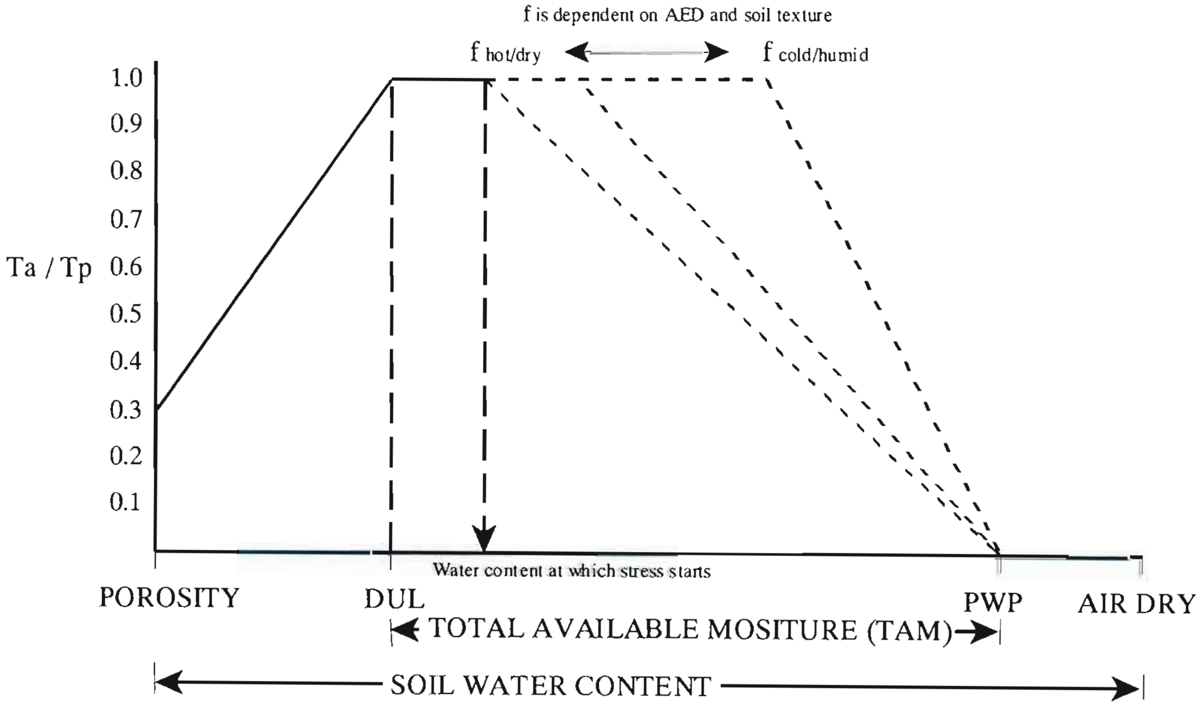


Figure 3.5 Interrelationships used in *ZIMsched 2.0* between soil water content and the ratio of actual to potential transpiration (Ta : Tp) and 'f' , i.e. the fraction of total available moisture (TAM) at which soil water stress starts. 'DUL' refers to the drained upper limit (field capacity) and 'PWP' the permanent wilting point. 'AED' is the atmospheric evaporative demand (after Schulze, 1995)

3.3.2 Surface runoff / stormflow

In *ZIMsched 2.0*, "surface runoff", or stormflow, is defined as the water which is generated on or near the surface of a field from a rainfall or irrigation application event. This water does not contribute to the crop available soil water budget and is, therefore, important for estimating the effectiveness of rainfall. Surface runoff is estimated using the Soil Conservation Service (SCS) stormflow equation (USDA, 1985) as modified by Schulze (1995) and used in the *ACRU* agrohydrological simulation model. The modified equation is given below as Equation 3.16.

$$Q = (P_g - cS)^2/(P_g + S(1-c)) \qquad \text{Eq. 3.16}$$

where

Q = stormflow (i.e. surface runoff) depth (mm)

P_g = gross daily precipitation amount (mm)

c = coefficient of initial abstraction

= 0.25 (*ZIMsched 2.0* default value)

S = potential maximum water retention of the soil, taken as the soil water deficit below porosity (mm), and with S calculated for the top 0.250 m of soil as a default in *ZIMsched 2.0*.

A major difference between Equation 3.16 (Schulze, 1995) and the original Curve Number (CN) based SCS stormflow equation (USDA, 1985) is that the potential maximum retention, S, is a soil water deficit *calculated by daily water budgeting techniques* and can thus inherently account for different growth stages of the crop as well as for different tillage practices. The soil water deficit is taken as the difference between water retention at porosity and the actual soil water content just prior to the rainfall event. This more dynamic approach represents a substantial refinement to the more static Curve Number approach to account for, *inter alia*, antecedent soil water conditions and is discussed in detail in Schulze (1995). Most other sugarcane models, including, the CANEGRO model (Inman-Bamber, 1991; Inman-Bamber, 2000) and the CANESIM model (Singels *et al.*, 1998; Bezuidenhout and Singels, 2003) use the conceptually static Curve Number based SCS equation to estimate runoff and hence rainfall infiltration.

Equation 3.16 has been well tested (Schulze 1995), with tests including some on sugarcane research catchments (Smithers *et al.*, 1997). The tests on the sugarcane catchments formed the basis for the recommended *ZIMsched 2.0* default values for c and the depth for which S is calculated.

3.3.3 Deep percolation / drainage

If, at the end of a day, the soil water content is still above the drained upper limit, DUL (i.e. field capacity), drainage of water from the bottom of the root zone is initiated. The drainage rate is calculated according to Equation 3.17 (after Jones *et al.*, 1986), *viz.*

$$D_d = (\Theta_t - \Theta_{DUL}).\ K_s \qquad \text{for} \quad \Theta_t > \Theta_{DUL} \qquad \text{Eq 3.17}$$

where

D_d = depth of deep percolation / drainage water (mm.day-1)

Θ_t = actual soil water content (mm equivalent)

Θ_{DUL} = soil water content at drained upper limit, DUL (mm equivalent)

K_s = saturated drainage coefficient, with default values used in *ZIMsched 2.0* related to soil texture (cf. Appendix B) according to values given by Schulze *et al.* (1995)

Drainage can take place over a number of days during which the plant can extract water, but plant extraction is at a reduced rate due to poor aeration (cf. Figure 3.5). The amount of drainage and the duration of drainage are dynamic, dependent on soil characteristics, antecedent soil water and the magnitude of the rainfall or irrigation event resulting in excessive soil water. Thus, when compared to many other water budgeting algorithms which assume a fixed drainage time, often of only one day, the time for the soil to drain to its drained upper limit (i.e. field capacity) in *ZIMsched 2.0* is highly variable. This is a very important aspect, as the tendency to over-simplify drainage assumptions and assume drainage to field capacity within a fixed time period, which is often too short, can result in grossly inaccurate water budgets and lead to a snowballing cycle of over-irrigation and poor root aeration, with large differences between the theoretical budget and actual field conditions. The author frequently observed such discrepancies with the over-simplified, hand-calculated water budgets typically used on the sugar estates in the Lowveld. Often the simple water budget calculations would indicate a substantial soil water deficit when, in fact, field observations showed that the soils were still close to their drained upper limit (field capacity). This discrepancy was especially prevalent with furrow irrigation, where irrigation water applications were typically excessive (cf. Chapter 4) and the 'time-to-drain' underestimated.

3.3.4 Effective rainfall

Effective rainfall was defined as that amount of rainfall that enters into the soil profile (infiltrates) and is available for use by the crop. In *ZIMsched 2.0* effective rainfall is calculated on a daily basis dependent on the runoff, drainage and ET relationships described in this section.

3.3.5 Crop yield estimate

The estimated recoverable crystal (ERC) algorithm in *ZIMsched 2.0* is based on simulating a reference potential ERC yield and then adjusting this reference potential yield according to the timing and magnitude of soil water stress. The reference potential yield estimate was based on a robust relationship between actual evapotranspiration (ET) and tons sucrose that was derived by Thompson (1976) using data from Hawaii, Australia, Mauritius and several locations in South Africa. In *ZIMsched 2.0,* rather than using ET, which could lead to spurious results when simulating watering strategies which may have resulted in high levels of evaporation from the soil surface (E_s), potential transpiration (T_p) was used in a modified form of Thompson's (1976) sucrose verus ET relationship. This modified relationship is given in Equation 3.18 and it was used in *ZIMsched 2.0* to derive an estimate of reference potential ERC for a given season.

$$Y_{pot} = -22.65 + 4.923((T_{pA}/100)x1.05) - 0.149((T_{pA}/100)x1.05)^2 \qquad \text{Eq 3.18}$$

where

Y_{pot} = reference potential yield of estimated recoverable crystal (t/ha)

T_{pA} = accumulated potential transpiration, i.e. assuming no soil water stress effects (mm)

The factor '1.05' used as a multiple of T_{pA} in Equation 3.18 was applied in order to substitute transpiration for ET in Thompson's (1976) original equation. The value of '1.05' was derived from a comparison between evapotranspiration (ET), and transpiration (T), simulated with

ZIMsched 2.0 assuming typical well watered conditions, i.e. 50 mm irrigation water applications applied at a soil water deficit of 50 mm, which is representative of overhead sprinkler irrigation systems.

The reference potential ERC estimated using Equation 3.18 was then further modified according to the timing and magnitude of water stress according to procedures based on research reported on by Doorenbos and Kassam (1979). In order to quantify the effects of soil water stress on crop yields, Doorenbos and Kassam (1979) used a function relating the relative yield decrease to the relative deficit of total evaporation (i.e. actual evapotranspiration). This relationship is given below as Equation 3.19:

$$1-Y_a/Y_p = K_y(1-ET/ET_m) \qquad \text{Eq 3.19}$$

where

Y_a = actual harvested yield of a given crop (t/ha)

Y_p = potential non-water-stressed harvested yield of a given crop, i.e. reference potential yield (t/ha)

ET = actual total evapotranspiration (i.e. $T_a + E_s$, mm)

ET_m = maximum potential evapotranspiration (i.e. $T_p + E_s$, mm)

E_s = evaporation from the soil surface (mm)

T_a = actual evaporation from the plant tissue, i.e. actual transpiration (mm)

T_p = maximum potential evaporation from the plant tissue, i.e. maximum potential transpiration (mm), i.e. assuming no soil water stress effects

K_y = growth stage specific yield response factor

The response of yield to water supply is quantified through the yield response factor, K_y , which relates the relative decrease in yield, $(1-Y_a/Y_p)$, to a relative deficit in total evaporation $(1-ET/ET_m)$. The K_y values for most crops were derived on the assumption that the relationship between relative yield (Y_a/Y_p) and relative evapotranspiration (ET/ET_m) is linear and is valid for water deficits of up to approximately 50%, i.e. $(1-ET/ET_m) = 0.5$. According to de Jager (1994), concerns about the transferability of the yield function given in Equation 3.19 can be obviated through the use of transpiration ratios (i.e. T_a/T_p) in the place of total evaporation ratios (i.e. ET/ET_m). In Equation 3.20, the influences of atmospheric vapour pressure deficits and climate-crop architecture on T_a/T_p , and hence Y_a/Y_p , cancel out (de Jager, 1994). Hence the yield response factor K_y defined in Equation 3.20 becomes a purely plant physiological entity and is thus determined by crop genetics and not climate. The K_y factor should thus be neither site nor climate specific (de Jager, 1994).

$$Y_a/Y_b = \prod_{i=1}^{i=G} [\, 1 - K_{yi}(1 - T_a/T_p)] \qquad \text{Eq. 3.20}$$

where

i = i-th growth stage in a growing season with a total of G growth periods

K_{yi} = yield response factor for the i-th growth period

De Jager (1994) tested a range of wheat yield functions, including Equation 3.20, using the water budgeting algorithms of the PUTU model to calculate T_a and T_p. Results of these tests showed that using a yield function based on Equation 3.20 with values for K_{yi} for wheat taken from Doorenbos and Kassam (1979), was the most accurate of the various different yield functions tested and that the accuracy was very acceptable for use in decision support applications.

Therefore, based on research, *inter alia*, by Doorenbos and Kassam (1979) and de Jager (1994), and a comparison between observed and simulated yields and water use (cf. Chapter 4), Equation 3.20 was adopted as an option for estimating ERC yields in *ZIMsched 2.0*. The overall growing season yield response factor (K_y) of 1.2 proposed by Doorenbos and Kassam (1979) is used in *ZIMsched 2.0* up until the ripening period (taken as 56 days before cutting), after which a K_y value of -0.01 was used. The yield response factor for the final growth period (ripening) was changed to -0.01 from the value of 0.1 proposed by Doorenbos and Kassam (1979) based on analysis of the results from the dry-off trials undertaken in Zimbabwe which showed that stress in this ripening period can have a very mild beneficial effect on ERC (Lecler, 2001, Appendix C).

3.3.6 Irrigation uniformity

In order to account for the effects of irrigation uniformity on systems performance, the water budget and yield estimate in *ZIMsched 2.0* were based on the average of three equal areas each receiving different amounts of water at each simulated irrigation water application, i.e. a multiple water budget. The simulated amount of water on each of the three areas was varied, dependent on the uniformity measure of the irrigation system. One third of the area was simulated to receive the mean irrigation water application, one third received the mean water application plus a percentage ($D_{\%}$) of the mean and one third received the mean minus a percentage ($D_{\%}$) of the mean. Assuming normally distributed irrigation water applications, Equations 3.21, 3.22 and 3.23 were derived to relate the percentage deviation ($D_{\%}$) corresponding to a given coefficient of uniformity (CU), statistical uniformity (SU) or low quarter distribution uniformity (DU_{lq}) respectively (cf. Chapter 2). For example, if the mean application for a furrow irrigation event was 50 mm, and the DU was equal to 60, one third of the area would receive an average of 50 mm, one third would receive an average of 69 mm and one third would receive an average of 31 mm at each simulated irrigation water application. The equations for $D_{\%}$ are:

$$D_{\%} = 149.97 - 149.96.(CU/100) \qquad \text{Eq. 3.21}$$

$$D_{\%} = 122.49 - 122.49.(SU/100) \qquad \text{Eq. 3.22}$$

$$D_{\%} = 96.48 - 96.50.(DU_{lq}/100) \qquad \text{Eq. 3.23}$$

where

$D_{\%}$ = percentage of mean application to be added and subtracted from the mean to determine irrigation application amounts for the three representative water budgets (%)

DU_{lq} = low quarter distribution uniformity (cf. Chapter 2)

SU = statistical uniformity (cf. Chapter 2)

CU = Christiansen's coefficient of uniformity (cf. Chapter 2)

The relationships between CU, SU, DU_{lq} and $D_{\%}$ shown as Equations 3.21, 3.22 and 3.23, were determined as follows:

Step 1 - three irrigation application amounts were determined for a given $D_{\%}$ value, i.e. x, $x + D_{\%}$ and $x - D_{\%}$, with an arbitrary integer value being assumed for x;

Step 2 - a CU value was calculated for these three irrigation application amounts, *viz.* x, ($x - D_{\%}$) and ($x + D_{\%}$) (cf. Equation 2.7, Chapter 2)

Step 3 - Step 1 and Step 2 were repeated for a range of $D_{\%}$ values so that a series of CU and associated $D_{\%}$ values were obtained

Step 4 - using the series of CU and associated $D_{\%}$ values, a least squares regression was used to determine a relationship between $D_{\%}$ and CU, *viz.* Equation 3.21

Step 5 - Equations 2.11 and 2.12 (cf. Chapter 2) where used together with Equation 3.21 to derive Equation 3.22 and Equation 3.23.

3.3.7 Validity of *ZIMsched 2.0*

The FAO Irrigation and Drainage Paper No. 56 (Allen *et al.*, 1998) was used as the major reference for determining evaporation losses. FAO 56 is an international standard and includes procedures for accounting for the effects of different types of irrigation systems on early season evaporation losses. The relationship between the rate of canopy development and thermal time that was developed using data from Pongola was checked against LAI data collected in Zimbabwe, and found to be representative. This relationship enables the effects of planting/ratooning in different months and the effects of hot or cold inter- and intra-seasonal temperature conditions on the rate of canopy development and associated water use to be represented.

Stormflow/runoff and deep percolation/drainage were based on algorithms well proven in the *ACRU* agrohydrological model (Schulze, 1995), including verification studies on sugarcane research catchments (Smithers *et al.*, 1997). The water budget presented in FAO 56 (Allen *et al.*, 1998) does not specifically account for stormflow or deep percolation, but both of these processes are of great importance in a water budget when rainfall can provide a significant portion of the crop's water requirements, as is often the case in the Lowveld.

The effects on water uptake and crop yield caused by both too much or too little water were based on algorithms used in the *ACRU* model, based on research by Dijkhuis and Berliner (1988), Slabbers (1980) and also FAO 56 (Allen *et al.*, 1998). The relationships account for the fact that under very hot and dry conditions a crop will experience stress at a relatively higher soil water content compared to when conditions are more cold and humid; when even with a relatively drier soil the crop may not necessarily be experiencing water stress. The algorithms also account for the fact that it is more difficult to withdraw water from a clay than from a sand, even if they are both at the same volumetric water content.

The crop coefficients and A-pan based evaporative demand estimates used in *ZIMsched 2.0* were found to correspond with both the FAO 56 approach, based on the Penman-Monteith reference evaporation equation used together with data from an automatic weather station, and data from irrigation trials undertaken at ZSAES (Lecler, 2001a). In addition to having been proposed as an international benchmark, the FAO 56 approach to estimating evaporation from sugarcane has been verified in southern Africa and Australia and found to compare closely to direct measurements of sugarcane evaporation collected using Bowen ratio apparatus (McGlinchy and Inman-Bamber, 2002).

The effect of various distribution functions to describe the variation of irrigation water applications on relative sugarcane yield and the water balance was investigated by Ascough and Lecler (2004) using *ZIMsched 2.0* (Appendix D). The results showed that the yield, deep percolation, runoff and efficiency were sensitive to using multiple water budgets. However, using up to thirteen simultaneous water budgets did not produce significant differences to the values simulated using three water budgets. In addition, different distribution functions with the same uniformity value did not produce significant differences in the variables simulated. Thus, it was considered computationally efficient to use three water balances and reasonable to assume a normal distribution to account for spatial variability of applied water in the *ZIMsched 2.0* model in this study.

3.4 Irrigation Systems Performance Measures

As discussed in Chapter 2, a multitude of indices has been proposed to quantify irrigation systems performance. There is also some confusion because many of the indices have been given different definitions and are perceived and interpreted differently by different people. The performance indices used in this study and their definitions are given in Equations 3.24 and 3.25.

$$IE = T.100 / (I_g + R_g) \qquad \text{Eq. 3.24}$$

where

IE = irrigation efficiency (%)

T = accumulated seasonal transpiration (mm), representing beneficial water use

R_g = total rainfall (mm), measured in the growing season

I_g = total gross irrigation water applied (mm), in the growing season

$$WUP = ERC.100 / (I_g+R_g) \qquad \text{Eq. 3.25}$$

where

WUP = water use productivity (t x 100/ha/mm)

Note: WUP has often been referred to as Water Use Efficiency, but since the numerator and denominator have different units, the term 'productivity' has been preferred

ERC = estimated recoverable crystal (t/ha/season)

'Irrigation Efficiency' and 'Water Use Productivity' as defined in Equations 3.24 and 3.25 and, indeed, other performance indices, provide a useful basis for comparisons. Equation 3.24 represents the main beneficial output required from irrigation water applications, namely transpiration divided by the total water input, i.e. rainfall and irrigation. It was a typical practice in the Lowveld to 'dry-off' the crop before harvesting. Therefore, in formulating Equation 3.24, the net contribution from stored soil water was assumed negligible, and therefore disregarded, because fields started the season dry and ended dry. An advantage of using *ZIMsched 2.0* was that it facilitated using transpiration rather than ET in the numerator in Equation 3.24. This made it possible to distinguish between irrigation systems and management practices which affect evaporation of water from the soil surface differently. The latter was considered important because evaporation from the soil surface was viewed as a non-beneficial water use.

While Equation 3.25 provides an indication of water use productivity (WUP), from a business perspective it has limitations. To illustrate this, consider two irrigation systems with different water use productivities. The system with the highest water use productivity may not necessarily be the most effective system, unless the cost of achieving the very high WUP has been taken into consideration. If this cost is too high, the system will not be viable from a business perspective, no matter how good its technical performance or WUP (cf. Figure 2.4, Chapter 2).

From a business perspective, the return on investment and the overall relative net return are key determinants in the evaluation of different irrigation and water management systems. Equations 3.26 and 3.27 were thus proposed to enable systems to be compared in terms of a Net Return per Hectare (NRH) and Relative Net Return (RNR). NRH and RNR (Equations 3.26 and 3.27) are defined and explained as follows:

Net Return per Hectare (NRH) = (Gross Revenue - Yield Dependent Costs - Irrigation Variable Costs - Base Production Costs - Irrigation Fixed Costs) / Hectares in production Eq. 3.26

Relative Net Return (RNR) = Net Return per Hectare x Relative Production Area Eq. 3.27

The relative production area is determined by considering the relative water use of different systems, i.e. relative production area for a given system = (maximum water used considering all systems and seasons)/(water used for the given system and season). Gross revenue is the product of ERC yield and price. Yield dependent costs are costs that depend on yield, e.g. harvesting and hauling, and possibly fertiliser (if fertiliser amount is applied relative to expected yield). Irrigation variable costs include the direct costs of water, energy (electricity or diesel), labour and maintenance. The irrigation variable costs depend on both the amount of irrigation water applied and the rate of application. The rate of application relates to the irrigation system's peak capacity, which impacts on the crop yields that can be obtained with the system and also the energy and fixed irrigation costs. Base production costs include all variable production costs other than yield dependent or irrigation variable costs, e.g. herbicides, labour and seed. Irrigation fixed costs include interest on investment and depreciation. The relative net return allows the opportunity cost of water to be accounted for. This opportunity cost, e.g. using water savings to increase the production area, or to increase average production over a number of seasons, is a vital consideration, especially when water is limited.

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In this chapter the integration of robust water budgeting and crop yield relationships into a unique computer simulation modelling tool, namely *ZIMsched 2.0*, was described. The water balance and associated crop yields simulated with *ZIMsched 2.0* are sensitive to:

- different types of irrigation system hardware, for example, the different surface wetting patterns of furrow irrigation versus overhead sprinkler irrigation,
- different levels of irrigation system performance, namely the uniformity with which water is applied and the flexibility of applying water applications of various magnitudes,

- different water management strategies / scheduling approaches, all in relation to
- different soil characteristics, and
- various weather conditions, including the impact of very wet or dry, hot or cold seasonal climates.

ZIMsched 2.0 was designed to be used together with information from a MIPU to evaluate existing irrigation and water management systems and also for more strategic purposes. For example, it can be used to determine how best to apply a limited amount of water and determine the most appropriate irrigation strategy to suit specific environmental and irrigation system constraints. The selected strategy can then be implemented using a simplified version of the same tool (cf. Chapter 5).

The net return per hectare (NRH) and relative net return (RNR) were proposed as performance measures best suited to comparing the performance of irrigation and water management systems from a business perspective. Estimates of crop yield and associated water use distributions derived using *ZIMsched 2.0* facilitate the calculation of NRH and RNR, together with estimates of other performance indices such as irrigation efficiency (IE) and water use productivity (WUP).

Although the concepts and algorithms in *ZIMsched 2.0* were based on valid and internationally proven algorithms, the unique synthesis and integration of these algorithms and the credibility of the model for Lowveld conditions, still needed to be established. Verification of *ZIMsched 2.0* for a range of soil, weather and irrigation watering conditions in the Lowveld of Zimbabwe, and application of the model for evaluating irrigation and water management systems, are the subjects of Chapter 4.

4. RESULTS

In this Chapter the application of *ZIMsched 2.0* to simulate the performance of irrigation and water management systems in the Lowveld is discussed. Simulations were undertaken using data and information collated by the Mobile Irrigation Performance Evaluation Unit, MIPU. The data and information provided by the MIPU were representative of the irrigation systems as they stood. Additional simulations were undertaken assuming that the uniformity and depth of irrigation water applied were at more optimal, but achievable, levels. The information derived from this combination of simulations showed the actual and also the potential performance of the different types of irrigation and water management systems in the Lowveld environment.

The credibility of the information reported here is dependent on the performance of the *ZIMsched 2.0* irrigation systems simulation model. Therefore, before describing the application of *ZIMsched 2.0*, verification of the model is discussed.

4.1 Evaluation of *ZIMsched 2.0*

In the context of this study, a sound model should provide accurate predictions of the relative yields of estimated recoverable crystal (ERC) for different soils, wet and/or dry seasons and for different watering/irrigation scheduling regimes. The data from two irrigation trials undertaken at the ZSAES provided excellent data for the verification of *ZIMsched 2.0* because they incorporated the requisite range of soil, climate and irrigation watering/scheduling regimes. Pertinent details of these trials are summarised below.

4.1.1 Trial 4200/1

Trial 4200/1 was an irrigation trial initiated at the ZSAES by Dr J Gosnell. The trial was planted to sugarcane in 1966 and terminated in 1972. Irrigation water was applied using overhead hand-moved sprinkler irrigation and the cane variety was NCo 376. One of the main objectives of the trial was to determine the effect of various irrigation watering regimes on the yields of cane and ERC. The irrigation watering regimes (treatments) used were:

- Treatment 1: pan factor 1.0, 50 mm of water applied following an accumulated A-pan evaporation of 50 mm;
- Treatment 2: pan factor 1.0 in summer and 0.5 in winter, 50 mm of water applied following an accumulated A-pan evaporation of 50 mm in summer, and 50 mm of water applied at an accumulated A-pan evaporation of 100 mm in winter;
- Treatment 3: pan factor 0.84, 50 mm of water applied following an accumulated A-pan evaporation of 59 mm;
- Treatment 4: pan factor 0.68, 50 mm of water applied following an accumulated A-pan evaporation of 73 mm;
- Treatment 5: pan factor 0.53, 50 mm of water applied following an accumulated A-pan evaporation of 94 mm;
- Treatment 6: pan factor 0.38, 50 mm of water applied following an accumulated A-pan evaporation of 133 mm.

The soils at the trial site were sandy clay loams with estimated total available moisture (TAM) of 76 mm. Irrigation and climate data for the plant, 1st, 2nd and 3rd ratoon crops were obtained from trial records kept at the ZSAES and these were used in *ZIMsched 2.0* to simulate the effects of the various treatments and associated seasonal weather conditions on yields of ERC. Rainfall for the seasons simulated ranged from 280 mm to 600 mm and seasonal irrigation water applications associated with the different treatments ranged from 660 mm to 1 778 mm. As the main objective of the verification study was to assess the capability of *ZIMsched 2.0* to represent relative differences between irrigation watering regimes and irrigation systems, the observed and simulated yields of ERC were compared in relative terms.

4.1.2 Trial 4200/12

Trial 4200/12 was an irrigation trial similar to trial 4200/1. However, the treatments were slightly different, the soils were different, the seasons were different and irrigation water was applied using flood beds as opposed to overhead sprinklers. The officer in charge was Mr C Nyati. The trial commenced in 1986 and was terminated in 1991 and the cane variety was NCo 376. The objective of the trial was to apply various irrigation watering regimes and determine their effect on crop yields. The irrigation watering regimes (treatments) were as follows:

- Treatment 1: pan factor 1.0, 50 mm of water applied following an accumulated A-pan evaporation of 50 mm;
- Treatment 2: pan factor 1.0, 100 mm of water applied following an accumulated A-pan evaporation of 100 mm;
- Treatment 3: pan factor 0.85, 50 mm of water applied following an accumulated A-pan evaporation of 59 mm;
- Treatment 4: pan factor 0.70, 50 mm of water applied following an accumulated A-pan evaporation of 71 mm;
- Treatment 5: pan factor 0.55, 50 mm of water applied following an accumulated A-pan evaporation of 91 mm;
- Treatment 6: pan factor 0.40, 50 mm of water applied following an accumulated A-pan evaporation of 125 mm.

The soils at the trial site were sandy clay loams with estimated total available moisture (TAM) of 100 mm. Irrigation and climate data for the 1st, 2nd and 3rd ratoon crops were obtained from records kept at the ZSAES and these were used in *ZIMsched 2.0* to simulate the effects of the various treatments on yields of ERC. Seasonal rainfall for the seasons simulated ranged from 328 mm to 728 mm and seasonal irrigation water applications associated with the different treatments ranged from 550 mm to 1 750 mm.

4.1.3 Results of a verification of *ZIMsched 2.0*

A scatter plot of observed and simulated ERC yields shown in relative terms, i.e. as fractions of the yield obtained by Treatment 1 for each of the two trials, *viz.* Trial 4200/1 and Trial 4200/12, is presented in Figure 4.1. The associated statistics of model performance are given in Table 4.1.

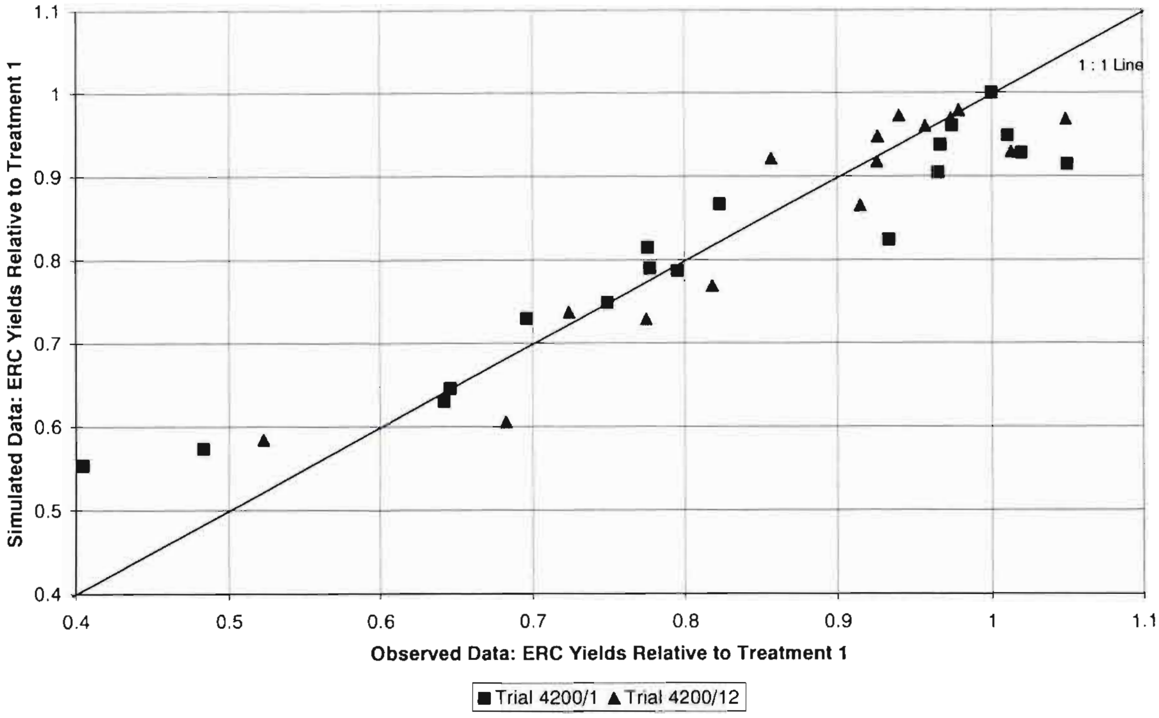

Figure 4.1 Scatter plot of observed and simulated Estimated Recoverable Crystal (ERC) yields shown in relative terms, i.e. as a fraction of the yield obtained by Treatment 1 for each of two irrigation trials, *viz.* Trial 4200/1 (1966-72) and Trial 4200/12 (1986-91), conducted at the Zimbabwe Sugar Association Experiment Station on sugarcane variety NCo376

Table 4.1 Quantitative performance measures for comparing simulated Estimated Recoverable Crystal (ERC) yields and observed ERC yields in relative terms, i.e. as fractions of the yield obtained by Treatment 1 for trials 4200/1 and 4200/12 combined[1]

O_{mean}	S_{mean}	N	A	b	RMSE	$RMSE_u$	$RMSE_s$	d	r
0.85	0.84	30	0.16	0.80	0.056	0.043	0.036	0.96	0.94

[1]Terms N, b, d and r are dimensionless, while remaining terms represent relative yields in terms of a fraction

O_{mean} = mean of observed relative yields of estimated recoverable crystal (ERC)

S_{mean} = mean of simulated relative yields of ERC

RMSE = root mean squared error

RMSEu and RMSEs = root mean squared errors, unsystematic and systematic, respectively

d = index of agreement, 1.0 indicates perfect agreement, 0.0 indicates no agreement (Wilmott, 1981)

r = correlation coefficient (Pearson's r)

N = number of data points

a (intercept) and b (slope) of a least squares regression between predicted relative yields as the dependent variable and observed relative yields as the independent variable.

The value for the index of agreement, 'd' was 0.96, which is very close to a value of 1.0. A value of 1.0 would indicate perfect agreement between observed and simulated relative ERC yields, i.e. yields relative to the yield obtained from Treatment 1. The root mean squared error (RMSE) was 0.056, indicating that on average the predicted relative yields were within 6 % of the observed relative yields. Most of the error was unsystematic although the intercept, 'a' and slope, 'b' values showed that the model was prone to slight overestimation of yield declines caused by mild soil water stressing and slight underestimation of the yield declines caused by more severe soil water stressing, with the model likely simulating too rapid canopy recovery after severe stressing events. The correlation coefficient, Pearson's 'r' of 0.94, nevertheless indicates a very high degree of correspondence between the observed and simulated relative yields. Overall the statistics of model performance were indicative of very good model performance. Therefore, the model was considered sufficiently accurate for the evaluation of irrigation water management systems, especially the comparison of one system to another in relative terms, which was the primary aim of this study.

4.2 Performance of Irrigation and Water Management Systems

Triangle Estates (TE), Hippo Valley Estates (HVE) and Mkwasine Estate (ME), the three major sugarcane estates in the Lowveld, each used a different set of water management guidelines. The Zimbabwe Sugarcane Production Manual, edited by Clowes and Breakwell (1998), contained a further set of water management recommendations. The application of these various irrigation water management (scheduling) guidelines in relation to different soils, seasons, types of irrigation system and levels of irrigation system performance, as represented by the distribution uniformity of applied water and the depth of irrigation water applications relative to the soil TAM values, was simulated using *ZIMsched 2.0*. The measurements of the typical magnitude, range and uniformity of irrigation water applications associated with the different estates and types of irrigation system were either recorded by the MIPU or by personnel on the large sugarcane estates who were trained by the MIPU team.

4.2.1 Analysis of MIPU data for floppy, drip and sprinkler irrigation systems

For the floppy, drip, hand-moved sprinkler and centre pivot irrigation systems, a frequency analysis was performed on either the CU, or SU, values (dependent on the type of irrigation system) reported by the MIPU. The results of this analysis are shown in Table 4.2.

Table 4.2 Ranked performance indices derived from field measurements undertaken by the Mobile Irrigation Performance Evaluation Unit (MIPU) for centre pivot, floppy, hand-moved sprinkler and drip irrigation systems in the Lowveld of Zimbabwe (after Griffiths and Lecler 2001; Griffiths, 2003)

System Type (Performance Measure, i.e. CU or SU)	Performance Rating	Representative Median Value of CU or SU[1]	Representative Median Irrigation Application depth as a Percentage of TAM (%TAM)[2]
Centre Pivot (CU)	Top third	90	< 50 %
"	Middle third	87	< 50 %
"	Lower third	82	< 50 %
	Benchmark[3]	> 90 (CU)	< 50 %
Floppy (CU)	Top third	81	< 50 %
"	Middle third	73	< 50 %
"	Lower third	69	< 50 %
	Benchmark[3]	> 82 (CU)	< 50 %
Hand-Moved Sprinkler (CU)	Top third	89	< 50 %
"	Middle third	82	< 50 %
"	Lower third	75	< 50 %
	Benchmark[3]	> 84 (CU)	< 50 %
Drip (SU)	Top third	84	< 50 %
"	Middle third	72	< 50 %
"	Lower third	54	< 50 %
	Benchmark[3]	> 88 (SU)	< 50 %

[1] SU = Statistical Uniformity
CU = Christiansen's Coefficient of Uniformity (cf. Chapter 2).

[2] If the application depth could be varied to less than 50 % of the value of the soil's total available moisture (TAM) value, a value < 50 was used for %TAM in the *ZIMsched 2.0* simulations, dependent on each estate's water management guidelines. The exception was for drip irrigation, where daily irrigation applications were simulated to occur in order to maintain the soil water at approximately 90 % of the TAM value.

[3] 'Benchmark' refers to the value of the relevant performance measure that should be expected and attainable in practice if the system was designed and installed according to reasonable standards.

The CU values for centre pivot and sprinkler irrigation systems were very high, reflecting sound design (i.e. adequate and uniform pressure) and maintenance (i.e. mainly routine replacement of worn nozzles). Centre pivots displayed the highest uniformities, followed closely by those of the overhead sprinklers and then the floppy irrigation systems. Although with proper design, installation and maintenance, drip systems can be used to apply water with very high uniformities, the MIPU results showed the drip systems to have the lowest uniformities of all the systems evaluated. The low uniformities in many drip irrigation systems could be attributed to excessive pressure variation and also too many blocked or semi-blocked emitters. The emitter blockages were often a direct result of poor designs which did not adequately cater for sufficient flushing velocities, nor provide correct chemigation injection facilities, nor address pump intake arrangements and water quality characteristics, especially in regard to the high levels of iron present (Griffiths and Lecler, 2001).

4.2.2 Analysis of MIPU data for furrow irrigation systems

The determination of representative low quarter distribution uniformity, DU_{lq} , values (cf. Chapter 2) for furrow irrigation systems was difficult. In addition to the variation in water applied to individual furrows, there was variation in the amount of water infiltrated down the length of a furrow. These variations also differed with each irrigation water application, dependent on both antecedent soil water conditions and management control (Griffiths, 2003). In addition, there were thousands of furrows on each estate and only a sample of these could be evaluated within the constraints of this study. Thus, for furrow irrigation systems, the following procedure was considered to be the most appropriate way to analyse the data reported by the MIPU.

- The average depth of water applied to every furrow was normalised by converting to an equivalent percentage of the associated field's reported TAM value (%TAM).
- The %TAM values derived from all the furrows and fields associated with a particular type of furrow irrigation system (i.e. in-row or inter-row) on each estate were used to calculate a globally representative DU_{lq} and %TAM value for each of the three large estates and types of furrow irrigation system (cf. Chapter 2).

Although these DU_{lq} and %TAM values represented only a sample of the water application characteristics for the different furrow irrigation systems on each estate, they were, nevertheless considered to be indicative of the major features of furrow irrigation systems in the Lowveld. The analysis showed that the variation in the amounts of water applied into individual furrows was very high. The average amount of water applied per application was also excessive, relative to the reported soil TAM values, particularly for the in-row furrows (cf Table 4.3).

Table 4.3 Average low quarter distribution uniformity (DU_{lq}) and irrigation application depths for furrow irrigation (after Griffiths and Lecler 2001 and Griffiths, 2003)

System Type	**Value Of DU_{lq} Calculated Using All Furrows[1]**	**Mean Irrigation Application Amount As A Percentage Of TAM (%TAM)**	**Number Of Furrow Measurements**
In-row Furrow (Hippo Valley Estate)	48	73	69
In-row Furrow (Triangle Estate - 1st, 2nd and 3rd irrigation applications)	35	116[2]	254
In-row Furrow (Triangle Estate - 4th and subsequent irrigation applications)	61	68	93
In-row Furrow (Mkwasine Estate)	52	71	96
Benchmark[3]	> 75	< 60	
Inter-row Furrow (Hippo Valley Estate)	60	62	12
Inter-row Furrow (Triangle Estate)	-	-	0
Inter-row Furrow (Mkwasine Estate)	28	62	38
Benchmark[3]	> 75	< 60	

[1] DUlq = low quarter distribution uniformity based on measurements of depth of water applied relative to the field's total available moisture (TAM), calculated using data from flow measurements into all furrows on all fields evaluated by the MIPU trained evaluation teams on each estate (cf. Chapter 2).

[2] According to Triangle Estate's irrigation scheduling recommendations, the magnitude of the first three irrigation applications after cutting or planting is meant to be equivalent to the soil's TAM, thereafter the applications are meant to be equivalent to 50% of the soil's TAM value. Approximately 3% percent of the furrow measurements were excluded from the analysis as outliers. Recorded applications in these furrows were so high that the results (especially the mean) would have been severely biased and not representative of 97% of the fields.

[3] 'Benchmark' refers to the value of the relevant performance measure that should be expected and attainable in practice if the system was designed and installed according to reasonable standards.

It should be noted that although the benchmark performance standards shown in Table 4.3 are generally applicable, they might be very difficult and/or expensive to achieve on certain fields, for example, if soils have very high infiltration rates, low values of TAM, or the topography is very variable, and/or if long furrows are desired for efficient mechanisation of field operations.

4.2.3 *ZIMsched 2.0* simulations

For floppy, drip, hand-moved sprinkler and centre pivot irrigation systems *ZIMsched 2.0* was used to simulate the water balance and associated yields of ERC using the CU, SU and the %TAM values shown in Table 4.2. The main watering (irrigation scheduling) strategy used in the Lowveld for each of these systems was simulated, together with a more optimal strategy.

For furrow irrigation systems *ZIMsched 2.0* was used to simulate the water balance and associated yields of ERC, using the DU_{lq} and %TAM values shown in Table 4.3. A key characteristic of the furrow irrigation systems was that the average magnitude of the irrigation water applications was excessive relative to the soil's TAM, for all systems and on all estates.

4.2.3.1 Floppy irrigation systems

A number of private farmers and Triangle Estates (TE) used floppy irrigation systems. The private farmers used a variety of water management approaches and TE followed prescribed irrigation scheduling guidelines which are detailed in Appendix E. The irrigation water management (scheduling) guidelines used by TE were programmed in *ZIMsched 2.0* so that they could be replicated. The performance of TE's scheduling guidelines in terms of the water balance and relative yields of ERC was then compared to scheduling using the water budget of *ZIMsched 2.0*. The results of this comparison are shown in Table 4.4. Spray evaporation and wind drift losses were assumed to be 8 % (cf. Chapter 2).

Dry seasons required up to 40 % more irrigation water than wet seasons. On average, gross irrigation water applied from the field edge could be reduced from 15.9 Ml/ha to 11.7 Ml/ha if the water management guidelines were changed and *ZIMsched 2.0* was used for irrigation scheduling. This represents a saving in water of approximately 26 %. The over-watering resulting from scheduling according to TE's recommendations compensated to an extent for the spatial variability in water applications, and resulted in a slight (4 %) benefit in the average yield of simulated ERC. Therefore, the scheduling recommendations derived using *ZIMsched 2.0* could be adjusted, depending on the uniformity (evenness) with which water is applied, especially during dry years when a larger portion of the crop's water requirement is supplied by irrigation rather than rainfall (cf. Table 4.4). Whether or not an adjustment is warranted would depend on whether, and how often, the extra revenue from the yield benefit exceeded the direct and opportunity cost of the additional water. Case studies on such topics are discussed in Chapter 5. The water productivity i.e. crop yield per unit of water applied, could be increased by approximately 19 % through the implementation of scheduling recommendations derived using *ZIMsched 2.0.*

Table 4.4 Comparison of the performance of floppy irrigation systems: Triangle Estates water management vs scheduling with *ZIMsched 2.0*. Values shown are representative of systems in the top third of systems in terms of performance (i.e. CU = 81) and averaged for April, June and October cut crops

Rainfall Season	**Gross Irrigation Applications (Ml/ha)**		**Irrigation Efficiency**[1]		**Relative Estimated Recoverable Crystal (%)**		**Relative Water Productivity (%)**[2]	
	Triangle[3]	***ZIMsched***	**Triangle**[3]	***ZIMsched***	**Triangle**[3]	***ZIMsched***	**Triangle**[3]	***ZIMsched***
High	14.3	9.9	56	67	102.4	100	100	120
Medium	15.4	11.3	63	76	104.7	100	100	121
Low	18.0	13.9	67	78	104.8	100	100	117
Mean	15.9	11.7	62	74	104	100	100	119

[1] Irrigation Efficiency = Transpiration (mm) x 100 / (Rain + Gross Irrigation Water Applied) (mm)
[2] Water Productivity = Estimated Recoverable Crystal (t/ha/annum) x 100 / Gross Irrigation Water Applied (mm)
[3] Triangle = Scheduling according to Triangle Estate guidelines (cf. Appendix E)

The effect of the standard to which floppy irrigation systems were designed and installed was evaluated by comparing simulated irrigation efficiency and relative yields of ERC for systems as they stood, to yields and efficiencies simulated assuming an appropriate (practically attainable) standard, i.e. with a CU equal to 82. Results of this comparison are shown in Table 4.5. The range of irrigation efficiencies and relative yields of ERC for the floppy irrigation systems evaluated in the Lowveld was small, indicating that it is a fairly robust system. Only relatively small gains could be attained by improvements to the design and installation, *viz.* 4 % in irrigation efficiency and 6 % in the yields of ERC.

Table 4.5 Performance of the top, middle and lower third of floppy irrigation systems evaluated in the Lowveld relative to a system designed and installed according to appropriate and practically attainable standard, and with irrigation water applications scheduled using *ZIMsched 2.0*

System Rating	**Median Irrigation Efficiency[1]**	**Median Relative Estimated Recoverable Crystal (%)**	**Median Amount of Drainage Water (mm)**
Upper Third of Systems	74	100	298
Middle Third of Systems	71	96	337
Lower Third of Systems	70	94	357
Benchmark[2]	74	100	294

[1] Irrigation Efficiency = Transpiration (mm) x 100 / (Rain + Gross Irrigation Water Applied) (mm) (Averaged for dry, normal and wet seasons)

[2] Benchmark = Performance simulated with a CU = 82

4.2.3.2 Drip irrigation systems

Most of the drip irrigation systems in the Lowveld were owned and operated by private growers. TE and HVE only had small irrigation 'trials'; approximately 85 hectares and 15 hectares respectively. Before the development of *ZIMsched 2.0,* most private growers were guided by the scheduling guidelines given in the Zimbabwe Sugarcane Production Manual (SPM) edited by Clowes and Breakwell (1998). In order to evaluate the SPM guidelines, they were programmed into *ZIMsched 2.0* so that they could be replicated and compared to scheduling with *ZIMsched 2.0*. The results of this analysis are shown in Table 4.6

As with the floppy irrigation systems, there were substantial variations between irrigation water applied depending on the rainfall of the season. On average, gross irrigation water applied from the field edge could be reduced from 13.7 Ml/ha to 10.2 Ml/ha if the water management was done according to recommendations provided by *ZIMsched 2.0* rather than the SPM. This represents a saving in water of approximately 26 %. The simulated reduction in applied water relative to floppy irrigation systems, i.e. an average of 1.5 Ml/ha when scheduling using *ZIMsched 2.0*, resulted because evaporation of water from the soil surface is explicitly represented in *ZIMsched 2.0* and with sub-surface drip irrigation, hardly any of the soil surface is wetted (depending on the depth of the drip emitters). Thus evaporation of water from the soil surface is minimal for sub-surface drip irrigation systems. In addition, no spray evaporation and wind drift losses were assumed for the drip irrigation systems. The reduction in evapotranspiration (ET) resulting from the reduction in evaporation of water from the soil surface is not reflected in the SPM scheduling recommendations. These were originally developed for furrow and overhead irrigation systems.

Table 4.6 Comparison of the performance of drip irrigation systems: Zimbabwe Sugarcane Production Manual water management guidelines vs scheduling with *ZIMsched 2.0*. Values shown are representative of systems in the top third of systems in terms of performance (i.e. SU = 84)

Rainfall Season	**Gross Irrigation Applications (Ml/ha)**		**Irrigation Efficiency**[1]		**Relative Estimated Recoverable Crystal (%)**		**Relative Water Productivity (%)**[2]	
	ZPM[3]	***ZIMsched***	**ZPM**[3]	***ZIMsched***	**ZPM**[3]	***ZIMsched***	**ZPM**[3]	***ZIMsched***
High	12.6	8.5	61	74	100.7	100	100	123
Medium	13.6	9.9	70	86	101.3	100	100	124
Low	15.0	12.3	78	89	101.9	100	100	115
Mean	13.7	10.2	70	83	101.0	100	100	121

[1] Irrigation Efficiency = Transpiration (mm) x 100 / (Rain + Gross Irrigation Water Applied) (mm)
[2] Water Productivity = Estimated Recoverable Crystal (t/ha/annum) x 100 / (Rain + Gross Irrigation Water Applied) (mm)
[3] ZPM = Scheduling using Pan guidelines given in the Zimbabwe Sugarcane Production Manual (Clowes and Breakwell, 1998)

The relative over-watering inherent in the SPM scheduling guidelines, when used with drip irrigation systems, compensated to a degree for the imperfect distribution uniformity or spatial variation in irrigation water applications. As a result, the simulated yields of ERC were marginally higher than the yields simulated using *ZIMsched 2.0* for scheduling (cf. Table 4.6). The simulated water productivity i.e. yield per unit of water applied, was increased by approximately 21 % using the irrigation scheduling recommendations derived using *ZIMsched 2.0*.

The effect of the standard to which drip irrigation systems were designed and installed was evaluated by comparing simulated irrigation efficiency and relative yields of ERC for systems as they stood, to yields and efficiencies simulated assuming an appropriate (practically attainable) standard, i.e. with a SU equal to 88. Results of this comparison are shown in Table 4.7

Table 4.7 Performance of the top, middle and lower third of drip irrigation systems relative to a system designed and installed with a SU equal to 88, and with irrigation water applications scheduled using *ZIMsched*

System Rating	**Median Irrigation Efficiency[1]**	**Median Relative Estimated Recoverable Crystal (%)**	**Median Amount of Drainage Water (mm)**
Upper Third of Systems	83	99	271
Middle Third of Systems	80	95	316
Lower Third of Systems	76	88	387
Benchmark[2]	84	100	258

[1] Irrigation Efficiency = Transpiration (mm) x 100 / (Rain + Gross Irrigation Water Applied) (mm) (Averaged for dry, normal and wet seasons)

[2] Benchmark = Performance simulated with a SU = 88

The range of irrigation efficiencies and relative ERC yields simulated for drip irrigation systems was relatively large compared with the floppy irrigation systems, indicating that drip irrigation is not as robust a system. Assuming proper scheduling, improvements to the design, installation and/or maintenance (thereby improving the value of the SU to the benchmark of 88) resulted in average simulated gains of 8 % in irrigation efficiency and 12 % in the yields of ERC for one third of the systems evaluated. This highlights that great care needs to be taken in the design, installation and maintenance of drip irrigation systems.

4.2.3.3 Centre pivot irrigation systems

Both HVE and TE and a number of private growers have centre pivot irrigation systems. In-field evaluations undertaken by the MIPU showed that most of these pivots had CU values above 85, which is very good (cf. Table 4.2) and concurs with evaluations of pivots undertaken in the South African sugar industry (Ascough and Kiker, 2002). Thus, it is apparent that a characteristic of centre pivots is that they have very good CU values. Consequently, assuming that the pivots were designed with water application rates well matched to soil infiltration characteristics, the major differences in the performance of centre pivots would be due to the water management system being followed. In the performance analysis reported here the focus was, therefore, on a comparison of the water management, i.e. irrigation scheduling, approaches used by HVE and TE. The results of this analysis are shown in Table 4.8. Spray evaporation and wind-drift losses were assumed to be 8 % of the net irrigation water applied to the soil in all cases (cf. Chapter 2).

There was little difference in the performance of centre pivots for the two water management systems used by TE and HVE, with TE's recommendations resulting in slightly higher simulated water use. Both estates' water management recommendations resulted in substantially higher simulated water use compared with scheduling with *ZIMsched 2.0*, i.e. between 18 % and 25 % more water respectively. The use of centre pivots often results in relatively high evaporation from the bare soil surface in the early season because of frequent watering. Relatively frequent and small irrigation water applications of approximately 25 mm per application are characteristic of centre pivots because larger water applications often result in excessive runoff due to the high water application rates at the outer towers (Reinders and Louw, 1984). Thus, the early season scheduling guidelines used by HVE (cf. Appendix F) resulted in slight under-watering in the early season, with gradual depletion of the available soil water store. The soil water store is then gradually replenished during the remainder of the season and prior to drying off, due to slight over-watering. The under-watering in the early season is because the HVE scheduling guidelines were originally developed for furrow irrigation systems. With furrow irrigation systems only approximately 60 % of the soil surface is wetted, and there are relatively fewer and larger early season irrigation water applications. Therefore, evaporation from the soil surface is relatively low. The result of the slight under-watering in the early season and over-watering later, associated with HVE's scheduling recommendations was reflected in the slight reduction in simulated yields of ERC relative to the yields of ERC which were simulated when scheduling with *ZIMsched 2.0*.

With centre pivots, because the water applications were relatively even, there was a different dynamic between over-watering and irrigation uniformity when compared with irrigation systems which have more uneven water applications, such as the furrow irrigation systems. The over-watering inherent, for example, in TE's scheduling recommendations, resulted in a slight simulated yield penalty.

Table 4.8 The performance of centre pivots with various water management guidelines. Results from simulations with *ZIMsched 2.0* assumed sandy clay soils with a TAM of 80 mm and a net 24 mm of water applied at each irrigation water application

Performance Measure	**Hippo Valley Estate's Water Management**	**Triangle Estate's Water Management**	***ZIMsched* Water Management**
Relative Irrigation Water Applied (%)	118 (14.2 Ml/ha)	125 (15.0 Ml/ha)	100 (12.0 Ml/ha)
Relative Estimated Recoverable Crystal (%)	96	98	100
Irrigation Efficiency[1]	63	62	72
Relative Water Use Productivity (%) [2]	85	84	100
Relative Drainage (%)	178	198	100

[1] Irrigation Efficiency = Transpiration (mm) x 100 / (Rain + Gross Irrigation Water Applied) (mm)

[2] Water use productivity = Estimated Recoverable Crystal (t/ha/annum) x 100 / (Rain + Gross Irrigation water applied) (mm)

4.2.3.4 Hand-moved sprinkler irrigation systems

A major portion of the sugarcane grown on TE is irrigated using hand-moved overhead sprinkler irrigation systems. The MIPU provided results for 68 'in-field' sprinkler uniformity evaluations. For these fields the performance of the irrigation hardware was excellent, with the majority of the CU values in excess of what would be expected if the systems were designed and installed according to appropriate standards, i.e. with a CU greater than 84. The effects of scheduling irrigation water applications using TE's water management recommendations were compared to scheduling irrigation water applications using *ZIMsched 2.0*. The irrigation water management (scheduling) guidelines used by TE (cf. Appendix E) were applied consistently for furrow, floppy and overhead sprinkler irrigation systems (Mtunzi, 2002). The results of this comparison of water management systems are shown in Table 4.9. Spray evaporation and wind-drift losses were assumed to be 10 % of the net irrigation water applied to the soil (cf. Chapter 2). Slightly higher losses for spray evaporation and wind-drift were assumed for the hand-moved sprinkler systems, because the sprinklers operate in relative isolation and therefore there is not as great a micro-climate effect as compared with centre pivot and floppy irrigation systems.

Again the simulated amounts of irrigation water applied were very dependent on rainfall. On average the simulated amount of irrigation water applied from the field edge was reduced from 15.9 Ml/ha to 11.3 Ml/ha when *ZIMsched 2.0* was used for irrigation scheduling. This represented a saving in water of approximately 29 %. In contrast to drip and furrow irrigation systems, the uniformity of the sprinkler irrigation systems, which were evaluated, was excellent and the over-watering resulting from scheduling according to Triangle's recommendations resulted in only a slight simulated yield benefit of 2 %. The high uniformity reflected the good maintenance practices, which were carried out at TE, especially the regular replacement of sprinkler nozzles. The simulated water productivity i.e. yield per unit of water applied, was increased by approximately 25 % through scheduling irrigation water applications with *ZIMsched 2.0*.

Table 4.9 Comparison of the performance of overhead hand-moved sprinkler irrigation systems: Triangle Estates' water management guidelines vs scheduling with *ZIMsched 2.0*. Values shown are representative of systems in the top third of systems in terms of performance (i.e. CU = 89 and averaged for April, June and October cut crops)

Rainfall Season	**Gross Irrigation Applications (Ml/ha)**		**Irrigation Efficiency**[1]		**Relative Estimated Recoverable Crystal (%)**		**Relative Water Productivity (%)**[2]	
	Triangle[3]	***ZIMsched***	**Triangle**[3]	***ZIMsched***	**Triangle**[3]	***ZIMsched***	**Triangle**[3]	***ZIMsched***
High	14.0	9.4	57	70	101	100	100	124
Medium	15.8	10.8	62	80	102	100	100	130
Low	17.8	13.6	68	82	102	100	100	122
Mean	15.9	11.3	62.3	77	102	100	100	125

[1] Irrigation Efficiency = Transpiration (mm) x 100 / (Rain + Gross Irrigation Water Applied) (mm)

[2] Water Productivity = Estimated Recoverable Crystal (t/ha/annum) x 100 / (Rain + Gross Irrigation Water Applied) (mm)

[3] Triangle = Scheduling according to Triangle Estate's irrigation water management guidelines

The potential to improve performance of the overhead sprinkler irrigation systems through improved distribution uniformities was considered minimal because the systems were already performing at a high standard (cf. Table 4.2).

4.2.3.5 Hippo Valley Estate: In-row furrow irrigation

The results of the analysis of the water management system used by HVE given the in-row furrow performance characteristics on that estate are shown in Table 4.10. The HVE scheduling recommendations are described in Appendix F. On average, the simulated gross irrigation water applied from the furrow edge was reduced from 17.2 Ml/ha to 12.5 Ml/ha using *ZIMsched 2.0*. This represented a saving in water of approximately 27 %. However, the over-watering of the HVE scheduling system compensated for the poor distribution uniformity (i.e. DU_{lq} = 48) and resulted in slight simulated ERC yield benefits of approximately 5 % relative to scheduling with *ZIMsched 2.0* and assuming good drainage rates.

Table 4.10 Comparison of the performance of in-row furrow irrigation systems: Hippo Valley Estate (HVE) water management guidelines vs scheduling with *ZIMsched 2.0*. Values shown are based on average system performance characteristics derived using all the in-row furrow evaluation data.

Rainfall Season	**Gross Irrigation Applications (Ml/ha)**		**Irrigation Efficiency[1]**		**Relative Estimated Recoverable Crystal (%)**		**Relative Water Productivity (%)[2]**	
	HVE[3]	**ZIMsched**	**HVE[3]**	**ZIMsched**	**HVE[3]**	**ZIMsched**	**HVE[3]**	**ZIMsched**
High	15.2	11	52	61	103	100	100	117
Medium	17.0	11.7	57	70	105	100	100	125
Low	19.5	14.7	60	72	105	100	100	119
Mean	17.2	12.5	56	68	105	100	100	120

[1] Irrigation Efficiency = Transpiration (mm) x 100 / (Rain + Gross Irrigation Water Applied) (mm)

[2] Water Productivity = Estimated Recoverable Crystal (t/ha/annum) x 100 / (Rain + Gross Irrigation Water Applied) (mm)

[3] HVE = Scheduling using pan factors and effective rainfall formulae given in the Hippo Valley Estate irrigation scheduling recommendations (Appendix F)

The simulated water productivity, i.e. yield per unit of water applied, was increased by approximately 20 % through the use of *ZIMsched 2.0* for irrigation scheduling. The increase in simulated amounts of water applied relative to floppy irrigation systems was small, and ranged from 0.8 Ml/ha to 1.3 Ml/ha. These differences occurred because the irrigation water applications of the furrow irrigation system were not well matched to the reported soil water holding characteristics, i.e. TAM values (cf. Table 4.3). This mismatch outweighed any potential water conservation advantages of the furrow irrigation system, which include reductions in spray evaporation and wind drift, as well as reduced evaporation from the soil surface due to partial surface wetting and less frequent irrigation applications. Losses in unlined furrow feeder canals were not added to the water requirements shown here. These conveyance losses constitute a separate and variable water loss which is potentially, but not always pertinent to furrow irrigation.

The effect of the design / lay-out and operation of furrow irrigation systems at HVE was evaluated by comparing simulated irrigation efficiency and the relative yields of ERC for systems as evaluated by the MIPU to the simulated performance of a furrow irrigation system with a DU_{lq} of 75 and with the amount of water applied per irrigation applications equal to 60 % of the soil's TAM value. Note, however, that such performance standards may be very difficult and/or costly to achieve, depending on a particular field's topography and soil characteristics. Results of this analysis are shown in Table 4.11.

Table 4.11 Performance of in-row furrow irrigation systems at Hippo Valley Estates compared to a hypothetical benchmark system which had a DU_{lq} of 75 and the amount of irrigation water applied per application equal to 60 % of the soil's total available moisture (TAM), and irrigation scheduling using *ZIMsched 2.0*.

System	Mean Irrigation Efficiency[1]	Mean Relative Estimated Recoverable Crystal (%)	Mean Drainage Water (mm)
HVE hve	56	105	958
HVE $_{ZIMsched}$	68	100	550
Benchmark	77	108	350

[1] Irrigation Efficiency = Transpiration (mm) x 100 / (Rain + Gross Irrigation Water Applied) (mm)
HVE hve = Furrow systems performance as measured, but scheduling using Hippo Valley's scheduling recommendations.
HVE $_{ZIMsched}$ = Furrow systems performance as measured, but scheduling using *ZIMsched 2.0*.

Simulated irrigation efficiency was increased from 56 percent to 77 percent through: improvements to the amount of irrigation water applied per application, the DU_{lq} and through scheduling irrigation water applications using *ZIMsched 2.0* (cf. Table 4.11). However, the potential to increase ERC when assuming HVEs' water management recommendations and adequate drainage was relatively small. This indicates that if HVE continue to use their own recommendations for water management, the major benefit from improved irrigation systems design, installation and operation would be reduced drainage and water use. The reduction in simulated water use resulted from irrigation water applications which were better matched to soil water holding characteristics (TAM values), i.e. the amount of water applied per application, was reduced from 73 % of the soil's TAM to 60 % of the soil's TAM (cf. Table 4.3). Simulations showed that the over-watering inherent in HVE's scheduling recommendations compensates, to an extent, for poor distribution uniformities, at a cost, however, of a substantial increase in water use and drainage (deep percolation). If *ZIMsched 2.0* was used for irrigation scheduling the benefit from having improved distribution uniformity, i.e. a DU_{lq} equal to 75, was substantial. Simulated yields of ERC increased by approximately 8 %. The reason for this was that the relative proportion of the area being under-watered with more precise irrigation scheduling was reduced through the improved distribution uniformity.

4.2.3.6 Hippo Valley Estate: Inter-row furrow irrigation

The results of the analysis of the water management system used by HVE, given the inter-row furrow performance characteristics on that estate, are shown in Table 4.12. On average, the simulated amount of irrigation water applied from the furrow edge was reduced by approximately 14 % relative to HVE's in-row furrow irrigation systems. This was expected because, from a conceptual viewpoint, the irrigation advance front times are less restricted with inter-row furrow irrigation systems compared with in-row furrow irrigation systems. The reason for this is that there is no sugarcane in the inter-row. Thus, for a given furrow length and slope, an overall reduction in the intake opportunity times and associated infiltration amounts could be expected with the inter-row furrow irrigation systems.

Average simulated irrigation water applications were reduced from 14.8 Ml/ha to 11.4 Ml/ha when the water management was effected according to recommendations provided by *ZIMsched 2.0* rather than the existing HVE recommendations. This represented water saving of approximately 23 %. As with the in-row furrow irrigation systems, the over-watering inherent in the HVE scheduling recommendations compensated for the spatial variation in water applications and resulted in a slight simulated benefit in the yield of ERC, i.e. a 3 %

increase relative to scheduling with *ZIMsched 2.0*. These yield benefits from over-watering were not as high as those simulated using the in-row furrow irrigation systems, because the distribution uniformity of the inter-row furrow irrigation systems was better, i.e. DU equal to 60 for inter-row furrow irrigation systems versus a DU equal to 48 for the in-row furrow irrigation systems (cf. Table 4.3). The simulated water productivity i.e. yield per unit of water applied was increased by approximately 16 % using *ZIMsched 2.0* to schedule irrigation water applications. Overall, although only relatively few inter-row furrows were evaluated, the performance of inter-row furrow irrigation systems on HVE was much better than the performance of the in-row furrow irrigation systems.

Table 4.12 Comparison of the performance of inter-row furrow irrigation systems: Hippo Valley Estate water management guidelines vs scheduling with *ZIMsched 2.0*. Values shown are based on average system performance characteristics derived using all the in-row furrow evaluations.

Rainfall Season	**Gross Irrigation Applications (Ml/ha)**		**Irrigation Efficiency[1]**		**Relative Estimated Recoverable Crystal (%)**		**Relative Water Productivity (%)[2]**	
	HVE[3]	***ZIMsched***	**HVE[3]**	***ZIMsched***	**HVE[3]**	***ZIMsched***	**HVE[3]**	***ZIMsched***
High	13.1	9.8	58	66	102	100	100	114
Medium	14.6	10.7	64	77	104	100	100	120
Low	16.8	13.8	69	77	103	100	100	113
Mean	14.8	11.4	64	73	103	100	100	116

[1] Irrigation Efficiency = Transpiration (mm) x 100 / (Rain + Gross Irrigation Water Applied) (mm)

[2] Water Productivity = Estimated Recoverable Crystal (t/ha/annum) x 100 / (Rain + Gross Irrigation Water Applied) (mm)

[3] HVE = Scheduling using guidelines recommended by Hippo Valley Estates (Appendix F)

The effect of the design / lay-out and operation of the inter-row furrow irrigation systems at HVE was evaluated by comparing simulating irrigation efficiency and relative ERC yields to the performance of a hypothetical furrow irrigation system designed and laid out according to appropriate standards, i.e. with a DU_{lq} of 75 and with the amount of water applied per irrigation application equal to 60 % of the soil's TAM value. The results of this analysis are shown in Table 4.13.

Table 4.13 Performance of inter-row furrow irrigation systems at Hippo Valley Estates compared with a hypothetical benchmark system which had a DU_{lq} of 75 and the amount of irrigation water applied per application equal to 60 % of the soil's total available moisture (TAM), and irrigation scheduling using *ZIMsched 2.0*.

System	**Irrigation Efficiency**[1]	**Relative Estimated Recoverable Crystal (%)**	**Average Drainage Water (mm)**
HVE $_{hve}$[2]	64	103	703
HVE $_{ZIMsched}$[3]	73	100	416
Benchmark	77	104	350

[1] Irrigation Efficiency = Transpiration (mm) x 100 / (Rain + Gross Irrigation Water Applied) (mm)

[2] HVE hve = Furrow systems performance as measured but scheduling using Hippo Valley's scheduling recommendations

[3] HVE $_{ZIMsched}$ = Furrow systems performance as measured but scheduling using *ZIMsched 2.0*

With the improved DU_{lq}, and the simulated irrigation efficiency was increased from 64 % to 77 %. However, the potential to increase yields of ERC using the HVE water management recommendations was minimal. Thus, assuming HVE's existing irrigation scheduling recommendations, the major benefit from improving the distribution uniformity of applied water and reducing the amount of irrigation water applied per application would be water saving, and reduced drainage, similar to the results for the in-row systems. If *ZIMsched 2.0* was used for irrigation scheduling, the benefit in simulated yields of ERC resulting from the improved DU_{lq} was approximately 4 %. This is not as high as the 8 % potential improvement for the in-row furrow irrigation systems because the inter-row furrows were already performing at a higher standard in terms of DU_{lq}.

4.2.3.7 Mkwasine Estate: In-row furrow irrigation

The results of the analysis of the water management system used by ME given the in-row furrow performance characteristics on that estate are shown in Table 4.14. The ME scheduling recommendations are described in Appendix G.

Table 4.14 Comparison of the performance of in-row furrow irrigation systems: Mkwasine Estate water management guidelines vs scheduling with *ZIMsched 2.0*. Values shown are based on average system performance characteristics derived using all the in-row furrow evaluations

Rainfall Season	**Gross Irrigation Applications (Ml/ha)**		**Irrigation Efficiency**[1]		**Relative Estimated Recoverable Crystal (%)**		**Relative Water Productivity (%)**[2]	
	ME[3]	***ZIMsched***	**ME**[3]	***ZIMsched***	**ME**[3]	***ZIMsched***	**ME**[3]	***ZIMsched***
High	15	9.5	52	64	104	100	100	125
Medium	17.4	11.0	55	74	105	100	100	135
Low	18.1	14.5	62	71	104	100	100	114
Mean	16.8	11.7	56	70	105	100	100	125

[1] Irrigation Efficiency = Transpiration (mm) x 100 / (Rain + Gross Irrigation Water Applied) (mm)
[2] Water Productivity = Estimated Recoverable Crystal (t/ha/annum) x 100 / (Rain + Gross Irrigation Water Applied) (mm)
[3] ME = Scheduling using guidelines given by Mkwasine Estate (Appendix G)

On average gross irrigation water applied from the furrow edge was reduced from 16.8 Ml/ha to 11.7 Ml/ha (i.e. 30 %) using *ZIMsched 2.0*. However, because of the spatial variations in applied water, reflected in the low DU_{lq} of 52 (cf. Table 4.3), the more precise irrigation scheduling resulted in a slight reduction in the simulated yield of ERC of approximately 5 %. The simulated water productivity was increased by 25 % through using *ZIMsched 2.0* for irrigation scheduling. There was a slight decrease in applied water relative to the in-row furrow irrigation systems on HVE. This was due to the deeper soils at ME, i.e. the average TAM of furrows evaluated at ME was 100 mm versus an average TAM of furrows evaluated at HVE of only 72 mm. The associated irrigation cycles were, therefore, slightly longer. Again, it should be noted that losses in unlined furrow feeder canals were not added to the water requirements shown here.

The effect of the design / lay-out and operation of furrow irrigation systems at ME was evaluated as for HVE. The results are shown in Table 4.15.

Table 4.15 Performance of in-row furrow irrigation systems at Mkwasine Estate compared with a hypothetical benchmark system which had a DU_{lq} of 75 and the amount of irrigation water applied per application equal to 60 % of the soil's total available moisture (TAM), and irrigation scheduling using *ZIMsched 2.0*

System	**Irrigation Efficiency**[1]	**Relative Estimated Recoverable Crystal (%)**	**Average Drainage Water (mm)**
ME $_{Me}$	56	104	946
ME $_{ZIMsched}$	70	100	509
Benchmark	77	105	360

[1] Irrigation Efficiency = Transpiration (mm) x 100 / (Rain + Gross Irrigation Water Applied) (mm)

ME $_{Me}$ = Furrow systems performance as measured but scheduling using Mkwasine Estate's scheduling recommendations

ME $_{ZIMsched}$ = Furrow systems performance as measured but scheduling using *ZIMsched 2.0*

The potential to increase the irrigation efficiency of the in-row furrow irrigation systems at ME was relatively large, with the results of this analysis showing that irrigation efficiency could be increased from 56 % to 77 %. The potential to increase yields of ERC using the ME water management recommendations was, however, relatively small, assuming drainage was adequate. These results were similar to those for the in-row furrow irrigation systems on HVE. Thus, assuming ME's existing irrigation scheduling recommendations, the major benefit from improving the distribution uniformity of applied water and reducing the amount of irrigation water applied per application would be water saving, and reduced drainage. If *ZIMsched 2.0* was used for irrigation scheduling, the benefit in simulated yields of ERC resulting from the improved DU_{lq} was approximately 5 %. This is not as high as the 8 % potential improvement for the in-row furrow irrigation systems at HVE because the soils at ME had higher values of TAM and the initial DU_{lq} values were slightly higher than those at HVE (cf. Table 4.3). Assuming irrigation water applications were scheduled using *ZIMsched 2.0*, the improved value of the DU_{lq} resulted in the average simulated irrigation efficiency increasing from 70 % to 77 %.

4.2.3.8 Mkwasine Estate: Inter-row furrow irrigation

The results of the analysis of the water management system used by ME given the inter-row furrow performance characteristics on that estate are shown in Table 4.16. On average, gross irrigation water applied from the furrow edge was reduced by approximately 12 % relative to ME's in-row furrow irrigation systems. However, because of the very poor uniformity of the inter-row furrow irrigation systems evaluated at ME, which resulted in a DU_{lq} of 28, the yields for ME's inter-row furrow irrigation systems were simulated to be 12 % lower than the yields on the in-row furrow irrigation systems. On average, water applications could be reduced from 14.7 Ml/ha to 10.8 Ml/ha using *ZIMsched 2.0* rather than the existing ME irrigation scheduling recommendations. This represented a saving in water of approximately 27 %. As with the in-row furrow irrigation systems, the over-watering of the ME scheduling system compensated for the spatial variation in water applications and resulted in slight simulated benefit in yield of ERC of approximately 3 % relative to scheduling with *ZIMsched 2.0*. The simulated water productivity i.e. yield per unit of water applied, was increased by approximately 21 % using *ZIMsched 2.0* to schedule irrigation water applications.

Table 4.16 Comparison of the performance of inter-row furrow irrigation systems: Mkwasine Estate water management guidelines vs scheduling with *ZIMsched 2.0*. Values shown are based on average system performance characteristics derived using all the in-row furrow evaluations

Rainfall Season	**Gross Irrigation Applications (Ml/ha)**		**Irrigation Efficiency**[1]		**Relative Estimated Recoverable Crystal (%)**		**Relative Water Productivity (%)**[2]	
	ME[3]	***ZIMsched***	**ME**[3]	***ZIMsched***	**ME**[3]	***ZIMsched***	**ME**[3]	***ZIMsched***
High	13.1	9.2	52	63	102	100	100	119
Medium	15.2	10.2	55	71	103	100	100	130
Low	15.8	13.11	62	70	102	100	100	114
Mean	14.7	10.8	56	68	103	100	100	121

[1] Irrigation Efficiency = Transpiration (mm) x 100 / (Rain + Gross Irrigation Water Applied) (mm)
[2] Water Productivity = Estimated Recoverable Crystal (t/ha/annum) x 100 / (Rain + Gross Irrigation Water Applied) (mm)
[3] ME = Scheduling using guidelines recommended by Mkwasine Estate (Appendix G)

The effects of the design / lay-out and operation of the inter-row furrow irrigation systems at ME was evaluated similarly to the HVE systems. The results of this analysis are shown in Table 4.17. Simulated irrigation efficiency was increased substantially from 56 % to 77 %, and the simulated increase in the yield of ERC, assuming the ME water management recommendations was also substantial, i.e. 14 %. When *ZIMsched 2.0* was used for irrigation scheduling the simulated benefit in the yield was even greater, i.e. approximately 17 %. These potential increases were very large because the inter-row furrows evaluated at ME were performing at a very low standard in terms of application uniformities, i.e. the initial DU_{lq} value of 28 was considerably lower than the benchmark DU_{lq} value 75 (cf. Table 4.3).

Table 4.17 Performance of inter-row furrow irrigation systems at Mkwasine Estate compared with a hypothetical benchmark system which had a DU_{lq} of 75 and the amount of irrigation water applied per application equal to 60 % of the soil's total available moisture (TAM), and irrigation scheduling using *ZIMsched 2.0*.

System	**Irrigation Efficiency**[1]	**Relative Estimated Recoverable Crystal (%)**	**Average Drainage Water (mm)**
ME $_{Me}$ [2]	56	103	849
ME $_{ZIMsched}$ [3]	68	100	508
Benchmark	77	117	360

[1] Irrigation Efficiency = Transpiration x 100/ (Rain + Gross Irrigation Water Applied)

[2] ME $_{Me}$ = Furrow systems performance as measured but scheduling using Mkwasine Estate's recommendations (Appendix G)

[3] ME $_{ZIMsched}$ = Furrow systems performance as measured but scheduling using *ZIMsched 2.0*

4.2.3.9 Triangle Estate: In-row furrow irrigation

All the furrow irrigation systems evaluated on TE were in-row furrow irrigation systems. The results of the analysis of the water management system used by TE, given the in-row furrow performance characteristics on that estate, are shown in Table 4.18. The Triangle scheduling recommendations are described in Appendix E. The scheduling approach used at TE was very different to the approaches used on HVE and ME. At TE, the first three irrigation water applications were timed according to calendar days, and were intended to be equivalent in magnitude to the soil's TAM value. Thereafter, a water budget was used based on A-pan equivalent evaporation and a crop factor of 1.0, with soil water deficits and associated irrigation water applications intended to be equivalent to 50 % of the soil's TAM (cf. Appendix E). The results for TE were based on the simulation of an April cut crop only.

Table 4.18 Comparison of the performance of in-row furrow irrigation systems: Triangle Estate water management vs scheduling with *ZIMsched 2.0*. Values shown are based on average system performance characteristics derived using all the in-row furrow evaluations undertaken by the MIPU trained evaluation teams

Rainfall Season	**Gross Irrigation Applications (Ml/ha)**		**Irrigation Efficiency[1]**		**Relative Estimated Recoverable Crystal (%)**		**Relative Water Productivity (%)[2]**	
	Triangle[3]	**ZIMsched**	**Triangle[3]**	**ZIMsched**	**Triangle[3]**	**ZIMsched**	**Triangle[3]**	**ZIMsched**
High	14.5	9.2	56	70	100	98.2	100	127
Medium	16.4	11.1	59	76	100	96	100	128
Low	18.3	14.9	66	76	100	99	100	117
Mean	16.4	11.7	60	74	100	98	100	124

[1] Irrigation Efficiency = Transpiration (mm) x 100 / (Rain + Gross Irrigation Water Applied) (mm)
[2] Water Productivity = Estimated Recoverable Crystal (t/ha/a) x 100 / Gross Irrigation Water Applied (mm)
[3] Triangle = Scheduling according to Triangle Estate irrigation scheduling recommendations (Appendix E)

As with HVE and ME there were significant variations between seasonal irrigation water applications, dependent on rainfall amounts. On average gross irrigation water applied from the furrow edge was reduced from 16.4 Ml/ha to 11.7 Ml/ha using *ZIMsched 2.0* rather than the existing TE irrigation scheduling recommendations. This represented a saving in water of approximately 29 %. However, because of the variations in applied water which are reflected in the DU_{lq} values, i.e. DU_{lq} equal to 35 for the first three water applications and DU_{lq} equal to 61 for the subsequent water applications, the over-watering of the Triangle scheduling system compensated for the poor spatial distribution uniformity of water applications and resulted in only slight benefits in the simulated yields of ERC of approximately 2 % relative to scheduling with *ZIMsched 2.0*, and assuming good drainage rates. Differences between TE, HVE and ME were due mainly to differences in the average amount of irrigation water applied per application, which were related to reported, soil TAM values. The average TAM of the soils for fields evaluated at Triangle was 92 mm, which was greater than the average at HVE, *viz.* 72 mm. The simulated water productivity, or yield per unit of water applied, was increased by approximately 24 % using *ZIMsched 2.0*. It should be reiterated that losses in unlined furrows were not added to the water requirements shown here as they constitute a separate and variable water loss, potentially but not always pertinent to furrow irrigation.

The effect of the design / lay-out and operation of in-row furrow irrigation systems at TE was evaluated similarly to HVE. The results of this analysis are shown in Table 4.19.

Table 4.19 Performance of in-row furrow irrigation systems at Triangle Estates compared with a hypothetical benchmark system which had a DU_{lq} of 75, the amount of irrigation water applied per application equal to 60 % of the soil's total available moisture (TAM), and irrigation scheduling using *ZIMsched 2.0*

System	**Irrigation Efficiency**[1]	**Relative Estimated Recoverable Crystal (%)**	**Average Drainage Water (mm)**
Triangle $_{Trg}$[2]	60	100	862
Triangle $_{ZIMsched}$[3]	74	98	575
Benchmark	79	100	463

[1] Irrigation Efficiency = Transpiration (mm) x 100 / (Rain + Gross Irrigation Water Applied) (mm)
[2] Triangle $_{Trg}$ = Furrow systems performance as measured, but scheduling using Triangle's scheduling recommendations (Appendix E)
[3] Triangle $_{ZIMsched}$ = Furrow systems performance as measured but scheduling using *ZIMsched 2.0*

The potential to increase the irrigation efficiency of the in-row furrow irrigation systems at TE was relatively small, with the results of this analysis showing that irrigation efficiency could be increased from 74 % to 79 %. The potential to increase yields of ERC using the TE water management recommendations was also relatively small, assuming adequate drainage. This indicates that at Triangle the major benefit in performance would come from improved water management, rather than improvements to the design and layouts and hence the DU_{lq}. The DU_{lq} for the fourth and subsequent irrigations of 61 was relatively good, although the DU_{lq} for the first three irrigation applications of 35 was very poor. Major benefits would likely come from adjusting the amount of irrigation water applied per application in the first three irrigation water applications. This amount should be reduced to 50 % of the soil's

TAM value rather than using 100 % of the soil's TAM value, as was recommended in the Triangle irrigation scheduling guidelines.

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In order to evaluate the performance of water management and irrigation systems in the Lowveld, a strategy was formulated which hinged on the development of an irrigation systems simulation model to interpret results from evaluations undertaken by a Mobile Irrigation Performance Evaluation Unit (MIPU). Based on in-field evaluations of irrigation systems, the MIPU provided information on the distribution uniformity of water applications (i.e. DU_{lq}, SU or CU), the magnitude of these water applications relative to soil water holding characteristics, and the watering (or irrigation scheduling) strategy used. While the information and data from the MIPU were useful in their own right, considerable value was added to the MIPU data and information by translating it into associated impacts on yields of estimated recoverable crystal (ERC), water budgets and associated indices of irrigation performance, such as irrigation efficiency and water use productivity. The credibility of *ZIMsched 2.0* for simulating yields of ERC for different soil, climate and irrigation regimes was established by comparisons between observed and simulated crop yields.

One of the key findings of this study was that, if *ZIMsched 2.0* were used for irrigation scheduling, up to 30 % of the water presently used on an annual basis when there are no water restrictions, could likely be saved. However, unless the distribution uniformity of applied irrigation water is improved on the furrow and drip irrigation systems, in particular, there was evidence that slight yield losses may occur with the more precise irrigation scheduling, assuming that fields are adequately drained.

Most of the floppy, overhead sprinkler and centre pivot irrigation systems were performing at levels close to those expected had they had been designed and installed to appropriate standards. However, most of the drip irrigation systems were performing below potential. This was largely due to in-field variations in applied water, caused by sub-standard system design, installation and/or maintenance. Nevertheless, provided drip irrigation systems are designed, installed and commissioned to an appropriate standard, and then operated and maintained correctly, simulations showed that they had a slight edge on the other irrigation systems in terms of potential efficiency.

The simulated crop yields and irrigation efficiencies for the furrow irrigation systems were limited by large variations in the amounts of water applied to individual furrows, and water applications which were, on average, excessively high. Although the large water applications did compensate, to a degree, for the variations in applied water between and down the furrows, they also compromised efficiencies and could lead to further development of other problems, including raised water tables and increased soil salinity levels. On deep soils with high values of TAM and on fairly level topography, furrow irrigation could, theoretically, be almost as efficient as sub-surface drip irrigation. The reason for this is that evaporation from the bare soil surface is limited (because only a portion of the soil surface is wetted, and then only relatively infrequently), there are no spray evaporation or wind drift losses and with proper design and layout, high distribution uniformities (DU_{lq} > 75) are theoretically achievable. However, this study has shown that with furrow irrigation, there is a big gap between potential theoretical performance and what is generally achieved in practice in the Lowveld, particularly on the soils with low water holding capacities (or TAM values).

Most of the original scheduling recommendations developed in the Lowveld were based on hand-moved sprinkler and furrow irrigation systems. This study has shown that the water balance can vary considerably for the different types of irrigation systems. Differences were attributed to variations in evaporation of water from the soil surface. Therefore, irrigation scheduling guidelines should be tailored to specific types of irrigation system.

In addition to being useful for the evaluation of irrigation and water management systems, *ZIMsched 2.0* has other applications. For example, it can be used for the determination of optimal irrigation system design capacities, deficit irrigation strategies and the development of irrigation scheduling aids. Examples of the use of *ZIMsched 2.0* for these applications are described in Chapter 5.

5. OTHER IRRIGATION AND WATER MANAGEMENT TOOLS AND APPLICATIONS EMANATING FROM THIS RESEARCH

The main focus of the research described in this thesis was the development and application of methods and tools to evaluate the performance of the irrigation and water management systems in the Lowveld of Zimbabwe. In addition to this, methods and tools to determine more optimal irrigation system design capacities and water management strategies were developed. Furthermore, in order to facilitate the implementation of improved irrigation and water management strategies, a range of irrigation scheduling aids was developed. These additional developments and applications are described in this Chapter.

5.1 Tools and Methods to Support Strategic Irrigation Design and Water Management Decisions

The maximum water delivery capacity of an irrigation system depends on limitations of hardware which can have considerable cost, flexibility and efficiency implications. In order to provide a high water delivery capacity, larger pumps, motors, pump-houses, mainlines, sub-mains, laterals and/or canals are required. Therefore, designing or specifying irrigation systems with excess capacity can result in substantial cost implications. On the other hand, if the peak irrigation system capacity is too small, excessive crop yield losses may occur (cf. Chapter 2, Section 2.3.4). For the purposes of this thesis, peak irrigation system capacity is defined as:

> *"the highest rate at which an irrigation system can be used to supply water to a crop, in units equivalent to millimetre per day (mm/d)"*

Thus, a centre pivot which could be used to apply 30 mm of water every five days would have a peak irrigation system capacity equivalent to 6 mm per day. In the majority of irrigation systems designs, a comprehensive and deterministic investigation into the relationships between peak irrigation system design capacities and predicted crop yields, seasonal irrigation water applications and economic returns is seldom undertaken. Irrigation systems are frequently designed (and potentially operated) such that a crop can be irrigated without experiencing stress, even though such a strategy is unlikely to be optimal (Lecler *et* *al.*, 1994; English *et al.*, 2002). The development of a methodology to enable the selection of more optimal peak irrigation system capacities and associated operating strategies, for example, an appropriate deficit irrigation strategy, would be of great value. The use of *ZIMsched 2.0* for such an application is described here.

Crop yields and associated seasonal irrigation water applications associated with different peak irrigation system capacities were simulated using daily climate data recorded at the ZSAES during the period 1975 to 1992. Details of other information used in these simulations are shown in Table 5.1. Frequency analyses of the simulated yields of estimated recoverable crystal (ERC) and seasonal irrigation water applications are shown in Figures 5.1 and 5.2 respectively.

Table 5.1 Information used in *ZIMsched 2.0* to simulate yields of estimated recoverable crystal (ERC) and associated irrigation water use. Simulations were for a crop cut in August and for different minimal irrigation cycle times of 7 days, 6 days, 5 days, 4 days and 3 days, i.e. equivalent to irrigation system capacity limitations of 10 mm/d, 7.5 mm/d, 6 mm/d, 5 mm/d and 4.3 mm/d

Soil Texture	**Irrigation System Type**	**CU**[1]	**Total Available Moisture (TAM) (mm)**	**Net Irrigation Water Application (mm)**	**Gross Irrigation Water Application (mm)**	**Per cent of TAM at which an Irrigation Water Application was Scheduled**[2] **(%)**	**Dry-off period**[3]
Sandy Clay	Centre Pivot	90	95	27	30	60	2 x TAM

---

[1] Christiansen's Uniformity coefficient (cf. Chapter 2)

[2] If the soil water content was at a level less than 60 % of the soil's TAM value, an irrigation water application was simulated to occur, provided the time in days since the last irrigation water application was greater than the minimum irrigation cycle time. Otherwise the irrigation application was delayed until the time in days since the last irrigation water application was greater than the minimum irrigation cycle time.

[3] All irrigation water applications ceased when the amount of A-pan evaporation which would accumulate prior to the harvest date was less than or equal to a value equivalent to 190 mm, or twice the value of the soil's TAM (2 x TAM).

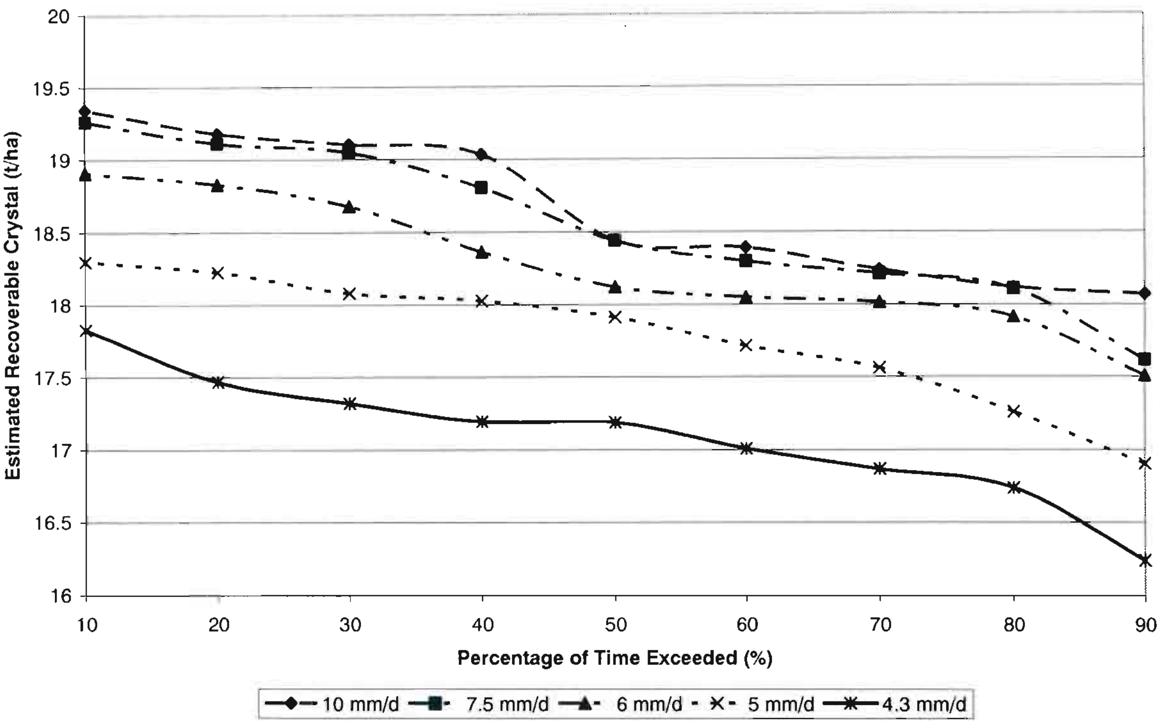


Figure 5.1 Frequency analyses of yields of estimated recoverable crystal for various peak irrigation system capacities

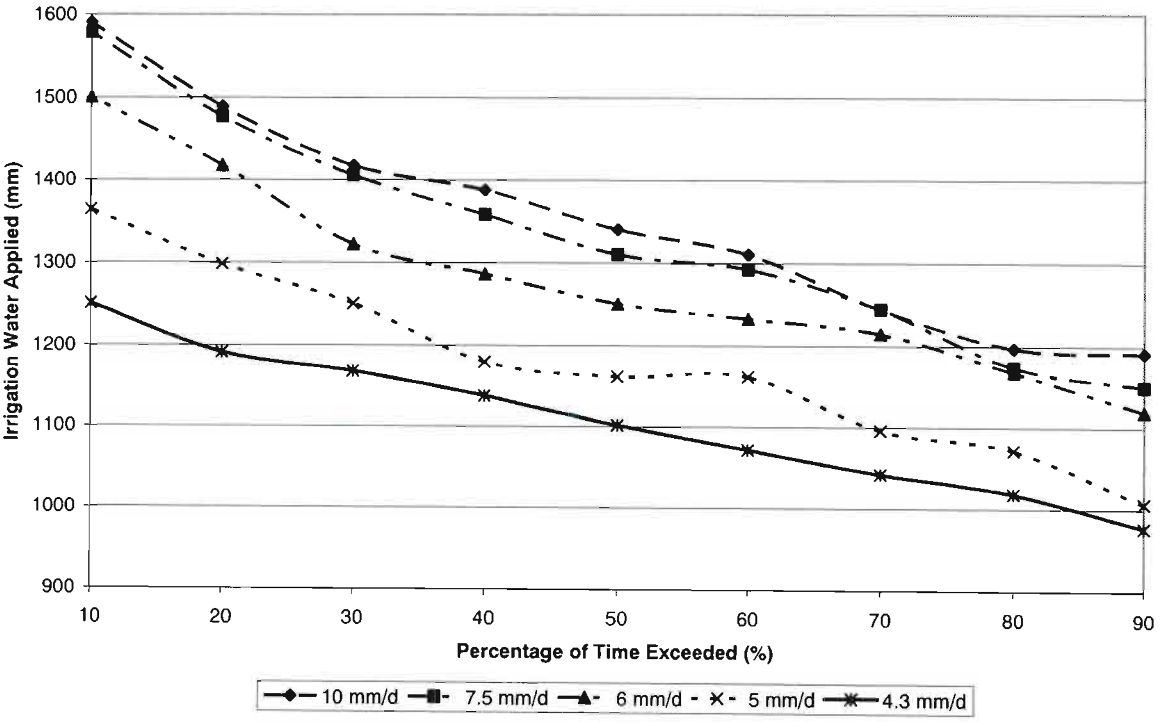


Figure 5.2 Frequency analyses of seasonal irrigation water applications for various peak irrigation system capacities

Examination of the results shown in Figures 5.1 and 5.2 shows that:

- the peak irrigation system capacity had a considerable effect on the total amount of irrigation water applied in a season (Figure 5.2);
- the potential yield which could be obtained was dependent on the system capacity limitations (Figure 5.1);
- the marginal yield benefits decreased as the system capacities increased (Figure 5.1);
- increasing the system capacity beyond a certain limit resulted in minimal further crop yield benefits, illustrated by a comparison of the water used and yields attained for systems with capacity limitations of 10 mm/d and 7.5 mm/d ;
- correct irrigation scheduling is important, as indicated in the range of seasonal irrigation water applications for a given system capacity (Figure 5.2); and
- with increasing system capacity the range in water applied becomes larger and the potential for wastage greater (Figure 5.2).

Even greater value and perspective can be added to the information shown in Figures 5.1 and 5.2 by placing it into an economic context. The economic implications of the different irrigation strategies were, therefore, estimated by calculating a net return per hectare (NRH) and relative net return (RNR) using the simulated crop yield and water use information together with reasonable production cost and revenue assumptions. Equation 5.1 and Equation 5.2 were used respectively to calculate the NRH and the RNR (cf. Chapter 3.3). To reiterate, the RNR reflects the opportunity cost of water by multiplying the NRH by a relative production area which could be achieved using a certain fixed volume of water. For example, assume Strategy 1 used 1000 mm of water per hectare and Strategy 2 used 500 mm of water per hectare. Therefore, for every hectare irrigated using Strategy 1, two hectares could be irrigated (in relative terms) using the same amount of water with Strategy 2.

NRH = (ERC yield x ERC price) – (base production costs) – (irrigation water applied x water cost) – (irrigation water applied x electricity cost) – (ERC yield x 100/12 x harvesting and haulage cost) – (fixed irrigation interest charges) – (fixed irrigation depreciation charges) Eq. 5.1

RNR = NRH x (maximum water used considering all systems and seasons)/(water used for the given system and season) Eq. 5.2

The estimated interest and depreciation charges for centre pivot irrigation systems with different peak capacity limitations are shown in Table 5.2.

Table 5.2 Fixed irrigation costs for different irrigation system capacities

Peak Irrigation System Capacity (mm/d)	Capital Cost[1] (R/ha)	Interest[2] (R/ha)	Depreciation[3] (R/ha)
10.0	13 961	838	1 396
7.5	12 088	725	1 208
6.0	11 858	711	1 186
5.0	10 872	652	1 087
4.3	10 723	643	1 072

[1] Capital costs were based on estimates provided by Zartmann (2004). These cost estimates included variations due to mainline pipe sizes, pump houses and pumps but assumed in-field costs of the centre pivot infrastructure were the same for all systems

[2] (Purchase Price + Salvage Value)/2) x i/100

[3] (Purchase Price – Salvage Value)/Lifespan

Salvage Value = R0.00

Lifespan = 10 years

Interest Rate (i) = 12 % p.a.

Other cost and revenue information which was assumed to be consistent for all systems is shown in Table 5.3.

Table 5.3 Revenue and cost information which was common to all systems and used in the economic analysis

Parameter	Value	Units
Water costs	0.1233	R/m^3
Electricity costs	1.15	R/mm.ha
Harvesting and Haulage Costs	45	R/ton [1]
Common Base Production Costs	4000	R/ha
Estimated Recoverable Crystal Price	1250	R/ton

[1] Harvesting and haulage costs were based on tons of sugarcane. Tons of sugarcane were estimated from yields of estimated recoverable crystal assuming a 12 % ERC content per ton sugarcane (cf. Equation 5.1).

The results of a frequency analysis of the NRH and RNR for the various irrigation system capacities are shown in Figures 5.3 and 5.4 respectively. The information shown in Figures

5.3 and 5.4 places a very different perspective on the information shown in Figures 5.1 and 5.2.

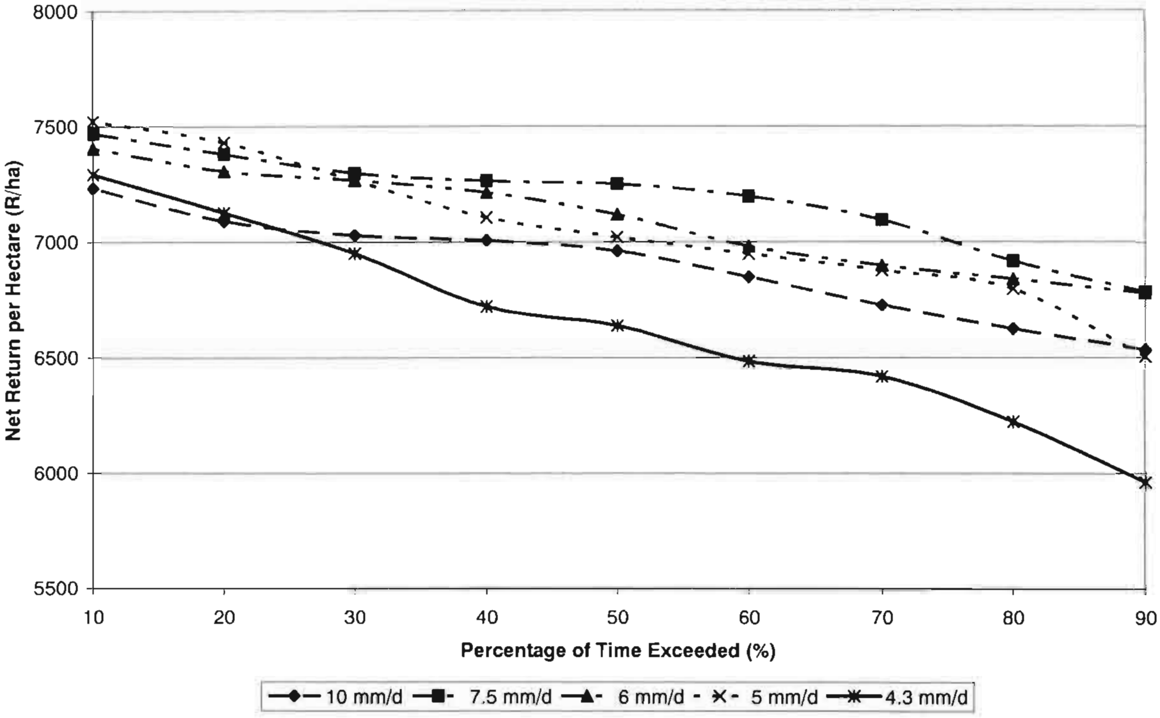


Figure 5.3 Frequency analyses of net returns per hectare for various peak irrigation system capacities

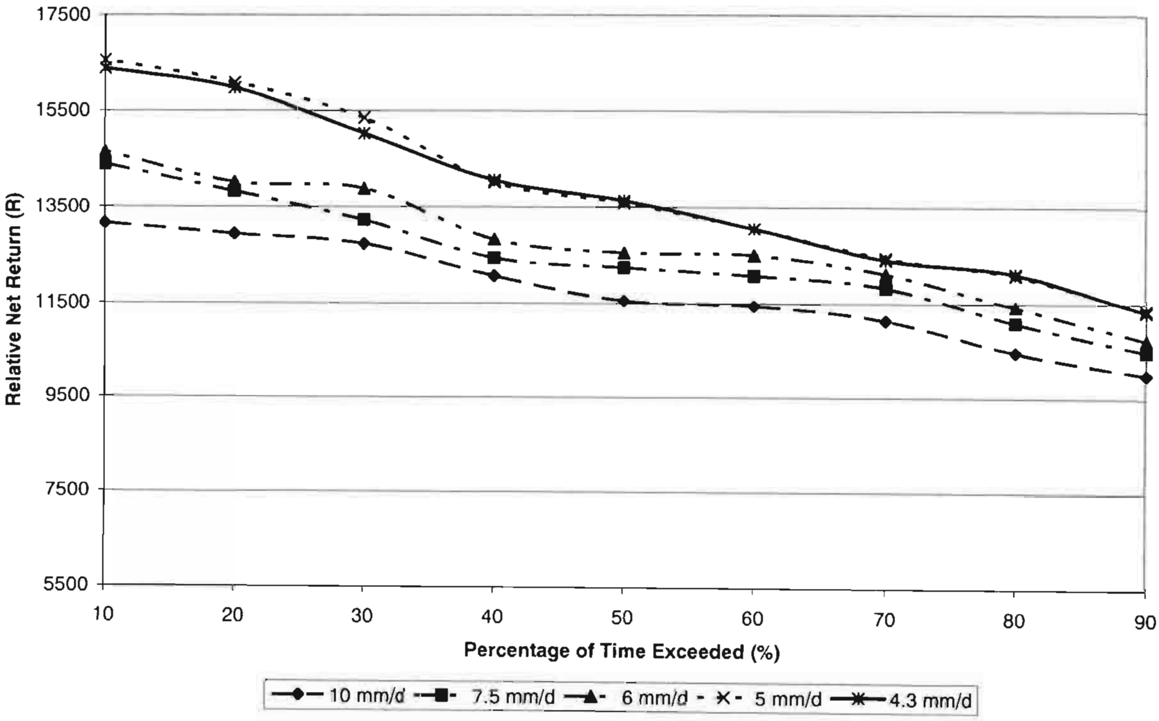


Figure 5.4 Frequency analyses of relative net returns per hectare (net return per hectare x relative irrigable area) for various peak irrigation system capacities

Although the system with the highest capacity of 10 mm/d gave the best yields of ERC (cf. Figure 5.1), from an economic perspective, this was not the best system. If availability of land limited production (relative to available water) then the system with a capacity equivalent to 7.5 mm/d was estimated to give the best overall returns (cf. Figure 5.3). However, if water was the factor which limited production (relative to available land), then the system with a capacity of only 5 mm/d (cf. Figure 5.4), gave the best overall profitability. This case study application thus reinforces, and provides an explicit demonstration, of the deficit irrigation concepts described in Chapter 2, Section 2.3.4.

Peak irrigation system capacities can also have an impact on irrigation efficiency, particularly with regard to centre pivots. The reason for this is that with centre pivots the outer towers cover a relatively larger area compared with the inner towers in a given time period. Thus the irrigation water application rate at the outer towers needs to be much higher than the water application rate closer to the centre of the pivot in order to maintain a constant irrigation water application depth. An associated constraint is that the irrigation water application rate at the outer towers of a centre pivot can often exceed soil infiltration rates leading to excessive runoff and reduced efficiency. This limits the recommended size of the pivot and can have further cost implications because the per hectare costs of in-field centre pivot irrigation systems infrastructure decreases with increasing pivot size (Reinders and Louw, 1984).

5.2 On-Farm Irrigation Water Management Tools

Many water-budgeting tools, or procedures for irrigation water management, have been developed (for example, Clowes and Breakwell, 1998; Singels *et al.*, 1998; Annandale *et al.*, 1999); however, few of these were seeing widespread use amongst growers in the Lowveld as effective management aids. Factors contributing to an explanation of this lack of application of these tools included the following.

- Water budgeting methodologies which are based on hand calculations can be confusing, excessively time-consuming, error prone and often require that the soil-plant-atmosphere continuum be over-simplified in order to facilitate easy calculations.

- Computer simulation models, whilst having great potential for facilitating more efficient and accurate water budgeting, are often unfamiliar and confusing to many growers, especially when it comes to configuring them for a particular situation or "resetting/re-initialising" them if simulations do not match field observations at a particular time.
- Furthermore, while many growers are computer literate, many other growers do not yet have access to computers or are averse to using computers.

Even if irrigation scheduling consultants operate computer simulation models and/or other tools and pass information on to farmers, this is not always ideal. Many consultants begin to lose touch with the realities on the ground as they are often located at some distance from farms.

There is no doubt, however, that water budgeting tools, when used correctly, can facilitate substantial improvements in irrigation water management (cf. Chapter 4). A major challenge is to match accurate water budgeting with ease of use from a farmer's perspective. With this in mind, two water management decision support tools were developed, namely:

- a spreadsheet-based water management and yield forecasting tool aimed at growers who were computer literate, and
- irrigation scheduling charts or calendars aimed at growers who were adverse to the use of computers. These tools are described as follows.

5.2.1 A spreadsheet-based irrigation scheduling and yield forecasting tool

Spreadsheets were selected as the basis for developing an irrigation scheduling tool option because they are familiar to many people and have very powerful in-built functionality. The water budgeting algorithms used in *ZIMSched 2.0* formed the basis of the spreadsheet-based irrigation scheduling tool. These algorithms and their validity are described in Chapter 3. They were further endorsed through a verification study described in Chapter 4. The spreadsheet-based irrigation scheduling and yield forecasting tool was essentially a simplified version of *ZIMsched 2.0*. It was tailored to suit the needs of growers for on-farm irrigation water management decisions whilst still incorporating enough of the complexities of water budgeting such that the following processes were represented:

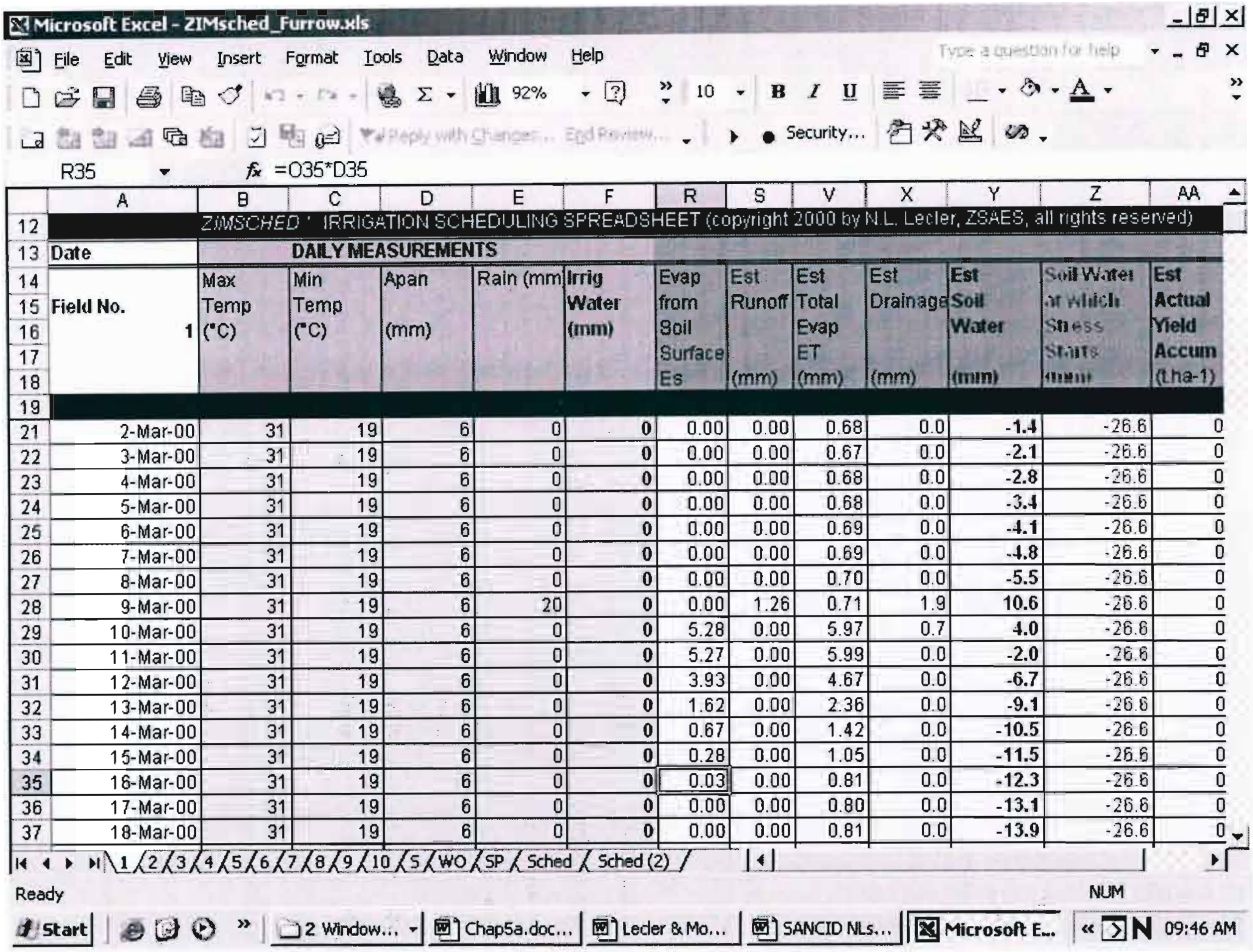
- evaporation from the soil surface and transpiration in relation to:
    - atmospheric evaporative demand,
    - available soil water, including excess and/or deficient conditions,
    - crop and rooting characteristics (the development of which were related to temperature),
    - irrigation system type, for example, sub surface drip irrigation versus overhead sprinkler irrigation,
- stormflow (surface runoff), and
- deep percolation, all of which relate to
- rainfall effectiveness.

The configuration, information/data requirements, operation and utilities of the spreadsheet-based irrigation scheduling tool, which was named *ZIMsched* are summarised as follows.

5.2.1.1 Input information / data

The various components of the water budget and the crop yield estimate are represented in columns in a spreadsheet, as shown in Figure 5.5. Upon initial configuration the user needs to input:

- soil texture class,
- maximum rooting/soil depth,
- estimated field drainage rate (rapid, average or slow),
- type of irrigation system, for example, furrow or sprinkler,
- initial soil cover fraction, for example, if the cane was harvested green and there was a decent trash blanket, this would be set to 0.99,
- plant or cut/harvest date,
- field name.



R35 =O35*D35

ZIMSCHED ' IRRIGATION SCHEDULING SPREADSHEET (copyright 2000 by N.L. Lecler, ZSAES, all rights reserved)

	A	B	C	D	E	F	R	S	V	X	Y	Z	AA
13	Date	DAILY MEASUREMENTS											
14–18	Field No. 1	Max Temp (°C)	Min Temp (°C)	Apan (mm)	Rain (mm	Irrig Water (mm)	Evap from Soil Surface Es	Est Runoff (mm)	Est Total Evap ET (mm)	Est Drainage (mm)	Est Soil Water (mm)	Soil Water at which Stress Starts (mm)	Est Actual Yield Accum (t.ha-1)
19													
21	2-Mar-00	31	19	6	0	0	0.00	0.00	0.68	0.0	-1.4	-26.6	0
22	3-Mar-00	31	19	6	0	0	0.00	0.00	0.67	0.0	-2.1	-26.6	0
23	4-Mar-00	31	19	6	0	0	0.00	0.00	0.68	0.0	-2.8	-26.6	0
24	5-Mar-00	31	19	6	0	0	0.00	0.00	0.68	0.0	-3.4	-26.6	0
25	6-Mar-00	31	19	6	0	0	0.00	0.00	0.69	0.0	-4.1	-26.6	0
26	7-Mar-00	31	19	6	0	0	0.00	0.00	0.69	0.0	-4.8	-26.6	0
27	8-Mar-00	31	19	6	0	0	0.00	0.00	0.70	0.0	-5.5	-26.6	0
28	9-Mar-00	31	19	6	20	0	0.00	1.26	0.71	1.9	10.6	-26.6	0
29	10-Mar-00	31	19	6	0	0	5.28	0.00	5.97	0.7	4.0	-26.6	0
30	11-Mar-00	31	19	6	0	0	5.27	0.00	5.99	0.0	-2.0	-26.6	0
31	12-Mar-00	31	19	6	0	0	3.93	0.00	4.67	0.0	-6.7	-26.6	0
32	13-Mar-00	31	19	6	0	0	1.62	0.00	2.36	0.0	-9.1	-26.6	0
33	14-Mar-00	31	19	6	0	0	0.67	0.00	1.42	0.0	-10.5	-26.6	0
34	15-Mar-00	31	19	6	0	0	0.28	0.00	1.05	0.0	-11.5	-26.6	0
35	16-Mar-00	31	19	6	0	0	0.03	0.00	0.81	0.0	-12.3	-26.6	0
36	17-Mar-00	31	19	6	0	0	0.00	0.00	0.80	0.0	-13.1	-26.6	0
37	18-Mar-00	31	19	6	0	0	0.00	0.00	0.81	0.0	-13.9	-26.6	0

Figure 5.5 *ZIMsched* spreadsheet columns for a sugarcane crop planted in March 2000

The required climate and irrigation input information, were:

- daily maximum temperature,
- daily minimum temperature,
- daily A-pan reference evaporation,
- daily rainfall, and
- irrigation water applied.

These are also shown as columns in the spreadsheet (cf. Figure 5.5).

Default values for a range of parameters needed for the water balance calculations, including, for example, field capacity, porosity and total available moisture (TAM) of the soil for the field in question, are estimated in *ZIMsched* based on lookup tables using values from Schulze *et al.* (1995) and Allen *et al.* (1998). Values for these parameters can also be input directly or modified by a user if better information is available.

5.2.1.2 Representation of fields

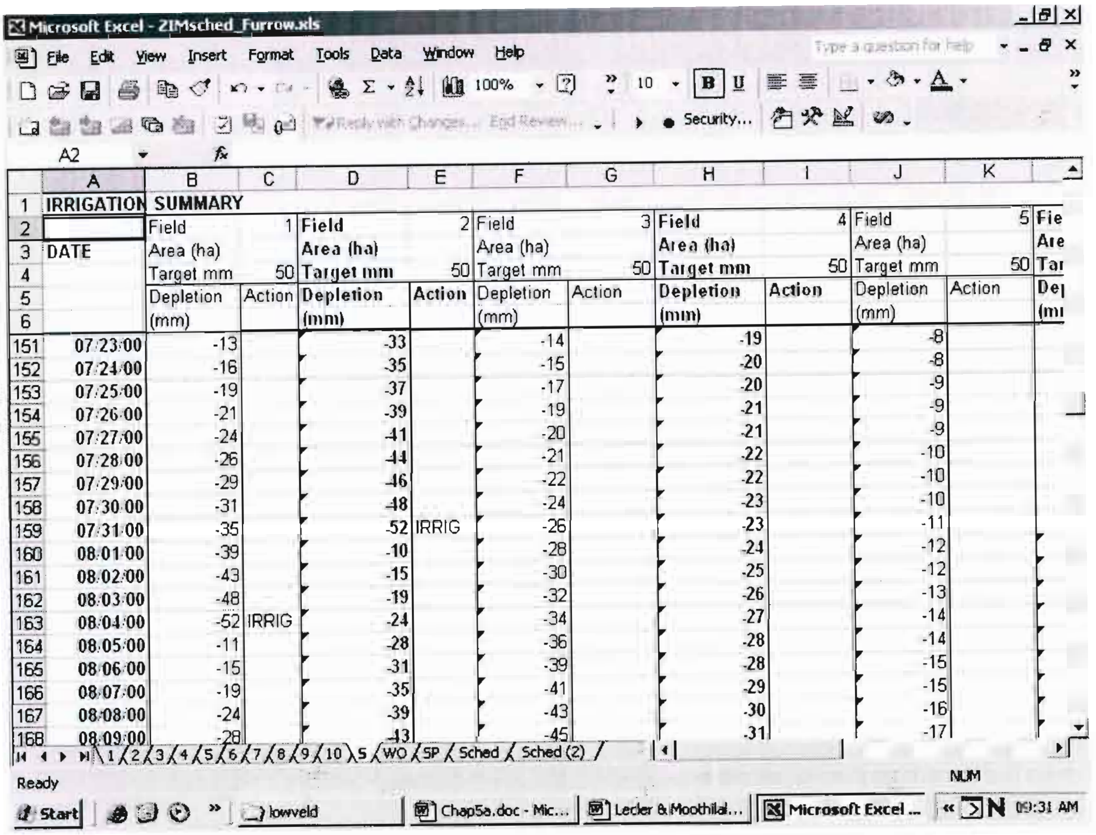
Numerous inter-dependent fields can be represented in a single spreadsheet file, with each field on a different notebook sheet. For example, a user may have a centre pivot divided into four sectors, with each sector planted at different times of the year. In *ZIMsched* each sector could be represented in the same file, but on a different notebook sheet. Input information for daily maximum temperature, minimum temperature, A-pan reference evaporation and rainfall need only be entered once in the climate file as the notebook cells for a particular date on the water balance sheets are linked to the corresponding notebook cells for the same date in the climate file, also via lookup functions. Thus the climate related input data/information is carried through automatically to all linked fields. The components of the water budget are calculated and updated automatically once changes to input information are made.

5.2.1.3 Determination of irrigation water applications

When using *ZIMsched*, a user enters recorded daily values for maximum and minimum temperature and A-pan equivalent evaporation in a common "weather.xls" weather spreadsheet file. Rainfall and irrigation water applications are best input per field and the user then simply observes changes to the estimated soil water status and the date when the estimated soil water is expected to reach a level at which an irrigation water application is needed. In order to extrapolate into the future, a user can use long term mean daily values for climate data (cf. Figure 5.5) or use the in-built spreadsheet functionality to calculate the mean of the previous 'x' days and extrapolate using these values. In the sugar industry in the Lowveld representative recorded values for daily maximum and minimum temperature as well as A-pan evaporation data were available from the ZSAES or from one of the three large Estates. Users were advised to record the rainfall and irrigation water applications associated with individual fields. In order to simplify the appearance of *ZIMsched*, users can elect to hide components of the water budget that may not be of interest, or that may be confusing, by using the 'columns hide' facility in spreadsheets.

5.2.1.4 Other *ZIMsched* utilities

Additions or modifications to *ZIMsched* to suit user requests were easily added. For example, a request by users was to have a summary notebook sheet which showed on a single page the estimated soil water status for a particular grouping of inter-dependent fields. This is shown in Figure 5.6.



	A	B	C	D	E	F	G	H	I	J	K	
1	IRRIGATION	SUMMARY										
2		Field	1	**Field**	2	Field	3	**Field**	4	Field	5	**Fie**
3	DATE	Area (ha)		**Area (ha)**		Area (ha)		**Area (ha)**		Area (ha)		**Are**
4		Target mm	50	**Target mm**	50	Target mm	50	**Target mm**	50	Target mm	50	**Tar**
5		Depletion (mm)	Action	**Depletion (mm)**	**Action**	Depletion (mm)	Action	**Depletion (mm)**	**Action**	Depletion (mm)	Action	**De**
151	07/23/00	-13		-33		-14		-19		-8		
152	07/24/00	-16		-35		-15		-20		-8		
153	07/25/00	-19		-37		-17		-20		-9		
154	07/26/00	-21		-39		-19		-21		-9		
155	07/27/00	-24		-41		-20		-21		-9		
156	07/28/00	-26		-44		-21		-22		-10		
157	07/29/00	-29		-46		-22		-22		-10		
158	07/30/00	-31		-48		-24		-23		-10		
159	07/31/00	-35		-52	IRRIG	-26		-23		-11		
160	08/01/00	-39		-10		-28		-24		-12		
161	08/02/00	-43		-15		-30		-25		-12		
162	08/03/00	-48		-19		-32		-26		-13		
163	08/04/00	-52	IRRIG	-24		-34		-27		-14		
164	08/05/00	-11		-28		-36		-28		-14		
165	08/06/00	-15		-31		-39		-28		-15		
166	08/07/00	-19		-35		-41		-29		-15		
167	08/08/00	-24		-39		-43		-30		-16		
168	08/09/00	-28		-43		-45		-31		-17		

Figure 5.6 An example of a tailored summary notebook sheet in *ZIMsched*, this example showing the soil water status of a particular grouping of fields

Another request was to have a notebook sheet which contained summaries of weekly water orders which depended on field areas, application amounts, conveyance and balancing dam losses. Conveyance losses are estimated as a percentage of water conveyed and farm balancing dam losses are estimated based on the surface area of the dam and daily A-pan values adjusted for open water bodies (Schulze *et al.*, 1995a) and an assumed percentage seepage loss. The information in these summary sheets was generated automatically, based on the water budgeting notebook sheets and user input regarding actual and expected irrigation water applications.

5.2.1.5 Crop yield benchmarks and forecasts

ZIMsched has powerful facilities for yield forecasting and benchmarking. Yield estimates for selected historical years can easily be compared to corresponding estimates for the present season. The present season can be extrapolated to a harvest date, assuming various climate scenarios, for example, using long term mean daily climate data or daily climate data from historical seasons associated with particularly good or bad climatic conditions. Both potential yields and actual yields can be compared. Potential yields are based on transpiration estimated under conditions of no soil water stress effects while actual yields are based on transpiration estimates as influenced by soil water stress resulting from either too much or too little water.

5.2.1.6 Useful in-built spreadsheet functions

The in-built charting options in spreadsheets are a particularly useful tool and enable various charts to be quickly updated or designed in *ZIMsched.* For example, a chart showing estimated soil water status, the soil water status at which water stress is initiated and the associated rainfall and irrigation applications is shown in Figure 5.7. Another useful chart option shows the soil water status of a particular inter-dependent field grouping which enables a user to see at a glance the relative wetness of the selected fields. *ZIMsched* has many other management applications, for example, managing and recording fertilizer applications so that chances of leaching are minimised, or displaying day-lengths so that a crop may be deliberately stressed when day-lengths may otherwise promote undesired flowering for crops harvested late in the season. Seasonal summaries and statistics of the various components of the water budget are available, for example, irrigation water applications are easily calculated in *ZIMsched* using the in-built spreadsheet functions, for example, “=average”, for averaging, or “=sum”, for summation. A major advantage of using spreadsheets is that the user can quickly tailor the basic tool to suit specific needs without having to wait for a specialist computer programmer to make the desired changes/additions.

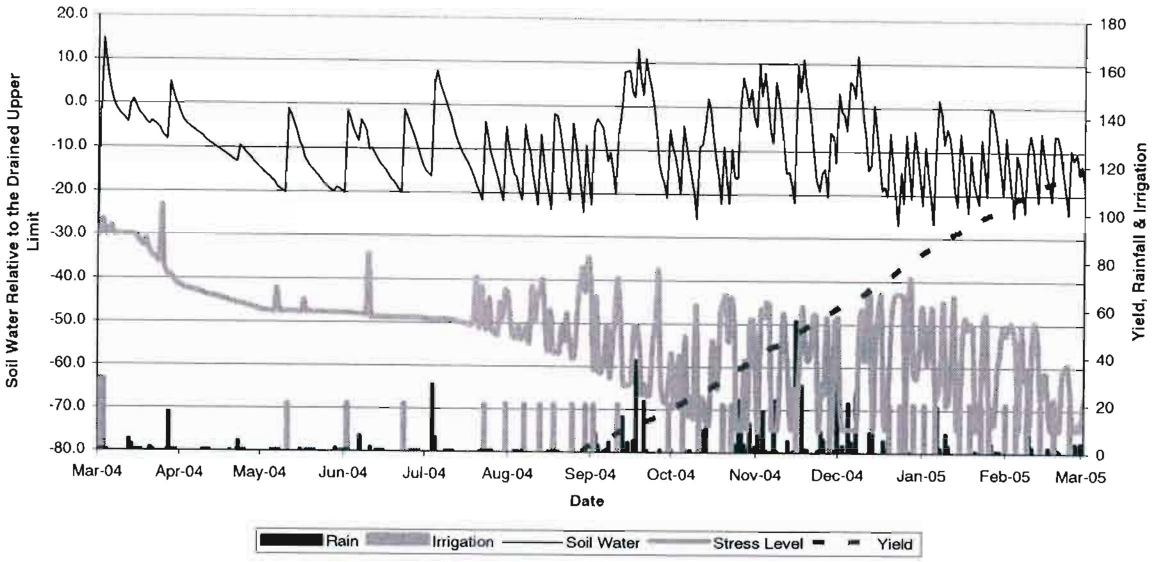


Figure 5.7 Graph showing variations in estimated soil water content (mm), soil water stress thresholds (mm) together with rainfall (mm), irrigation (mm) and cane yield (t/ha). Note: -ve soil water values indicate depletion below the drained upper limit

5.2.2 Irrigation scheduling charts and calendars

While many farmers growing sugarcane under irrigation already were, or were becoming, computer literate, many others were either averse to the use of computer-based decision support tools, or did not have easy access to computers. This was particularly evident with emergent small-scale farmers. Therefore, simple-to-use charts showing when irrigation water should be applied were developed to provide such farmers with an appropriate water management decision support option.

Initially, *ZIMsched* was used to develop charts which showed the average number of days between successive irrigation water applications for cane cut at different times during the harvest season, and for different types of irrigation systems on different soils. A robust methodology to determine and account for effective rainfall was also developed for use with the charts. The information provided in the charts could easily be transcribed to standard calendars which provided an easy-to-use format for an irrigation scheduling and planning tool.

The potential benefits of these irrigation scheduling charts, which are described in detail in Appendix H, based on Lecler (2003) were not, however, quantified nor assessed in comparison to either more sophisticated or less sophisticated irrigation scheduling approaches. Thus, following on from this initial work, the author together with an undergraduate final year Agricultural Engineering student, Ria Moothilal, developed a similar set of irrigation scheduling guidelines for the Pongola region of South Africa, and evaluated this approach to irrigation scheduling by comparison with more sophisticated and less sophisticated approaches to irrigation scheduling (Lecler and Moothilal, 2004). The irrigation scheduling guidelines developed by Lecler and Moothilal (2004) showed the recommended irrigation cycles for different months of the year, dependent on ratooning/cutting dates and type of irrigation system. The potential use of these guidelines for scheduling irrigation water applications using centre pivot irrigation systems was evaluated and is discussed here, based on the paper by Lecler and Moothilal (2004).

5.2.2.1 Background to an evaluation study of the irrigation scheduling charts

Daily climate data obtained from the Pongola weather station in South Africa for the period 1968 to 2001 were used in the evaluation study. The Pongola weather station is located at latitude 27° 24’ south and longitude 31° 35’ east. Mean values of maximum and minimum temperatures and sugarcane reference evaporation were determined for each day of the year. This information was then used in the CANESIM sugarcane crop yield and water budgeting computer simulation model (Singels *et al.*, 1998) to determine the number of days between successive 25 mm irrigation water applications, assuming no rainfall to have occurred. This is termed the ‘dry cycle’. Dry cycle values were determined for the first and second half of each month of the year, for harvest dates coinciding with the first day of each month in the March to December cutting season. An example of the dry cycle values for a crop cut on 1 March is shown in Table 5.4, where the irrigation cycle (or days between irrigation water applications) for the first half of May is given as eight days, and for the second half of May, nine days. The CANESIM model was used rather than *ZIMsched* because CANESIM had been developed and verified under South African conditions (Singels *et al.*, 1998; Singels *et al.*, 1999) and the study was undertaken after the author had left Zimbabwe and was located in South Africa.

Table 5.4 Irrigation cycle lengths for use with centre pivots in Pongola. The cycles were determined for the first and second half of each month (shown by /) using the CANESIM computer simulation model (Singels *et al.*, 1998) assuming no rainfall, a March cut crop, no drying-off period and water applications of 25 mm per application (Lecler and Moothilal, 2004)

Month	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**
Cycle	28/10	10/9	8/9	9/9	8/8	6/5	4/4	3/3	3/3	3/3	3/3	3/3

The methodology used to account for rainfall was an adaptation of that originally proposed by the author (Lecler, 2003; cf. Appendix H). It is described here as follows. Using the daily mean cane reference evaporation (E_{cref}) values for Pongola, the monthly E_{cref} values were determined, as shown in Table 5.5. To account for effective rainfall, the amount of rain recorded was divided by the respective mean monthly E_{cref} value. This result, rounded down to the nearest whole number, was the number of days to be added to the dry cycle associated with a particular month. The number of days that were added per 'rainfall cycle' was limited to a maximum of six. A rainfall cycle was defined as a group of consecutive days on which some rain falls, i.e. a rainfall cycle starts on the first day of rainfall and ends when there is a day of no rain. For example, if the following amounts of rainfall were recorded for 10 days: 0 mm, 20 mm, 48 mm, 23 mm, 0 mm, 40 mm, 0 mm, 0 mm, 60 mm and 0 mm, there would be three rainfall cycles, namely, days 2, 3, 4, day 6, and day 9. The procedures used to determine the E_{cref} values are described by McGlinchey and Inman Bamber (1996a).

Table 5.5 Monthly mean values of daily cane reference evaporation (E_{cref}) for Pongola (Lecler and Moothilal, 2004)

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
E_{ref} (mm/day)	6.1	5.3	4.4	3.5	2.9	2.6	2.8	3.6	4.5	4.9	5.5	5.9

5.2.2.2 Using the irrigation scheduling charts

The irrigation scheduling charts show the irrigation cycle lengths for each month. These are dependent on a particular harvest date, and the rainfall rule is used to account for the effect of rainfall on these pre-determined irrigation cycles. For example, consider a crop cut on 1 March:

Step 1: Within the first week after cutting, apply sufficient water to refill the soil profile to the drained upper limit (i.e. field capacity), typically around 50 mm.

Step 2: Look up the dry cycle value for the current month, i.e. March initially in this example. This dry cycle value is the number of days between successive irrigation water applications. The next irrigation water application would therefore be planned for 30 March, i.e. the dry cycle value for the first half of March is 28 (cf. Table 5.4), and there are 28 days between 1 March when the crop was cut and 30 March, which is the date of the next planned irrigation water application.

Step 3: If it rains before the next proposed irrigation water application, apply the rainfall rule and delay the proposed irrigation application date for a period equal to the number of days determined using the rainfall rule. Continue this procedure until the proposed irrigation application date is reached. For example, say rain caused a further five days to be added on to the March dry cycle value, this would result in the next application date being delayed until 4 April. An irrigation water application of 25 mm should then be applied on this day. April would now be the current month, therefore look up the dry cycle value associated with the beginning of April (for a March cut crop), which is given as 10 days in Table 5.4. The next irrigation application should then take place on 15 April (after counting 10 days) if there is no further rain.

Steps 2 and 3 would be repeated until drying off or harvest. In this investigation it was assumed that irrigation continued until harvest.

5.2.2.3 Evaluation of the irrigation scheduling charts

Scheduling irrigation water applications using the pre-determined irrigation cycle guidelines and rainfall rule (CY-RR), was compared with scheduling using near-real-time daily weather data and the CANESIM model (C-NRW). In addition, both these scheduling approaches were compared with another two less sophisticated, irrigation scheduling approaches. To expedite this procedure, a computer program was written by Ria Moothilal (under the author's guidance and supervision) to perform the abovementioned CY-RR implementation steps for crops harvested in months March until December of each year from 1968 to 2001. The program determined the dates on which irrigation application amounts of 25 mm would have been applied if the cycle guidelines and rainfall rule had been used in each of these cropping seasons.

Simulated trials for each season were then carried out. First, CANESIM was set to irrigate automatically whenever 25 mm of water had been depleted from the soil profile, with the constraint of a minimum irrigation cycle time of three days, i.e. based on the assumption that to apply 25 mm with a centre pivot would require at least three days. After this, CANESIM was set such that irrigation water applications were simulated to take place according to the irrigation dates applicable to the CY-RR scheduling method. As a comparison with what a grower may be doing in practice, a further two methods of scheduling were simulated in CANESIM. Both methods had fixed irrigation cycles, described as follows:

Method 1: 25 mm of water applied on a 3-day cycle in summer and a 7-day cycle in winter.
Method 2: 25 mm of water applied on a 7-day cycle in summer and a 14-day cycle in winter.

'Summer' included the months of October through to March, and 'winter' the months April through to September. Other information used in the simulations is given in Table 5.6.

Table 5.6 Information used for the CANESIM simulation trials.

CANESIM Variable	Value
Total available moisture (mm)	100
Allowable depletion level (mm)	70
Irrigation refill level (mm)	95
Crop starting year, month, day	As per trial
Crop ending year, month, day	As per trial
Irrigation system	Sprinkler
Initial soil water content (mm)	70
Row spacing (m)	1.5
Ratoon or plant crop	Ratoon

5.2.2.4 Economic analysis of the irrigation scheduling charts

For the economic analysis, the four different scheduling approaches were compared in terms of Net Returns per Hectare and Relative Net Returns, as defined in Equations 5.3 and 5.4. Note that for this analysis base production costs were assumed constant for every scenario.

NRH = (Gross revenue) – (base production costs) – (irrigation water applied x water cost) – (irrigation water applied x electricity cost) – (RV yield x 100/12 x harvesting and haulage cost) Eq. 5.3

RNR = NRH x (maximum water used considering all scheduling options and seasons)/(water used for the given system and season) Eq. 5.4

In South Africa, payment is determined by the 'relative value' (RV) of the cane rather than estimated recoverable crystal (ERC), thus gross revenue is the product of tons 'relative value' (RV) and the RV price. Base production costs, for example, herbicides, labour and seed, were assumed equal for all scheduling scenarios. The relative net return allowed for the opportunity cost of water to be accounted for; for example, when water savings could be used to increase the production area, or to increase average production over a number of drought seasons.

The mean of the simulated crop yields and associated mean of irrigation amounts applied for the four different methods of scheduling were used in the economic analysis. A management factor was used to reduce the simulated cane yields to 80% of their initial values, so that the analysis was more representative of typical conditions in practice rather than under research conditions. The cost and revenue assumptions made for the economic analysis are shown in Table 5.7.

Table 5.7 Information and costs used for the economic analysis

Parameter	Value	Units
Water costs	0.1233	R/m^3
Electricity costs	1.15	R/mm.ha
Harvesting and haulage costs	45	R/ton
Common base production costs	4000	R/ha
RV price	1250	R/ton

5.2.2.5 Results and discussion: Yield analysis

A scatter plot of simulated yields is shown in Figure 5.8. On average, the yields simulated when scheduling according to the pre-determined cycles and rainfall rule (CY-RR) were very close to the yields simulated when scheduling according to the CANESIM model and near-real-time weather data (C-NRW). Quantitative measures of the yield comparison are given in Table 5.8. The 2 % difference in mean simulated crop yields, coupled with the close to unity values of d and r, showed that, overall, scheduling using the CY-RR method was very effective when compared with the C-NRW method, even though there were a few years when the yields were substantially lower (cf. Figure 5.8).

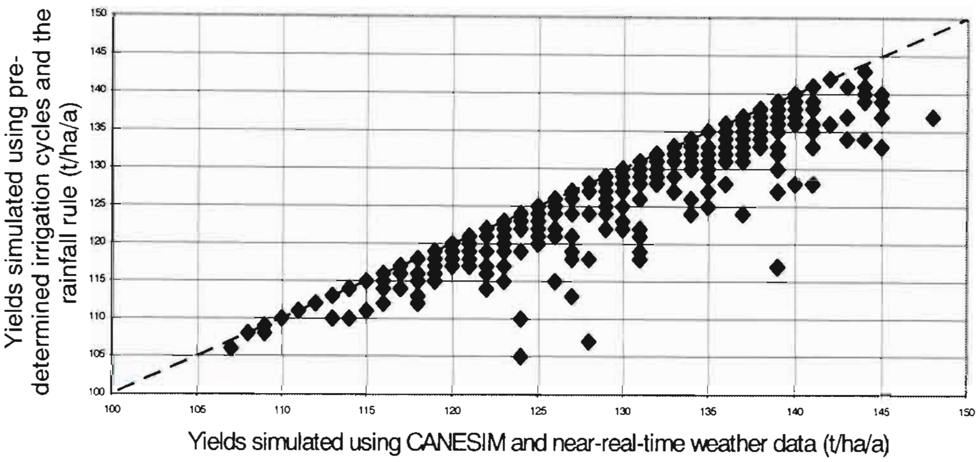


Figure 5.8 Scatter plot comparison of simulated sugarcane yields using CANESIM and near-real-time weather data and cane yields using the pre-determined irrigation cycles and rainfall rule, to schedule irrigation water applications (Lecler and Moothilal, 2004)

Table 5.8 Quantitative measures of a comparison between cane yields simulated using the CANESIM model and near-real-time weather data (C-NRW) to schedule irrigation water applications and cane yields simulated using the pre-determined cycles and rainfall rule (CY-RR) to schedule irrigation water applications (Lecler and Moothilal, 2004)

C-NRW$_{mean}$	CY-RR$_{mean}$	N	a	b	RMSE	d	r
129	126	340	13.323	0.876	4.428	0.930	0.914

Terms N, b, d and r are dimensionless, whereas the other terms are in tons/hectare.

C-NRW$_{mean}$ = mean of simulated yields obtained using the CANESIM model and near-real-time weather data (t/ha)

CY-RR$_{mean}$ = mean of simulated cane yields if irrigation applications were timed using the pre-determined cycles and rainfall rule (t/ha)

N = sample size (number of simulated trials run)
a, b = y-intercept and slope respectively, of least squares regression between CY-RR yields as the dependent variable and C-NRW yields as the independent variable
RMSE = root mean squared error (CY-RR compared with C-NRW)
d = index of agreement where a value of 1.00 would indicate perfect agreement (Wilmott, 1981)
r = correlation coefficient (Pearson's r)

5.2.2.6 Results and discussion: Analysis of seasonal irrigation water applications

A scatter plot of annual (seasonal) amounts of irrigation water applied is shown in Figure 5.9. Irrigation water applied varied greatly, depending on the climate during the cutting season. However, an important result was that the majority of the data points were below the 1 : 1 line, indicating that, on average, scheduling using the CY-RR method used less water than scheduling according to C-NRW. Quantitative measures of amounts of irrigation water applied are given in Table 5.9.

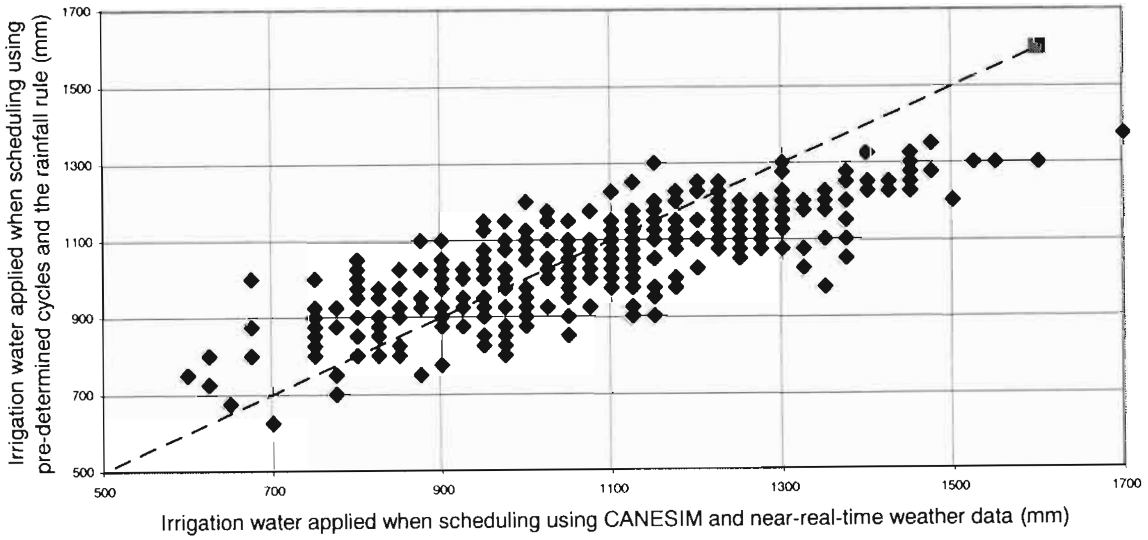


Figure 5.9 Scatter plot comparison of simulated amounts of irrigation water applied using CANESIM and near-real-time weather data and cane yields using the pre-determined irrigation cycles and rainfall rule, to schedule irrigation water applications (Lecler and Moothilal, 2004)

The RMSE value of 129 mm shows that there was about a 11% difference in simulated seasonal irrigation water applications, even though the means of all simulated seasons were much closer. On average, the amount of irrigation water applied simulated using CY-RR is less than that simulated using C-NRW. The values of 'd' and 'r' both indicate reasonable agreement and correlation. This is important because, ideally, the CY-RR approach should reflect the influence of a particular season's climate, in particular rainfall, similarly to scheduling with C-NRW. The regression coefficients, a and b and scatter plot shown in Figure 5.9, show that in low rainfall years when seasonal irrigation amounts are high, the CY-RR method of scheduling results in less water being applied than when scheduling using the C-NRW method, whereas the opposite is true in seasons of high rainfall. Although there were differences in excess of 200 mm in the seasonal amounts of irrigation water applied, this had a limited detrimental effect, as the difference in means of simulated crop yields over all seasons was only 2%. This indicates that the CY-RR method of scheduling is robust, but not necessarily optimal in all seasons. Further evaluation of the CY-RR approach on soils with lower TAM values, which may not be as 'forgiving', is advised.

Table 5.9 Quantitative measures of a comparison between annual amounts of irrigation water applied, simulated using the CANESIM model and near-real-time weather data (C-NRW), compared with annual amounts of irrigation water applied simulated if irrigation applications were timed using the pre-determined cycles and rainfall rule (CY-RR) (Lecler and Moothilal, 2004)

C-NRW$_{mean}$	**CY-RR$_{mean}$**	**N**	**a**	**b**	**RMSE**	**d**	**r**
1086	1055	340	469.5	0.539	129	0.849	0.800

Terms N, b, d and r are dimensionless, whereas the other terms are in tons/hectare

C-NRW$_{mean}$ = mean of simulated irrigation water applied using the CANESIM model and near-real-time weather data (t/ha)

CY-RR$_{mean}$ = mean of simulated irrigation water applied if irrigation applications were timed using the pre-determined cycles and rainfall rule (t/ha)

N = sample size (number of simulated trials run)

a, b = y-intercept and slope respectively, of least squares regression between CY-RR water applied the dependent variable and CY-NRW water applied as the independent variable

RMSE = root mean squared error (CY-RR compared with C-NRW)

d = index of agreement, where a value of 1.00 would indicate perfect agreement (Wilmott, 1981)

r = correlation coefficient (Pearson's r)

5.2.2.7 Results and discussion: Economic comparison

The results of the economic analysis are shown in Table 5.10. The difference between the NRH, whether scheduling with C-NRW or CY-RR, was negligible. However, the difference between either one of these more scientific scheduling approaches, and the less sophisticated scheduling approaches typical in practice and represented by Method 1 or Method 2, was substantial, i.e. from R1 079 per hectare up to R2 687 per hectare. The inefficiency of

Method 1 meant that it required 21.93 Ml of water per hectare, which was more than double the water required when scheduling using the CY-RR, C-NRW or Method 2. Apart from the high power and water costs, this meant that for every one hectare irrigated using Method 1, the same amount of water could have been used to irrigate more than two hectares using any of the other scheduling methods. Relative overall returns if water limited production could, therefore, be increased by approximately R3 485 per hectare irrigated according to Method 1, by increasing the relative production area, for example, during droughts, and scheduling according to C-NRW or CY-RR. While Method 2 used the lowest amount of water and had relatively low power and water costs, the timing of the water applications was not optimal. This was reflected in the low simulated crop yields and the relatively lower NRH and RNR compared with scheduling using C-NRW and CY-RR. The mean of the yields simulated using Method 2 for scheduling, was approximately 14% less than the mean of yields simulated using C-NRW, CY-RR or Method 1.

Table 5.10 Economic comparison of simulated irrigation scheduling scenarios (Lecler and Moothilal, 2004)

	C-NRW	**CY-RR**	**Method 1**	**Method 2**
Mean simulated cane yield (t/ha/a)[a]	103	101	102	89
RV equivalent @ 12% RV (t/ha/a)	12.4	12.1	12.3	10.7
Irrigation water applied (Ml/ha)	10.86	10.55	21.93	9.79
Affected variable costs:				
Water (R/ha)	1 304	1 266	2 631	1 175
Power (R/ha)	1 249	1 213	2 522	1 126
Harvesting and haulage (R/ha)	4 644	4 546	4 607	4 007
Common base production costs (R/ha)	4 000	4 000	4 000	4 000
Revenue (R/ha)	15 480	15 153	15 356	13 358
(a) Net return per hectare (NRH, R/ha)[b]	4 283	4 128	1 596	3 049
(b) Relative water limited production area (ha)	1	1.03	0.50	1.12
(c) Relative net returns = (a) x (b) (RNR, R)	4 283	4 251	798	3 415

C-NRW = irrigation scheduling using the CANESIM model and near-real-time weather data
CY-RR = irrigation scheduling using the pre-determined irrigation cycles and the rainfall rule
Method 1 = 25 mm of irrigation water applied every 3 days in summer and every 7 days in winter
Method 2 = 25 mm of irrigation water applied every 7 days in summer and every 14 days in winter

[a] Simulated yields shown here have been adjusted downwards, assuming an 80% management factor

[b] Net return per hectare, and therefore, the relative net returns shown here include affected variable costs of water, power and harvesting and haulage and common base production costs, for example, fertiliser, herbicides, seedcane and labour, which were assumed equal to R4 000/ha.

The aim of this investigation was to refine and to evaluate a potentially simple, but effective, irrigation scheduling approach proposed by the author whilst he was in Zimbabwe (Lecler

(2003; Appendix H). In essence, *ZIMsched* was used to determine average intervals between successive irrigation water applications and a simple rule was used to account for effective rainfall. In this case study evaluation, rather than determining the intervals between successive irrigation water applications, the approach was refined to show recommended irrigation cycle times for each month of the year, dependent on a particular harvest date and irrigation application amount. There were instances when the use of the pre-determined irrigation cycles and the rainfall rule resulted in a substantial reduction in simulated crop yields relative to yields simulated using the comprehensive CANESIM computer simulation model and near-real-time daily weather data for scheduling. Nevertheless, in 340 computer simulation trials, the average reduction in crop yields was only 2%.

In terms of impacts on profitability, there was a negligible difference between using CANESIM and near-real-time weather data for irrigation scheduling and scheduling using the pre-determined cycles and rainfall rule. Importantly, there was a substantial gain in simulated profitability compared with less scientific, but typical, approaches to irrigation scheduling which have been observed in practice, ranging from R1079 up to R3485 per hectare, if an opportunity cost of water was considered.

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Traditionally, in the design and operation of irrigation systems, the focus has usually been on maximising crop yields. With increasing competition for limited resources, the pressure to rather maximise net benefits via, for example, the formulation and adoption of deficit irrigation strategies, is likely to increase. The contrast between designing and operating irrigation systems for 'maximum crop yields' as compared to 'maximum economic benefit' was illustrated in Section 5.1 by way of an example case study analysis. This type of analysis was made possible by the development of *ZIMsched 2.0*. In this case study, deficit irrigation strategies yielded considerably higher overall economic returns compared to full irrigation, for both land and particular for water limited production scenarios.

Analyses of the results of this 'peak irrigation system capacity' case study (cf. Chapter 5.1), together with the results presented in Chapter 4, highlighted the importance of correct irrigation scheduling. Therefore, a range of irrigation scheduling decision support tools aimed at catering for the needs of growers who are computer literate, but also for growers who are averse to the use of computers, was also developed.

In Section 5.2.1, *ZIMsched,* a robust, scientifically sound and yet simple spreadsheet-based irrigation management and yield forecasting tool is described. This was developed for farmers who were computer literate. Because many such farmers were already familiar with spreadsheets, they experienced a high degree of familiarity and competency within a short period of time after having been introduced to *ZIMsched.* This was considered to be a key aspect of successful technology transfer. *ZIMsched* incorporates robust algorithms to account for the components of a water budget that are of major importance to irrigation, yet which are often either ignored, over-simplified or over-complicated, namely, runoff, drainage, effective rainfall and evaporation under conditions of excess or deficient soil water. *ZIMsched* was developed to be flexible enough to be reset/adjusted with ease, should field soil water observations indicate a need for resetting, for example, if a drainage problem became apparent, or a disease or nutritional deficiency resulted in conditions different to the norm. There are facilities to include various management strategies, for example, for controlled soil water deficits at certain stages under water limited conditions, or to inhibit flowering in cane crops harvested late in the season (i.e. harvested after mid October). The efficient options included for managing input data and executing calculations were considered very important, because they could potentially reduce the time required for scheduling irrigation water applications so that management time can be freed for other operations.

For farmers who did not have access to computers or who were averse to their use, an alternative irrigation scheduling option was also proposed (cf. Section 5.2.2), namely charts showing recommended intervals between irrigation water applications for crops cut at different times in the year and assuming various irrigation water application depths. Importantly, given the potential contribution of rainfall to crop water requirements in the Lowveld (cf. Chapter 4), a simple ‘rule-of-thumb’ to account for rainfall was also developed for use with the irrigation scheduling charts. The only tools required to schedule irrigation water applications would, therefore, be the cycle guidelines or charts themselves, a rainfall gauge and a calendar. This makes for a relatively simple method of irrigation scheduling, potentially effective not only in terms of water management, but also in terms of costs and appropriateness, which is a concern for all growers, but especially the small scale growers. Scheduling irrigation water applications using these pre-determined irrigation cycles and the rainfall rule proved to be robust and effective in a case study evaluation undertaken for the Pongola region in South Africa. This approach to irrigation scheduling could, therefore, represent an innovative way of utlilising and tailoring the output of more complex computer simulation models so that they have wider application and impact.

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In the context of the near collapse of the sugar industry in the Lowveld of Zimbabwe following the 1991/2 drought, there was a need to assess the performance of the water management and irrigation systems being used in the industry. Following a review of literature on irrigation systems performance, given in Chapter 2, a methodology to evaluate the performance of irrigation and water management systems was formulated and was described in Chapter 3. Results of the application of this methodology and the associated tools which were developed were presented in Chapter 4 in an assessment of the actual and the potential performance irrigation systems, including, furrow, drip, sprinkler, floppy and centre pivot irrigation systems. Furthermore, various existing and refined water management approaches, applied in conjunction with the different types of irrigation systems, were also assessed. In Chapter 5 additional applications of the tools and information which were developed as a result of this study, were presented. These included an integrated economic assessment of peak irrigation system design capacities and associated watering strategies, including deficit irrigation and the development of a range of water management tools. Important consequences and recommendations resulting from this research are discussed in the following chapter.

6. DISCUSSION AND CONCLUSIONS

A review of relevant literature showed that the quantification of the water balance in space and time is most important in an assessment of irrigation systems performance. Furthermore, while many indices for irrigation systems performance have been proposed, the challenge is to determine values for the numerators and denominators of these performance indicators and to develop and quantify performance indices which are useful from a business/economic perspective. Another issue is that many of the irrigation systems performance descriptors given in the literature are based on over-simplified assumptions. One example, is the assumption that an irrigation water application is ideal when it is of such a magnitude that the quarter of the field receiving the least amount of water, receives sufficient water to replenish the soil water deficit. Such simplifying assumptions have led to the derivation of useful indices and comparisons. Nevertheless, the perspective of irrigation systems performance given in Chapter 2, especially the section on water management and deficit irrigation (cf. Section 2.3), showed that, particularly from a business perspective, the dynamics of the soil, plant, atmosphere, management and economic interactions are complex. Thus, a sophisticated approach to assessing the performance of irrigation and water management systems is required, if such interactions are to be suitably represented.

Computer simulation models can, potentially, represent the dynamics of the water balance in relation to crop yields and, thereby, provide information needed for associated economic analyses. Furthermore, models can be applied to provide water budget and crop yield information assuming a wide range of interacting conditions, for example, of different soils, seasons, types of irrigation systems and water management approaches. Obtaining similar crop yield and water budget information from experiments would be extremely complex, time consuming, costly and, not least, highly impractical. However, with regard to sugarcane in the Lowveld of Zimbabwe, there were no wholly appropriate computer simulation modelling tools available when the research described in this thesis was initiated in late 1998. Furthermore, information on the in-field operating characteristics of the various types of irrigation hardware in use in the Lowveld was also not available then, neither had the irrigation water management or scheduling approaches been scientifically assessed in relation to the different types of irrigation system hardware, in particular with regard to the newer centre pivot, floppy and drip irrigation systems.

Thus, in order to evaluate the performance of irrigation and water management systems in the Lowveld, a strategy was formulated which hinged on the development of an irrigation systems simulation model, namely *ZIMsched 2.0*, to interpret results from a Mobile Irrigation Performance Evaluation Unit, MIPU. In essence the MIPU assessed the in-field operating characteristics of the various irrigation systems hardware, providing information on the uniformity and depth of water applications, while *ZIMsched 2.0* was used to interpret this MIPU information in terms of associated water budget and crop yield impacts. In order to achieve this interpretation of MIPU data and information, algorithms were developed and/or integrated to account for:

- surface runoff,
- drainage,
- crop canopy and root development in relation to thermal time,
- irrigation non-uniformity,
- transpiration in relation to both too much and too little soil water, at different stages in the crop's growth cycle,
- soil water evaporation losses in relation to different irrigation hardware characteristics, and
- yields of estimated recoverable crystal, ERC, in relation to all of the above processes,

in a unique and original synthesis which resulted in the *ZIMsched 2.0* model. The credibility of *ZIMsched* 2.0 was established through a verification study in which close agreement and correspondence between the relative differences of observed and simulated yields of ERC for a range of soil, climate and water management conditions was shown. The index of agreement, 'd', between observed and simulated yields of ERC relative to a reference treatment, was 0.96 and Pearson's 'r' was 0.94.

While MIPUs in themselves are not unique, the data and information collated by the MIPU in the Lowveld of Zimbabwe and, in particular, the analysis of the MIPU data and its translation into associated impacts on yields of ERC, and water budgets, was considered novel and yielded new information and perspectives. Furthermore, as a result of the activities of the MIPU, persons were trained and methods and specialist tools were developed for the collation and analysis of essential in-field irrigation systems performance data and information. Thus, apart from the valuable data and information gathered in this research, a major benefit has been that sectors of the sugar industry in the Lowveld of Zimbabwe were sensitised to improved standards for irrigation systems design, installation and operation, and the capacity of human resources was developed.

Implementation of the research strategy resulted in unique and specific information on the performance of irrigation and water management systems in the Lowveld. In this regard, a key finding was that if the sugar industry in Zimbabwe were to improve its water management recommendations, it is likely that more than 20% of the water presently used on an annual basis when there are no water restrictions, could be saved. However, unless irrigation application uniformities are also improved, particularly on the furrow irrigated fields, there was evidence that slight crop yield losses may occur with the more precise irrigation scheduling, assuming fields are well drained, i.e. the portion of the fields receiving relatively low water applications due to poor uniformities would receive even less water with more precise irrigation scheduling. On poorly drained fields, however, crop yields are likely to improve with the reduced irrigation water applications associated with more precise irrigation scheduling, especially in the long term.

The sugar industry in the Lowveld of Zimbabwe is located in an area prone to recurring droughts, where historically there have been long periods during which water supply and demands have not been well balanced. This imbalance in water supply and demand led to the near collapse of the sugar industry following the 1991/2 drought. Therefore, it is recommended that the potential water savings shown in this research should be stored, and used to support the industry through the drought years. If such water savings are not made, or a portion of the sugar industry's water is re-allocated to another user, there is every chance that another economic disaster such as that which occurred after the 1991/2 drought, could recur. Thus, appropriate institutional arrangements to give incentives to conserve water, for example, through arrangements which facilitate 'water banking' by individual growers, should also be developed and implemented.

Questions regarding the actual and potential performance of the various types of irrigation systems were addressed. In this regard, it was found that most of the floppy, centre pivot and overhead sprinkler irrigation systems were performing at levels close to those expected, had they been designed and installed to appropriate engineering standards. However, most of the drip irrigation systems were performing below potential. Simulations showed that potential crop yields were limited by an average of approximately 12 % for one third of all the drip systems evaluated. This was largely due to in-field variations in water applied, caused by substandard system design, installation and/or maintenance. The crop yield potentials and irrigation efficiencies of the furrow irrigation systems were limited by large variations in water applied to individual furrows, and water applications which were, on average, excessively high. Although the simulations showed that the large water applications did compensate, to a degree, for the variations in applied water between and along the furrows, they also compromised efficiencies and could lead to further development of other problems, including raised water tables and increased soil salinity levels. Also, adequate drainage was assumed for the simulations. If drainage is impaired, yield reductions due to poor soil aeration are likely to occur. Most furrow designs and layouts were not operator friendly. The high variation in water applied to individual furrows showed that it was difficult for operators to control water applications and application variability using siphons. This is an area which could be improved through better, albeit more complex and expensive, designs and installations. For example, well designed supply furrows discharging through pipe spiles could be used to control flows into the furrows more evenly and would be much more operator friendly.

In terms of the potential performance of the various irrigation systems, it was shown that, provided drip irrigation systems are designed, installed and commissioned to an appropriate standard, and then operated and maintained correctly, sub-surface drip has a slight edge over the other irrigation systems which were evaluated. Average water savings ranged from approximately 2.2 to 1.5 Ml/ha relative to sprinkler type systems, and 3.5 to 2.3 Ml/ha relative to typical furrow irrigation systems, depending on how water applications were scheduled. With sub-surface drip, water savings occur as a result of reduced evaporation from the bare soil surface, no spray evaporation or wind drift losses, and the inherent flexibility in applying water which makes it possible to control runoff and deep percolation relatively easily compared with, say, furrow irrigation. However, this study revealed that, in practice, most drip systems in the Lowveld were not performing at potential optimum levels. There needs to be a greater level of professionalism in the design and installation of drip systems and growers need to have appropriate drip irrigation management training.

Furthermore, it was shown that on deep soils with high TAMs and on fairly level topography, furrow irrigation could, theoretically, be almost as efficient as sub-surface drip irrigation. The reason for this is that with furrow irrigation, evaporation from the bare soil surface is limited because only a portion of the soil surface is wetted, there are no spray evaporation or wind drift losses and with proper design and layout, irrigation water applications can be applied uniformly. However, this study revealed that with furrow irrigation, there is a big gap between potential theoretical performance and that generally achieved in practice in the Lowveld conditions, particularly on the sandier soils with low TAM values. With many furrow irrigation systems, feeder water losses constitute an additional, but very variable loss. Water losses in unlined feeders of up to 30% have been measured on an estate in the Lowveld.

Simulations with the *ZIMsched 2.0* irrigation system model showed that drainage under furrow irrigation, in particular, was excessive. Unless remedial actions are initiated, for example, through improvements to irrigation scheduling and better control of water applications, the development of high water tables and associated salinity problems is likely to get increasingly worse. In many cases, soils and topography may dictate that changes to another type of irrigation system would improve profitability. In this regard, a unique potential application of *ZIMsched 2.0* is to interpret in-field irrigation systems evaluations carried out by a MIPU, and then to compare these results, through an economic analysis, by using the simulated crop yields and water budgets predicted when other types of irrigation systems, or an upgrade to the existing system, are assumed.

The centre pivots and overhead hand-moved sprinkler systems which were evaluated by the MIPU were found to apply water with very good uniformities. It was also found that operators were able to control the amount of water applied with these systems relatively easily, compared with furrow irrigation. As a result, simulated efficiencies where higher than with furrow irrigation, generally leading to an annual saving in water of at least 1 Ml/ha. Nevertheless, a potential limitation regarding the efficiency of floppy, sprinkler, and centre pivot irrigation systems was highlighted, namely, that of water losses attributable to evaporation from the wet soil surface. The reason for this is that with floppy, sprinkler and centre pivot irrigation systems the entire soil surface is wetted and if water is applied frequently, the evaporation losses from the bare soil surface can be excessively high prior to the development of full crop canopies. Early season water management approaches should, therefore, take cognisance of the potential for such losses and aim at applying relatively larger water amounts less frequently, *viz.* initiating irrigation applications after at least 35 mm of water has been depleted.

Applying such large water applications with overhead sprinkler irrigation systems, particular with centre pivots, can, however, present a challenge in the sense that surface runoff is likely to increase. Therefore, appropriate surface mulching, for example, using the trash and tops from sugarcane should also be considered. When the soil surface is protected from the impacts of water droplets, it is less prone to crusting and higher infiltration rates can be maintained. If the soil surface is mulched, the water budget / schedule should also be adjusted accordingly, otherwise excessive water is likely to be applied in the early season with increased potential for leaching, denitrification and lowering of crop yields. The reason for this is that with surface mulching the water budget is impacted in a positive way through reduced evaporation from the soil surface. Sugarcane varieties which ratoon well under trash conditions should also be targeted, otherwise the potential for delays in germination and canopy development resulting from the trash blanket may offset any potential gains from water savings.

In order to address two major outcomes of the research, namely, that there is a great need for improved irrigation scheduling by the three large estates and by individual growers in the Lowveld, and that the application of all the existing water management recommendations resulted in excessive irrigation water applications, two new and original irrigation scheduling tools were developed. The first tool, *ZIMsched*, is a spreadsheet-based scheduling tool, which incorporates the unique water budgeting algorithms in *ZIMsched 2.0*. Spreadsheets were selected as the design platform in order to take advantage of the familiarity that many growers had already developed with spreadsheets. This gave *ZIMsched* a distinct advantage relative to other computer-based irrigation scheduling tools in terms of ease of use. Furthermore, *ZIMsched* could easily be tailored to specific needs of growers and allowed for relatively complex water management strategies, for example, deficit irrigation strategies, which could be developed using *ZIMSched 2.0*, to be implemented at grower level.

For growers averse to the use of computers, another new irrigation scheduling approach was formulated. This irrigation scheduling approach used pre-determined irrigation cycles suited to particular soil, irrigation systems and average growing season conditions and an innovative, yet simple, rule-of-thumb to account for effective rainfall. Although less flexible and representative when compared with irrigation scheduling tools which make use of near-real-time daily weather data, such as *ZIMsched*, the use of the pre-determined cycles and rainfall rule proved very robust and profitable in a case study evaluation undertaken using data from Pongola in South Africa. It is thus considered to have good potential as an appropriate and novel technology transfer option, particular suited to small scale and/or emerging farmers.

To reiterate, the provision of irrigation water management support systems is considered vitally important to improving performance. With *ZIMsched* the accuracy with which the water budget is calculated, was improved considerably relative to existing budget calculations prevalent in the Lowveld and simulated water savings of 20 % to 30 % were achieved.

Additional to the implementation of *ZIMsched*, or the pre-determined irrigation cycles, the following changes to the existing irrigation water management recommendations and practices in the Lowveld of Zimbabwe should also result in improved efficiencies.

- Change the full canopy 'pan factor' from 1.0 to 0.9 for the October to March period and then to 0.85 for the remainder of the season until the drying-off period is initiated.
- Assume when calculating water applications, that application efficiency is above 90 % for all sprinkler systems and 100 % for furrow and drip systems. If a low efficiency is assumed, excessive water is applied and the low efficiency assumed will be realised due to excessive runoff and deep percolation losses!
- Use the methodology described in Chapter 5 (Section 5.2.2.1) to account for effective rainfall, i.e. when calculating soil water depletion levels, and rain then falls, only resume adding deficits after the period of days determined using the methodology described in Chapter 5.
- After an excessive irrigation application which, for example, can occur frequently with many furrow fields, wait at least two to three days (dependent on the field's drainage characteristics and the amount of excess) to allow the excess water to drain, before starting to add deficits to the calculated soil water budget.

- Mkwasine Estate's early season 'pan factors' are too high for furrow irrigation. The pan factors used by Hippo Valley, or the date system used by Triangle are better suited for furrow irrigation.
- After the first irrigation, further irrigation water applications using Triangle Estate's time based scheduling system need only be equivalent of 50 % of the soil's TAM, as opposed to Triangle's recommendation of applying water applications equivalent to 100 % of the soil's TAM value. Simulations with *ZIMsched 2.0* showed that the actual soil water depletion at the time of Triangle's recommended second and third irrigation water applications was not likely to exceed 45 mm. For the furrows sampled, the amount of water applied in the first three irrigations at Triangle was excessive.
- The early season, pre-full canopy pan factors used by Hippo Valley are well suited to furrow irrigation, but are too low for centre pivots if there is no surface mulching. The reason for this is the higher level of evaporation from the bare soil surface for pivots compared with furrow systems. After the first month the factor of 0.2 should be increased to 0.3, and the factors of 0.3 increased to 0.4 (cf. Appendix F).
- An intensive exercise to monitor and control the amount of water siphoned into individual furrows should be supported. The author together with the MIPU has developed simple apparatus and trained personnel on the three estates to facilitate this. Fields which have excessive applications need to be examined and the water applications reduced where possible.
- When planning to upgrade an irrigation system or install a new system, the MIPU should be consulted to check that the system is designed, installed and commissioned to appropriate standards.

A further outcome of the research described in this thesis is that techniques and tools to support strategic irrigation and water management decisions in the Lowveld of Zimbabwe were developed. Used together with case specific financial and production cost information, the tools and methods described in this thesis make possible the calculation of comparative Net Returns per Hectare and associated Relative Net Returns (reflecting an opportunity cost of water) for different irrigation and water management systems. Thus, unique and original information to support sound business decisions regarding the design, upgrading or replacement of existing irrigation systems or the selection of an appropriate irrigation and water management system for a given environment can be provided. For example, in Chapter 5, the application of *ZIMsched 2.0* to determine peak irrigation system design capacities and associated water management strategies, including deficit irrigation strategies, suited to either land limited or water limited production conditions, is discussed and serves to highlight the utility value of this research.

In final conclusion, the research effort described in this thesis has highlighted opportunities to increase the productive and sustainable use of resources through the development and application of a unique set of tools and methodologies. Furthermore, tools and information to facilitate improvements to both strategic and on-farm water management were developed, in an effort to translate theoretical water savings into practical realities.

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APPENDIX A: SUGARCANE EVAPOTRANSPIRATION ESTIMATES IN THE LOWVELD OF ZIMBABWE (Lecler, 2001a)

SUGARCANE EVAPOTRANSPIRATION ESTIMATES IN THE LOWVELD OF ZIMBABWE

N LECLER

Zimbabwe Sugar Association Experiment Station
Private Bag 7006, Chiredzi, Zimbabwe
(Email zsaes@zol.co.zw)

Abstract

In order to benchmark and improve estimates of sugarcane evapotranspiration (ET) and thereby facilitate increased irrigation water use efficiencies, a study was undertaken to compare, for the south east lowveld of Zimbabwe:

- the world standard, Food and Agricultural Organisation (FAO) Penman Monteith reference evaporation (E_{FAOpm}), with
- evaporation from United States Weather Bureau, Class A evaporation pans (E_{apan}), and
- evaporation from a relatively simple commercially available atmometer device, called an ETgage, which has been designed to mimic many of the evaporation characteristics of a plant (E_{etg}).

In addition, ET estimates for sugarcane, derived using state-of-the-art procedures presented in the FAO publication No.56 were used to derive refined monthly pan and ETgage factors in order to relate data from these instruments to benchmark FAO-based estimates of sugarcane ET.

The comparisons between evaporation estimates showed that there were large differences between E_{apan} and E_{FAOpm}, especially when E_{apan} was above 8 mm. At these high E_{apan} values, E_{apan} was shown to exceed the equivalent E_{FAOpm} by more than 30%. Nevertheless, the relationship between E_{apan} and the E_{FAOpm} estimates was very consistent, especially when averaged over a period of five days or longer. Accurate estimates of E_{FAOpm} could be predicted from E_{apan} data using a linear regression relationship. When compared with the A-pan, it is easier to install and operate the ETgage according to standard recommendations. The ETgage is also simpler and significantly cheaper than an automatic weather station and was shown to have potential to provide a good practical reference evaporation estimate. The study revealed that, for the data analysed, both sets of derived pan and ETgage factors showed seasonal trends, with values relatively lower in winter months than in summer months. The derived pan factors ranged from 0.85 in June to 1.01 in January. These pan factor values tally with the results of irrigation trials. The derived ETgage factors were slightly lower than corresponding FAO-based sugarcane crop coefficients. The greatest benefit of using data from an automatic weather station for the calculation of E_{FAOpm} is likely to be in situations when the crop is irrigated daily, as with drip irrigation.

Introduction

In Zimbabwe, estimates of sugarcane water requirements which are vital for irrigation planning, development, day-to-day water management, and crop yield forecasting, have usually been determined with reference to the evaporation from United States Weather Bureau, Class A evaporation pans (A-pan). While it has been routinely accepted that water loss from an A-pan is very closely related to water loss from a sugarcane crop (Thompson and Boyce, 1972; Cackett, 1984; Clowes and Breakwell, 1998), the suitability of the A-pan as a reference evaporation estimate for crops, has also been questioned (de Jager and van Zyl, 1989; Jensen *et al.*, 1990; Schulze and Kunz, 1995).

In a number of comprehensive comparative evapotranspiration (ET) studies, the often erratic and poor performance of A-pans has been contrasted with the superior performance of the Penman Monteith (PM) approach (Jensen *et al.*, 1990; Choisnel *et al.*, 1992, cited by Allen *et al.*, 1998). A panel of experts from the International Commission of Irrigation and Drainage, the World Meteorological Organization and the Food and Agricultural Organisation (FAO) have, therefore, recommended the adoption of the PM combination method as a new, globally valid standard for crop water requirement calculations (Allen *et al.*, 1998).

The FAO PM approach accounts for differences in crop canopies and aerodynamic resistances, relative to a defined reference crop, within a 'crop coefficient' (K_c). K_c can be split into two factors which separately describe the evaporation from the soil surface, K_e, and the transpiration, K_{cb}, components. Under conditions of low relative humidity and/or high windspeeds, the aerodynamic differences between tall crops like sugarcane and the defined reference crop can be significant. In order to account for these differences, K_cs can be further adjusted for the influences of climatic conditions using an equation that contains crop height, wind speed and minimum relative humidity as variables (Allen *et al.*, 1998).

An alternative methodology to using K_cs, is to use the PM equation in a one-step procedure for the direct calculation of ET because the surface and aerodynamic resistances in the PM equation are crop specific. This approach is being researched for sugarcane, for example, by McGlinchey and Inman-Bamber (1996). The one-step approach for sugarcane is, however, proving challenging and problems have been reported ([1] personal communication). It is pertinent to note that Pereira and Allen (1999) state that, due mainly to difficulties in describing changes in resistance and net radiation,

> 'the research community is probably some 10 to 15 years away from producing one-step procedures that are consistent, predictable and reliable'.

With this background and evidence that there is potential for deriving improved estimates of sugarcane ET, thereby benefiting irrigation water use efficiencies, a study was initiated to compare, for the south east lowveld of Zimbabwe, relationships between:

- the FAO PM reference evaporation estimates (E_{FAOpm})
- evaporation from A-pans (E_{apan}), and
- evaporation from a relatively simple commercially available atmometer device, called an ETgage which has been designed to mimic many of the evaporation characteristics of a plant (E_{etg}) (Asbell, 1999).

The ETgage was included in the study because literature (e.g. Broner and Law, 1980; Asbell,1999) had indicated that it has potential to give reference evaporation estimates comparable to those from a full automatic weather station (AWS), at a substantial reduction in cost and complexity.

In addition, ET estimates for sugarcane, derived using the state-of-the-art procedures presented in the FAO publication No.56 were used to derive monthly pan and ETgage factors. These factors can be used to relate data from these instruments to benchmark FAO-based estimates of sugarcane ET. This will help facilitate objective comparisons to be made between the water requirements of sugarcane and other, sometimes competing, crops.

The evaporation comparisons were based on 20 years of daily weather data collected at a manual weather station, three years of data from an automatic weather station and one years data from the ETgage atmometer device, all at the Zimbabwe Sugar Association Experiment Station (ZSAES). Data from pan factor irrigation trials were used in order to assess the pan factor values derived using the FAO-based ET estimates. The research methodology, results of the comparative studies and implications for irrigation water management are discussed in this paper.

Methodology

Weather data were recorded at the ZSAES which is located at latitude 21° 2.5' south and longitude 31° 57' east and altitude 420 m.a.s.l. The manual weather station (MWS) measurements which included radiation data were for the period from 1970 to 1990. Thereafter radiation data were not collected from the MWS because the Bellani pyranometer which had been used for the purpose broke and was not be replaced. The automatic weather station (AWS) was commissioned in April 1998, and the ETgage in February 2000.

Instrumentation and reference evaporation calculations

A Fortran 90 computer programme was written to calculate E_{FAOPM} according to procedures described by Allen *et al.* (1998). The options selected for the calculation of vapour pressures, the type of radiation instruments and the apparatus used for recording E_{apan} and E_{etg} are described as follows.

Manual Weather Station, E_{FAOpm}

For the weather data recorded manually, vapour pressures from wet and dry bulb readings recorded at 08:00h and 14:00h were averaged to estimate the average daily vapour pressure for the E_{FAOPM} calculations. Radiation was measured using a Bellani pyranometer. All instruments were installed according to standard recommendations (Doorenbos, 1976).

Manual Weather Station, E_{apan}

Two adjacent A-pans painted black inside (not standard according to FAO recommendations) and silver outside and covered with wire screens with a mesh size of 25 mm were read daily at 08:00h using a hook gauge, and the values averaged. No adjustment for the screening or black paint were made.

Manual Weather Station, E_{etg}

A single ETgage was read daily at 08h00 by recording the water level in a sight tube. A green canvas #30 vapor diffusion cover was used on the Etgage, which was installed according to standard recommendations (Asbell, 1999).

Automatic Weather Station, E_{FAOpm}

For data recorded using the AWS, average daily vapour pressure and saturated vapour pressure, based on relative humidity measurements recorded at ten second intervals using a Vaisala CS 500 air temperature and relative humidity sensor, were used for the daily E_{FAOPM} calculation. A LI-COR LI200X silicon pyranometer was used to measure solar radiation. The AWS was installed according to standard recommendations (Savage, 1998).

Evapotranspiration, pan factor and ETgage factor calculations

For the ET comparisons, the FAO methodology (Allen *et al.*,1998), which is also considered to be the most accurate estimate of sugarcane ET, was used as a benchmark (Equation 1).

$$ET_{FAOd} = E_{FAOpm}\, Kc_{(u2,RH)d} \qquad \text{Eq 1}$$

where ET_{FAOd} = FAO-based benchmark evapo-transpiration estimate for a 3 m tall full canopy sugarcane crop (mm/d)

$Kc_{(u2,RH)d}$ = FAO recommended sugarcane crop coefficient adjusted on a daily basis for influences of relative humidity and windspeed

$= 1.25 + (0.04(u_2-2) - 0.004(RH_{min}-45))(h/3)^{0.3}$

where u_2 = windspeed measured at a height of 2 m (m/s)

RH_{min} = minimum daily relative humidity (%)

h = crop height, taken as 3 m for sugarcane (m)

In order to:

- investigate the potential for refining pan and ETgage factors so that these instruments could be used to give ET estimates similar to benchmark ET_{FAOd} estimates

- observe whether there were any apparent seasonal trends in the pan and ETgage factors
- assess the derived pan factors in relation to existing pan factor recommendations and irrigation trial data, weather data recorded by the AWS during the period 1998 to 2001 were used to derive refined monthly pan factors. These were taken as the median monthly values of daily factors calculated according to Equation 2, *viz.*

$K_{pr} = ET_{FAOd} / E_{apan}$ Eq 2

where K_{pr} = refined pan factor to relate evaporation from an A-pan to sugarcane ET as estimated using the FAO methodology (Allen *et al.*, 1998)

E_{apan} = evaporation from a Class A evaporation pan (mm/d)

Similar calculations were used to derive refined monthly ETgage factors using data recorded during the period February 2000 to March 2001. The monthly ETgage factors were taken as the median monthly values of daily factors calculated according to Equation 3, *viz.*

$K_{etgr} = ET_{FAOd} / E_{etg}$ Eq 3

where K_{etgr} = refined ETgage factor to relate evaporation from an ETgage to sugarcane ET as estimated using the FAO methodology (Allen *et al.*, 1998)

E_{etg} = evaporation from the ETgage (mm/d)

Results

A scatter plot showing comparisons between daily E_{apan} and E_{FAOpm} calculated using data recorded manually from 1970 to 1990 is shown in Figure 1. A second scatter plot showing the same data smoothed with a five day moving average is shown in Figure 2. The use of a moving average encapsulates all possible five day average values and is relevant as an appropriate representation of typical minimal irrigation application intervals, for most systems except drip. Similar scatter plots with E_{FAOpm} calculated using data recorded with the AWS from April 1998 to March 2001 are shown in Figures 3 and 4 respectively.

Both sets of data show similar trends, *viz.* the differences between E_{apan} and the E_{FAOpm} increase as the magnitude of the evaporation increases. For the months April to August (winter when evaporation is relatively low), the differences are small but during September to March (summer, when evaporation is higher), the differences can exceed 30%, (cf. Figure 4). From an irrigation management perspective, it is pertinent to note that the relationship between five day averaged values is much better than the relationship between daily values.

Using data from the AWS and the MWS resulted in two different linear regression relationships between five day average E_{apan} data and five day average E_{FAOpm} estimates, as shown in Table 1. Investigation of the Bellani pyranometer apparatus, which was used for the MWS radiation measurements, revealed that:

- the reading is temperature dependent, therefore

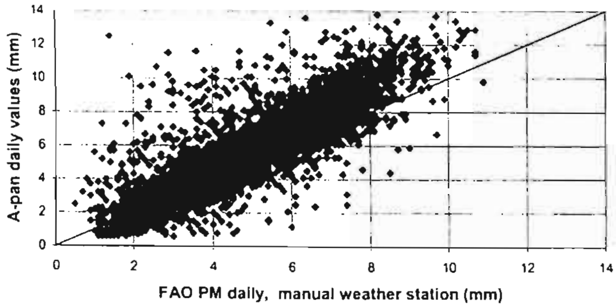

Figure 1. Scatter plot showing Eapan vs EFAOpm daily values, data were recorded at the manual weather station.

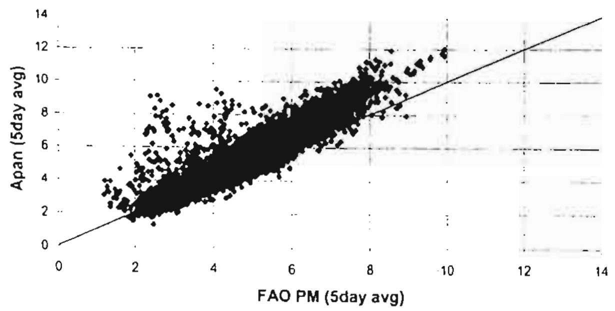

Figure 2. Scatter plot showing Eapan vs EFAOpm , values are five day moving averages, data were recorded at the manual weather station.

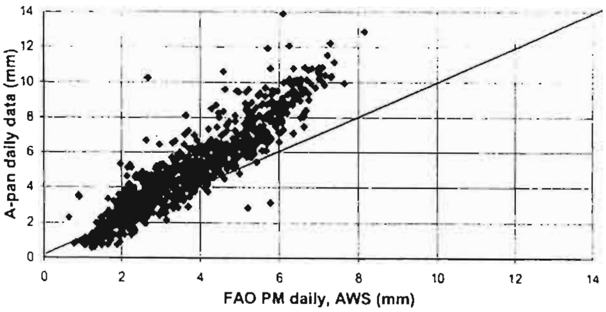

Figure 3. Scatter plot showing Eapan vs EFAOpm daily values, data were recorded by the automatic weather station.

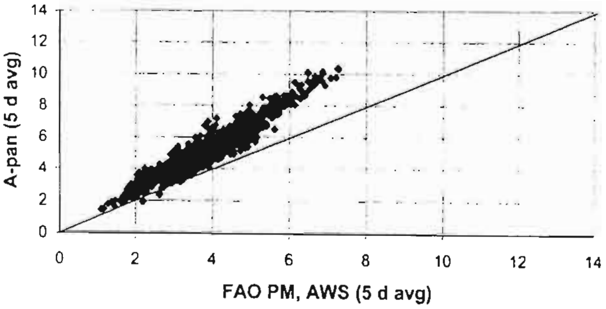

Figure 4. Scatter plot showing Eapan vs EFAOpm, values are five day moving averages, data were recorded by the automatic weather station.

- it needs to be calibrated in the field against a solarimeter in a special calibration programme that covers different seasons, and
- its accuracy is ± 10 to 20% (Doorenbos, 1976).

At ZSAES, it seems that only one calibration equation was used, despite large variations in mean air temperatures. As the Bellani pyranometer is no longer at ZSAES, the derivation of temperature dependent calibration relationships in order to 'correct' all the historical radiation data was not feasible. The inaccuracies in the Bellani pyranometer radiation measurements would have translated to similar inaccuracies in the estimates of E_{FAOpm}. For this reason, E_{FAOpm} and associated relationships derived using data from the MWS were considered unreliable.

For the relatively short period for which concurrent ETgage, E_{apan} and AWS data were available, *viz.* within 1 February 2000 to 22 March 2001, E_{etg} data and E_{apan} data were compared with E_{FAOpm} estimates derived from the AWS. Scatter plots of these comparisons are shown in Figures 5 and 6, and comparative statistics for the five day moving averages are shown in Table 2. When compared to the average of two A-pans read with a hook gauge, the resolution of the reading from the single ETgage, read from a sight tube, was relatively coarse at a daily time scale, *viz.* it was apparent from the data that the data-recorder *normally* read the site tube to the nearest 1.0 mm (cf. Figure 5). However, this had little effect on the five day averages because the sight tube readings on the ETgage were inter-dependent. Compared to the E_{apan} data, E_{etg} data were much closer to E_{FAOpm} estimates. The RMSE, for E_{etg} compared to E_{FAOpm} was 0.98 mm and the difference between the means, 13.6%, compared to a RMSE of 1.3 mm and difference between means of 32.7% for the corresponding comparison between E_{apan} and E_{FAOpm}. However, if E_{apan} readings were used as input to a linear regression model used to calculate an estimate of E_{FAOpm}, the model performance was excellent, in fact, better than a similar linear regression model using E_{etg} data, *viz.* the RMSE is lower, a greater proportion of the RMSE is unsystematic and the index of agreement, d, is closer to 1.0 (cf. Table 2). This indicates that for the period under consideration, the A-pan was an excellent *predictor* for E_{FAOpm}, in fact better than the ETgage.

The refined median monthly A-pan and ETgage factors calculated to relate data from these instruments to ET_{FAOd} (cf. Equations 2 and 3) are given in Table 3. Both sets of factors show a definite seasonal trend, being lower in winter than in summer. The pan factor values compare well with irrigation trial data collected at ZSAES, which are shown in Figure 7. The data in Figure 7 are from the irrigation of full canopy sugarcane using various pan factors to determine irrigation intervals. These trials showed that optimum ET estimates result from pan factors which are greater than 0.8 and less than 1.0, but gave little information on how pan factors may vary throughout a season. It is likely, therefore, that taking cognisance of the seasonal trends in the pan factors shown in Table 3 may lead to improved estimates of sugarcane ET, however, an appropriate trial is needed to test this hypothesis. When considering the likely gains in irrigation efficiency from slight under-irrigation (Lecler, 1998), the use of a constant pan factor of 0.85 is also well justified. The derivation of median monthly FAO K_cs ($K_{c(u2,RH)m}$), shown in Table 3, should facilitate the use of E_{apan} as a predictor of E_{FAOpm} which can then be used without windspeed and relative humidity data to estimate ET_{FAOd}. A further independent data set is, however, needed in order to

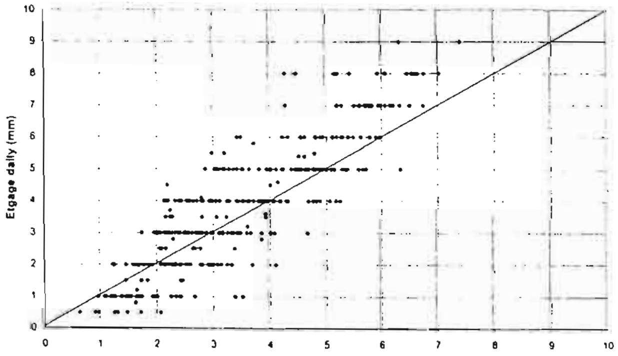

Figure 5. Scatter plot showing Eetg vs EFAOpm, daily values.

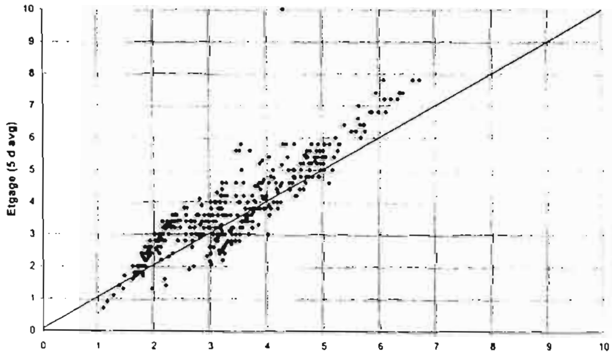

Figure 6. Scatter plot showing Eetg vs EFAOpm, values are five day moving averages.

Table 1. Regression statistics for linear regression equations used to predict E_{FAOpm} from E_{apan}, (y = bx + a), showing differences between relationships derived using the AWS and the MWS*.

Dependent Variable (y)	Independent Variable (x)	Slope (b)	Constant (a)	Std Error of E_{FAOPM} estimate (SEy)	Correlation Coefficient (Pearson's r)
E_{FAOpm} MWS	E_{apan} 1970 -1990	**0.734**	**0.82**	0.57	0.92
E_{FAOpm} AWS	E_{apan} 1998 -2001	**0.676**	**0.31**	0.34	0.95

*All units except b and r are mm/d

Table 2. Quantitative measures of five day reference evaporation comparisons for concurrent data from the ETgage, the AWS and the A-pan, *viz.* within 1 February 2000 to 22 March 2001.**

Name of P	Mean E_{FAOpm}	Mean P	N	a	b	RMSE	$RMSE_u$	$RMSE_s$	d	r
E_{apan}	3.44	4.57	370	-0.3	1.4	1.3	0.42	1.23	0.8	0.97
E_{etg}	3.44	3.91	370	0	0.9	0.98	0.85	0.49	0.88	0.85
E_{FAOpm} predicted from E_{apan}	3.44	3.44	370	0.19	0.94	0.29	0.28	0.07	0.99	0.97
E_{FAOpm} predicted from E_{etg}	3.44	3.44	370	0.95	0.72	0.64	0.54	0.34	0.91	0.85

** Terms N, b, d and r are dimensionless, while remaining terms have units of mm/d

RMSE = root mean squared error

$RMSE_u$ and $RMSE_s$ = root mean squared errors, unsystematic and systematic, respectively

d = index of agreement, 1.0 indicates perfect agreement, 0.0 indicates no agreement (Wilmott, 1981)

r = correlation coefficient (Pearson's r)

a (intercept) and b (slope) of a least squares regression between P as the dependent variable (predicted) and E_{FAOpm} as the independent variable (observed)

N = number of data points

Table 3. Derived full canopy 'pan factors', 'ETgage factors' and median monthly FAO-based sugarcane crop coefficient ($K_{c(u2,RH)m}$) values for the south east lowveld of Zimbabwe.

Factors	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Refined "Pan Factors" (K_{pr})	1.01	1.01	0.96	0.96	0.90	0.85	0.88	0.87	0.91	0.96	0.96	0.97
Median Monthly FAO $K_{c(u2,RH)m}$	1.22	1.18	1.18	1.21	1.25	1.23	1.25	1.27	1.30	1.31	1.29	1.25
Refined "ETgage Factors" (K_{etgr})	1.11	1.03	1.15	1.04	0.95	0.90	1.06	0.87	1.02	1.12	1.11	1.21

verify this approach, and to compare it with the use of pan factors alone.

Conclusions

- There is a large difference between E_{apan} data and equivalent estimates of E_{FAOpm}, especially when the A-pan reads above 8 mm. At such high evaporation values, E_{apan} can exceed E_{FAOpm} by more than 30 %. However, the relationship between the E_{apan} and E_{FAOpm} was very consistent, and E_{FAOpm} estimates were reliably predicted from E_{apan} data using a linear regression relationship.
- Differences between the E_{FAOpm} : E_{apan} relationship using data collected from instruments read manually, and data recorded by the AWS were likely due to:
  - the different time periods for which data were recorded, but more importantly,
  - the likely errors in the manually recorded radiation data.

  E_{FAOpm} estimates, calculated using data from the AWS were, therefore, considered more reliable for deriving E_{FAOpm} : E_{apan}, E_{FAOpm} : E_{etg} and associated relationships.
- When considering general uncertainties in irrigation water budgeting, including rainfall measurement and effectiveness, soil water properties, estimates of irrigation water applications, crop canopy conditions, nutrition status and also irrigation (non-) uniformity, the relative errors in ET estimates arising from the use of the ETgage and/or the A-pan are not likely to be significant in most practical applications. This is especially so if appropriate locally calibrated ETgage or pan factors are used to adjust recorded E_{apan} or E_{etg} values to associated sugarcane ET estimates, and the ET estimates are for periods of five days or longer.

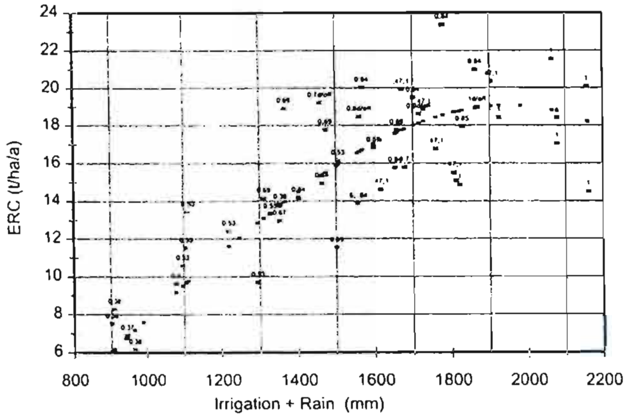

Figure 7. Estimated Recoverable Crystal (ERC) vs total water (irrigation + rain) for various 'pan factors', shown as data labels.

- The average of two A-pans read with a hook gage in a research environment, proved a better predictor than E_{etg} in a linear regression model to estimate E_{FAOpm}. Nevertheless, the relative simplicity, low and simple maintenance, standardisation and robustness of the ETgage are likely to prove it a more reliable and practical instrument in many on-farm/estate contexts. There is evidence, however, that the use of standard FAO-based sugarcane crop coefficients with E_{etg}, will lead to slight over-estimation of ET_{FAOd}. Refined monthly ETgage factors, suitable for use in the lowveld of Zimbabwe, have been derived in order to adjust E_{etg} to give better estimates of ET_{FAOd}. These new derived ETgage factors need to be tested on independent data once more E_{etg} data become available.
- Refined monthly pan factors, suitable for use in the lowveld of Zimbabwe were derived using data recorded by the AWS. These refined pan factor values showed a definite seasonal trend and were relatively higher in summer than in winter. The values, which ranged from 0.85 in June to 1.01 in January tally with results from irrigation pan factor trials. Taking cognisance of the apparent seasonal trend in pan factor values which was revealed in this study, may lead to improved irrigation water use efficiencies.
- World wide research studies show that the 'Rolls Royce' method for the prediction of crop ET is likely to be the use of data from an AWS to determine E_{FAOpm} combined with the FAO recommended K_cs adjusted for influences of windspeed and relative humidity. To benefit from this technology, will, however, require careful application of a good water budget and regular maintenance, calibration and representative placement of the AWS sensors. Drip irrigation water management, which entails daily irrigation water applications, is likely to benefit the most through the use of AWS data.

Acknowledgements

The author would like to thank the data processing personnel at ZSAES, especially Mr Emmanuel Chigaro, Lindiwe Mativenga (now Banda), Enoch Masokovere and Robert Chamisa, for their painstaking input of manually recorded weather station data into digital format. Mr Steven Dlomo, who faithfully records data at the ZSAES weather station, also deserves acknowledgement. The new Director of the ZSAES, Dr Muntubani Nzima, for reading an early draft of the paper and giving useful comments.

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[1] During discussions and as a result of data presented at the year 2000 International Irrigation Workshop, at the SASA Experiment Station

APPENDIX B: DEFAULT SOIL TEXTURE-BASED PARAMETERS USED IN *ZIMsched 2.0*

Table B1 Soil texture-based parameters used in *ZIMsched 2.0* (after Schulze *et al.*, 1995; Allen et al., 1998)

Texture Class	PWP (m/m)	DUL (m/m)	PO (m/m)	REW (FAO 56) (mm)	Adjustment to Slabber's 'f' (%)	Saturated Drainage Coefficient 'Ks'
Cl	0.298	0.416	0.482	10	-8.0	0.15
ClL	0.195	0.312	0.468	9	-1.8	0.4
L	0.128	0.251	0.464	9	0.6	0.5
LSa	0.068	0.143	0.432	6	5.5	0.7
Sa	0.050	0.112	0.430	4.5	8.0	0.8
SaCl	0.228	0.323	0.423	8.5	-1.8	0.4
SaClL	0.159	0.254	0.402	8.5	0.6	0.5
SaL	0.093	0.189	0.448	8	4.3	0.65
SiCl	0.253	0.390	0.480	10	-5.5	0.25
SiClL	0.190	0.335	0.473	9.5	-3.1	0.35
SiL	0.121	0.272	0.495	9.5	-0.6	0.45

Note:

PWP = permanent wilting point
DUL = drained upper limit (i.e. field capacity)
PO = porosity
REW = 'Stage 1' soil water evaporation limit

APPENDIX C: OPTIMAL WATER MANAGEMENT STRATEGIES FOR SUGARCANE (Lecler, 2001)

Optimal Water Management Strategies for Sugarcane

Neil Lecler
Zimbabwe Sugar Association, Private Bag 7006, Chiredzi

Abstract

Uncertain water availability requires the use of innovative water management strategies to ensure the long term viability of the Zimbabwe sugar industry. In this paper the potential of 'deficit irrigation' is presented using empirical data from more than 40 'crop-years' of irrigation trials. These trials confirmed theoretical concepts of deficit irrigation and showed that a reduction in efficiency accompanied increased watering. Trials have also highlighted the benefits of using a well judged 'dry-off' period (to 3 x TAM) as a simple, low risk water saving strategy. Trials cannot, however, be used to answer questions on how to manage streamflow, irrigation strategy/water demand and available storage interactions over time. There are tools available to investigate these relationships, for example, the *ACRU* agrohydrological simulation model. Evidence given in this paper and in other reports on the water status of the industry suggests that the commissioning of such an investigation and the adoption of irrigation strategies on the basis of these insights could be of great benefit to the sugar industry. A tool to implement target irrigation strategies and schedule irrigation applications at the field level has been developed. This tool can be used to guide the application of a given target of water in the optimal fashion, taking into consideration different harvest dates, soils, long range climate forecasts, the characteristics of different types of irrigation system and the timing of water stress, so that limited water is used in the most effective manner.

Introduction

The sugar industry in the Lowveld of Zimbabwe is heavily dependent on available water resources. After a near catastrophic drought in 1992, consultants were tasked with assessing the reliability of these resources. They highlighted serious limitations in the numerous methods that have been used to assess available water and reservoir yields and presented evidence suggesting that reservoir yields have been grossly over-estimated. In their conclusions they recommended that a 'state of the art' computer simulation model of the system needs to be developed in order to:
(i) obtain a more reliable assessment of water availability, and
(ii) operate the "complex" system in the most efficient manner (Binnie and Partners, 1993).

In the twelve years prior to 1993 the average level of reservoir storage in the Runde catchment showed a gradual but fairly consistent decline from 100% of potential to nearly 0 % of potential (Kaseke 1998). Thus supply and demand interactions were not well managed, further evidence that reservoir yields have been overestimated. Whilst building more dams to increase the level of available storage could help, the supply and demand interactions will become more complex and questions as to the optimal level of land development for the increased water storage, still remain. Increased insight into water availability and well matched water management strategies are needed to ensure the long term viability of the industry.

In this paper the potential of deficit irrigation as a strategic option is investigated and the tools and information needed to transfer strategy to practice are discussed.

Deficit Irrigation: Concepts

Deficit irrigation is an optimising strategy whereby net returns as opposed to crop yields, are maximised. This is often achieved by reducing the amount of irrigation water applied to a crop to a level that results in some yield reduction caused by water stress. The fundamental goal of deficit irrigation is to improve water use efficiency and maximise profits through a reduction in capital and operating costs. A major challenge to the introduction of deficit irrigation strategies is to convince irrigation practitioners not only of their value but also of their practicality.

Recognition of the following points is fundamental to an understanding of deficit irrigation:
i) that the efficiency of irrigation water applications decreases as the number and the magnitude of the applications increases,
ii) that the application of irrigation water is costly, in terms of both direct costs but more importantly in terms of lost opportunities, and
iii) that the determination of an optimal irrigation strategy is very dependent on water supply and demand interactions over time, particularly on whether a shortage of water or a shortage of land is the factor limiting production.

Irrigation water losses include those due to spray evaporation, wind-drift, evaporation from the soil surface and potentially through surface runoff and deep percolation, especially if the performance of an irrigation system is poor and water is applied unevenly. The potential for losses through surface runoff and deep percolation increases as the number and magnitude of irrigation applications increases and in addition, the effective use of rainfall is likely to diminish. The net result is that if a plot of crop yield versus actual transpiration and applied irrigation water is drawn, the yield versus applied irrigation water line will curve away from the yield versus transpiration line as shown in Figure 1. This is one of the reasons why the application of the large amounts of irrigation water needed to maximise yield does not always result in maximum economic return.

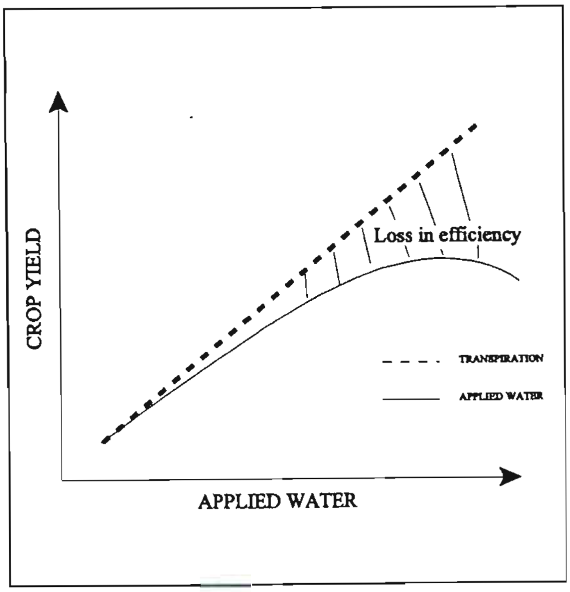

Figure 1 General form of a crop production function (after English, 1990)

Irrigation water application costs are related to actual costs of water, interest on capital equipment, energy, labour and also opportunity costs, especially if water is limited. When water as opposed to land is limited, the water saved by reducing irrigation applications per hectare may be used to irrigate additional land possibly resulting in an increase in total income. The potential income from the irrigation of the additional land is an opportunity cost of water. If land is limited the question reverts to what irrigation application amount results in the maximum difference between irrigation application costs and yield related returns.

In Figure 2, two cost functions and a revenue function are shown. The revenue function has the same shape as the yield versus applied water curve (see Figure 1) as revenue is simply the product of yield and crop price. The lower limit of the cost functions represents fixed field costs, for example, capital costs, crop insurance, fixed costs of irrigation, planting, tillage, chemical use and harvesting. The slope of the cost functions represents the marginal variable field costs of production, for example, pumping costs, water costs and yield related costs, like fertiliser and transport. The upper limit of the cost functions represents the maximum water delivery capacity of the two different irrigation systems. The maximum water delivery capacity of an irrigation system is a hardware limitation that can have very significant cost and flexibility implications. For example, for the two systems shown in Figure 2, the system with the smaller capacity, i.e. System 2, does not have sufficient capacity to irrigate for maximum crop yields, however, the implications of lower capital and operating costs are such that the net returns are nearly double those attainable with the larger system, i.e. System 1.

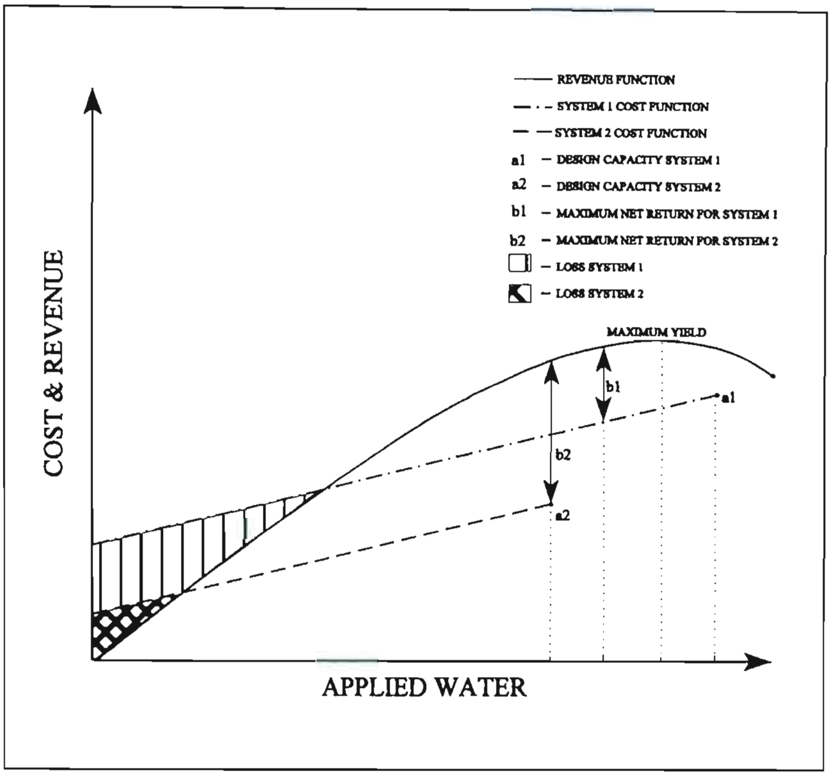

Figure 2 Revenue and cost functions (after English, 1990)

Sugarcane Production and Revenue Functions

Data recorded during irrigation trials performed at the Zimbabwe Sugar Association Experiment Station (ZSAES) were collated and analysed in order to determine relationships between the various irrigation treatments and crop yields. The trials could be separated into three main groups of treatments, *viz.*

(i) the irrigation of full canopy sugarcane using various fractions of evaporation from a class A-pan to determine irrigation intervals (so-called "pan factor" trials),
(ii) varying the way sugarcane was irrigated during the early growth period, i.e. after harvesting to the development of a full canopy, and
(iii) varying the way sugarcane was "dried-off" prior to harvesting.

The trials with different irrigation treatments during early growth showed a wide scatter in results and it was difficult to reconcile actual irrigation treatments with those reported on in the experiment designs.

For this reason only data from the "pan factor" and "dry-off" trials have been included in this paper. The data from these trials are shown in Figures 3 and 4. The data from the pan factor trials were used to derive a sugarcane production function, which is given in Equation 1, and also shown in Figure 3.

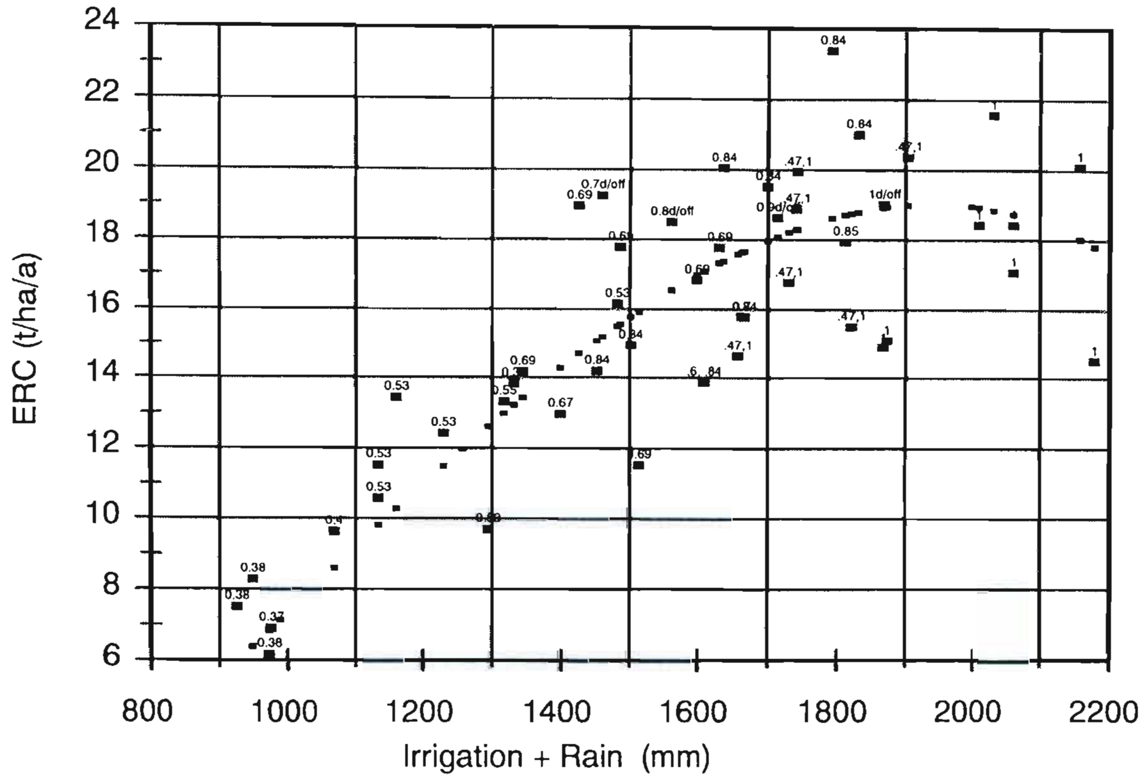

Figure 3 ERC vs total water (irrigation + rain) for various pan factors

Equation 1 can be used to estimate a relationship between total water, i.e. irrigation and gross rainfall, and ERC yield.

$$Y_{erc} = -3.8355 - 0.00329.W_{tot} + 2.1561.10^{-5}.W_{tot}^{2} - 7.1098.10^{-9}.W_{tot}^{3} \quad ....\text{Eq 1.}$$

where Y_{erc} = ERC yield ($t.ha^{-1}.a^{-1}$)
W_{tot} = Total Water (irrigation + rain) (mm)

The derived relationship between ERC and total water is curva-linear. This substantiates theoretical considerations, confirming the reductions in marginal gains and efficiencies with increased watering. ERC yield increases with increasing application of water up to a limit of approximately 1900 mm of irrigation and rainfall. Further application of water is not beneficial and appears to cause some reduction in yield.

The "dry-off"trials showed a much flatter relationship with little change in the yield of ERC for various levels and methods of "drying-off" with optimum yields obtained with as little as 1600 mm of total water. This is to be expected because of senescence during the latter stages of the crop's growth, with associated reductions in water requirements. In addition, slowed growth caused by water stress at this time can have a ripening affect on the cane and any losses in yield of dry matter are likely to be compensated for by increased ERC content. Saving water by 'drying-off' cane is thus a very simple, effective and low risk strategy. Ellis (1993) has developed a simple dry off scheduling tool, based on week of harvest and Total Available Moisture (TAM).

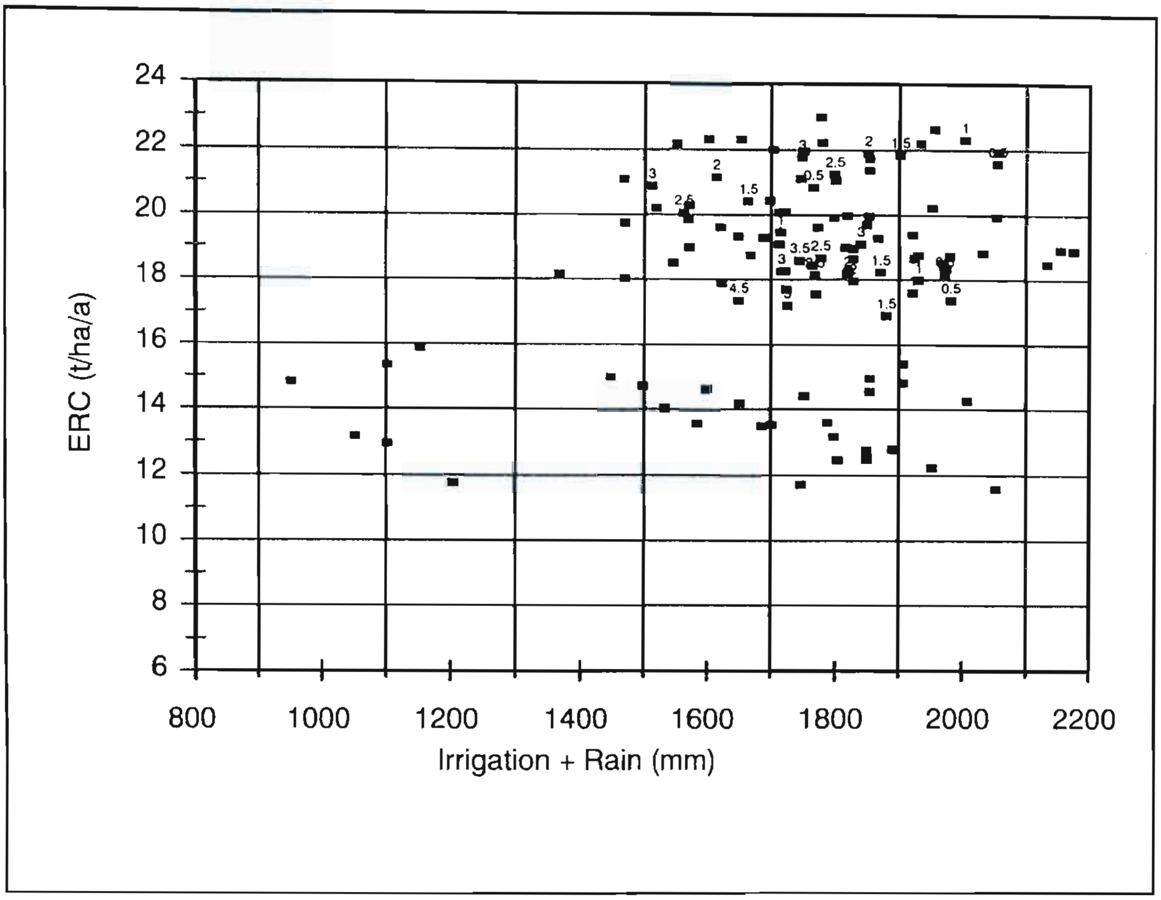

Figure 4 ERC vs total water (irrigation + rain) for various 'drying-off' treatments. The labels on the data represent the multiple of TAM to which the crop was 'dried- off'. Non-labelled data are from 'dry-off' treatments using various pan factors or time periods.

In order to derive a sugarcane revenue function, the yield derived from the production function was multiplied by the sugar price. For this paper it was assumed that a grower received Z$5904 per ton ERC (1999 price when Z$37.00. = US$1.00).

Sugarcane Field Cost Function

A spreadsheet computer package was used to develop a framework for an irrigated sugarcane field cost function. The cost function used in this paper included: fixed costs of irrigation system equipment, land preparation, harvesting and haulage machinery, and variable costs of field production. The variable costs included: water, energy, labour, land preparation and stool kill, planting inputs (seedcane, fungicide and pesticide), fertilizer, weed and pest control, harvesting and haulage. The energy and labour costs were related to the irrigation system specifications, including peak system capacity and mainline pipe sizes. The size of the main pipeline has a significant effect on friction losses, pump and motor requirements and operating costs. The variable costs of fertilizer, harvesting and haulage were a function of sugarcane yield which was determined as a function of total water using Equation 1. Fertilizer was varied according to expected crop yield and assumed to comprise, 160 kg.ha^{-1} N, 75 kg.ha^{-1} P_2O_5 and 150 kg.ha^{-1} K_2O per 150 t.ha^{-1} crop. Energy and water costs varied according to rainfall and applied water. Rainfall was assumed to be 500 mm for this paper.

Profit Calculations

The sugarcane production and cost functions were used to determine a measure of profitability at different levels of irrigation. For land limited production the optimum level of irrigation is when the marginal cost equals the marginal return, or when the difference between the cost and revenue functions is a maximum. For water limited production the opportunity cost of water needs to be taken into consideration. This was achieved by calculating a relative measure of profitability which reflects relative total returns to water. For example, given two irrigation strategies, *viz.* Strategy 1 and Strategy 2,

- Strategy 1 uses, say 1500 mm of water per hectare (15 Ml) and
- Strategy 2 uses, say 1000 mm of water per hectare (10 Ml),
- Strategy 2 could therefore be used to irrigate 1.5 times the area irrigated using Strategy 1 for a given amount of water.

If Strategy 1 realised a return of Z\$1000/ha and Strategy 2 Z\$800 per hectare, the total returns could by maximised by using Strategy 2 and irrigating 1.5 times the area that could be irrigated using Strategy 1, *viz.* Z\$1000x1 vs Z\$800x1.5, realising an additional Z\$200 for every ha that could have been irrigated using Strategy1. A summary of the sugarcane field costs and revenues for different levels of irrigation is shown in Table 1. If land limits production, maximum field profitability is attained when irrigation is applied to achieve close to maximum yields, *viz.* irrigation and rainfall totalling approximately 1700 mm, on average.

If water limits production, Z\$(80923-66737 = 14186) extra income per hectare irrigated with irrigation and rainfall totalling 1800 mm could be attained by irrigating 1.37 that area using a total (irrigation and rain) of only 1450 mm per hectare. For an estate of some 12000 ha this could equate to an additional Z\$170 (US\$4.5) million per annum on average and for an industry of some 45000 ha, some Z\$638 (US\$ 17.2) million per annum on average. The question of whether or not the extra area should be irrigated every year or 'banked' and 'used' during drought years depends on how Mill capacity, water supply, demand and storage interact over time. There may be years when due to reservoir water levels, a switch from a land limited to water limited strategy would be advisable and *vice-versa*. These interactions can be assessed by investing in the development of the databases and tools needed to configure and apply the *ACRU* agrohydrological computer model (Schulze,1995) to simulate the Lowveld water supply and demand interactions and associated irrigation operating strategies.

Table 1 Irrigation Profitability for Land or Water Limiting Conditions

Total Water with Dry-Off [1] (mm)	Total Water for Yield Calculations (mm)	ERC Yield (t.ha^{-1}.a^{-1})	Revenue @Z\$5904. tERC^{-1} (Z\$)	Field Costs (Z\$)	Profitability Measure [2] (Z\$.ha^{-1}) (a)	Relative Area for Equivalent Water (ha) (b)	Relative Profit (water limiting) (Relative Z\$) (a) x (b)

1350	1500	15.75	92962	40925	52037	1.53	79586
1400	1559	16.50	97395	41596	55799	1.44	80598
1450	1618	17.17	101350	42214	59136	1.37	80923
1500	1676	17.75	104776	42773	62003	1.30	80604
1550	1735	18.23	107622	43266	64356	1.24	79679
1600	1794	18.60	109837	43689	66148	1.18	78175
1650	1853	18.86	111369	44036	67333	1.13	76116
1700	1912	19.00	112167	44300	67867	1.08	73523
1750	1971	19.00	112180	44476	67704	1.04	70412
1800	2029	18.86	111357	44620	66737	1.00	66737
1850	2088	18.57	109646	44729	64917	0.96	62512

[1] It has been assumed that a 15 % saving in water can be realised through drying off to 3 x TAM (cf. Figures 1 and 2)

[2] The profitability measure is dependent on numerous assumptions regarding input costs. This figure is based on estimated costs of erecting a pivot on cleared land and conducting operations according to the guidelines provided by the ZSAES

Derivation and Application of Selected Irrigation Strategies at Field Level Using *ZIMsched*

ZIMsched (Lecler, 2000; 2001) is a simple to use, spreadsheet-based water management tool. Whilst it is simple to use, it has water budgeting routines based on state-of-the-art research by, *inter alia*, Allen *et al.* (1998) and Schulze (1995). The water budget in *ZIMsched* accounts for:

- evaporation from the soil surface and transpiration in relation to:
  - atmospheric evaporative demand
  - available soil water,
  - crop and rooting characteristics (the development of which are related to temperature),
  - irrigation system type,
  - irrigation system performance,
- stormflow (surface runoff),
- deep percolation, all of which relate to
- rainfall effectiveness.

The timing and application of water can be adjusted according to various management options, including, user selected:

- early and/or late season reference pan factors,
- dry-off periods, given as a multiple of the soil's total available moisture (TAM).

The influence of these water application strategies in relation to different soils, expected climates, different types of irrigation system and different irrigation system performance levels in terms of:

- total applied water and
- expected ERC yield

can be simulated.

The ERC yield estimate in *ZIMsched* is based on a robust relationship between actual evapotranspiration (ET) and tons sucrose that was derived by Thompson (1976) using data from Hawaii, Australia, Mauritius, Mt Edgecombe, Chakaskraal and Pongola. *ZIMsched's* estimate of potential transpiration is used in a modified form of Thompson's (1976) sucrose verus ET relationship in order to derive an estimate of potential ERC for a given season. This potential ERC is then further modified according to the timing and magnitude of water stress according to procedures based on research reported on by Doorenbos and Kassam (1979).

In order to quantify the effects of soil water stress on crop yields, Doorenbos and Kassam (1979) utilised a function relating the relative yield decrease to the relative deficit of total evaporation (i.e. actual evapotranspiration). This relationship is given below as Equation 2

$$(1-Y_a/Y_p) \quad = \quad K_y(1-E/E_m) \qquad \text{... Eq 2}$$

where:

Y_a = actual harvested yield of a given crop (t)
Y_p = potential non-water-stressed harvested yield of a given crop (t)
E = actual total evaporation (i.e. $E_t + E_s$, mm)
E_m = maximum evaporation (i.e. $E_{tm} + E_s$, mm)
E_t = actual evaporation from the plant tissue, i.e. actual transpiration (mm)
E_{tm} = maximum evaporation from the plant tissue, i.e. maximum transpiration (mm)
E_s = evaporation from the soil surface (mm)
K_y = growth stage specific yield response factor

The response of yield to water supply is quantified through the yield response factor, K_y, which relates the relative decrease in yield, $(1-Y_a/Y_p)$ to a relative deficit in total evaporation $(1-E/E_m)$. The K_y values for most crops were derived on the assumption that the relationship between relative yield (Y_a/Y_p) and relative total evaporation (E/E_m) is linear and is valid for water deficits of up to approximately 50%, i.e. $(1-E/E_m) = 0.5$. Values for K_y, for a wide range of crops, were derived based on the analysis of experimental field data covering a range of different growing conditions. Details of the numerous experiments analysed to derive the K_y values are given in the Appendices of the publication by Doorenbos and Kassam (1979). In the analysis of these experiments, the magnitude and duration of water deficits, expressed as relative deficits of total evaporation, were made to correspond closely to individual crop growth periods. As a result, in most cases, 80 to 85 % of the yield variations due to different water treatments could be explained (Doorenbos and Kassam, 1979).

According to De Jager (1994), concerns about the transferability of the yield function given in Equation 2 can be obviated through the use of transpiration ratios (i.e. E_t/E_{tm}) in the place of total evaporation ratios (i.e. E/E_m). In Equation 3 the influences of atmospheric vapour pressure deficits and climate-crop architecture on E_t/E_{tm} and hence Y_a/Y_p cancel out (De Jager, 1994). Hence the yield response factor, K_y, defined in Equation 3 becomes a purely plant physiological entity and is thus determined by crop genetics and not climate. The K_y factor should thus be neither site nor climate specific (De Jager, 1994).

$$Y_a/Y_b \quad = \quad \prod_{i=1}^{i=G}[1-K_{yi}(1-E_t/E_{tm})] \qquad \text{...Eq 3}$$

where:

i = i-th growth stage in a growing season with a total of G growth periods
K_{yi} = yield response factor for the i-th growth period

De Jager (1994) tested a range of wheat yield functions, including Equation 3, using the water budgeting algorithms of the PUTU model to calculate E_t and E_{tm}. Results of these tests showed that using a yield function based on Equation 2 with values for K_{yi} for wheat taken from Doorenbos and Kassam (1979), was the most accurate of the various different yield functions tested and that the accuracy was very acceptable for use in decision support applications.

Based on research by, *inter alia*, Doorenbos and Kassam (1979) and De Jager (1994), and a preliminary comparison between observed and simulated yields and water use, Equation 2 has been adopted as an option for estimating ERC yields in *ZIMsched*. With this facility for estimating crop yields, it is possible to plan and design, *inter alia*, irrigation strategies, taking into account the effects of different water application targets and scheduling practices on crop production, and utilising commonly available data/information.

It should be emphasized that yield estimates based on Equation 3 are particularly sensitive to the duration of the different growth periods, and care should be exercised to ensure realistic values. This is an area that needs research attention and ideally should be related to thermal time. In the interim it is strongly suggested that users should refer to their local agricultural research stations to obtain local cultivar trial information on growth periods. Potential users of this approach to estimating yield should also be aware that the rationale for adopting this function is based primarily on theoretical considerations and literature studies. Verification studies are still ongoing, however, initial results, shown in Figures 5 and 6 indicate that the approach is sound with simulated yields and water use for different pan factors and dry off strategies very close to those derived from experimental trials (cf. Figures 5 and 6).

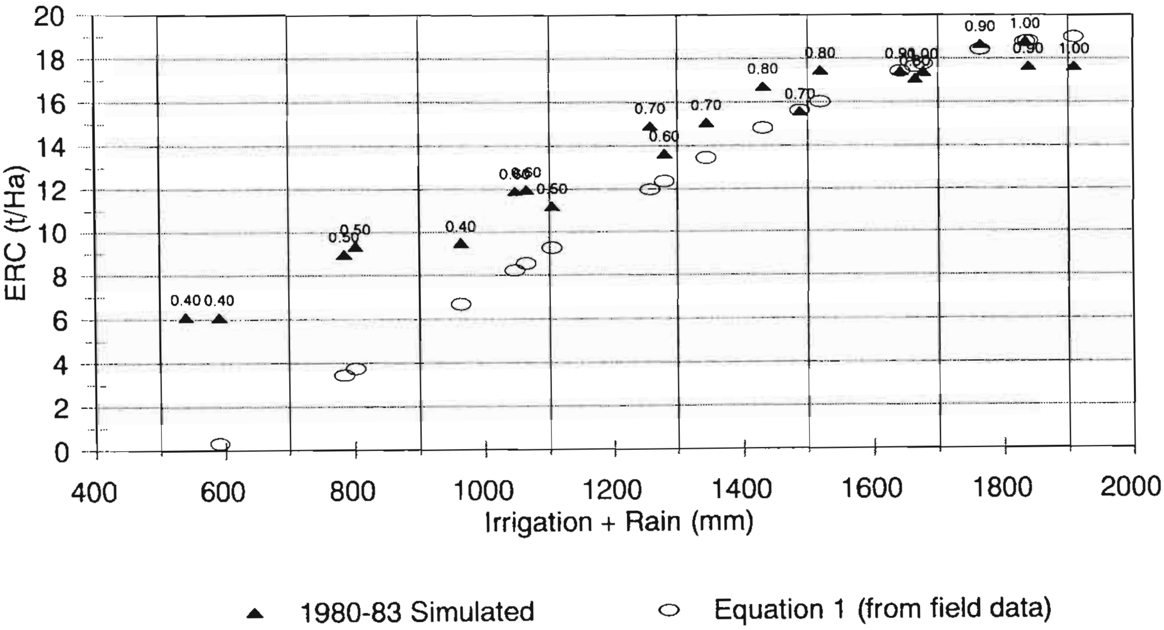

Figure 5 Simulated ERC versus total water using various reference pan factors to control the timing of irrigation water applications. The relationship between ERC and applied water, *viz.* Equation 1, derived from experimental trial data is also shown. The 1980 to 1983 years represents above normal, normal and below normal rainfall seasons.

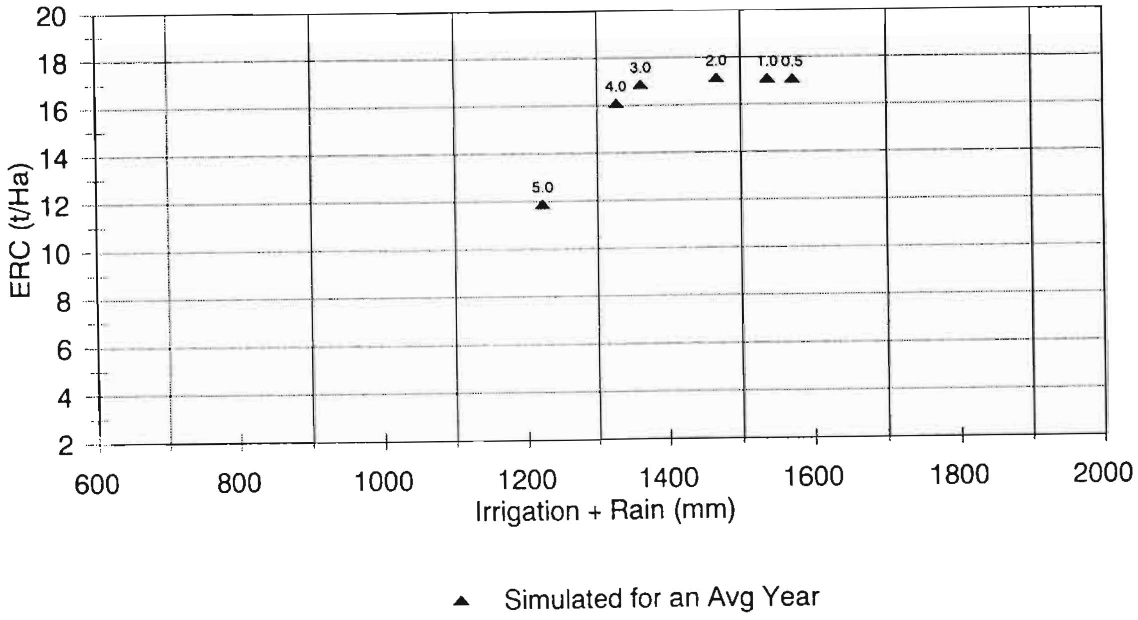

Figure 6 Simulated ERC versus total water for various 'drying-off' periods. The length of the dry-off periods was determined as a function of the soils' total available moisture (TAM), the multiple of which (shown as data labels) in accumulated A-pan evaporation units determined the last irrigation date.

General guidelines on, *inter alia*, growing periods and yield response factors for sugarcane are given in Table 2. The yield response factors shown in Table 2 are in general agreement with research reported on by Chaudhry and Leme (1996) who conducted an experiment in Brazil where cane was stressed at different stages of its growth cycle. Analysis of their data showed that:

- water stress during the two month period following the establishment of full canopy had the most severe effects on yields,
- water stress during the period where canopy cover ranged from 75% to 100% had the next greatest effect on yields, and
- water stress periods during the later stages of the crop cycle showed smaller and smaller yield effects.

No stress treatments were imposed prior to the 75 % canopy stage. Based on results from the dry-off trials undertaken in Zimbabwe (cf. Figure 4) the yield response factor for growth period 4 (ripening) has been changed to -0.01 in *ZIMsched*, thus stress in this period is simulated to have a very mild beneficial effect on ERC.

Table Growing period durations and yield response factors, K_y, for sugarcane (after Doorenbos and Kassam, 1979)

Growth Period	Growing Period Duration (days)			K_y
	Short Season (Zimbabwe)	Medium Season	Long Season	
0	20	20	35	-
1	200	275	320	0.75
3	90	100	150	0.50
4	50	60	70	0.1*
Total	360	455	575	-

Growth Periods: 0 = establishment
1 = vegetative
3 = yield formation
4 = ripening

*0.1 has been changed to -0.01 in *ZIMsched* based on dry-off trial data

Discussion and Conclusions

A basis for deficit irrigation has been established using empirical data from more than 40 'crop-years' of irrigation trials. These trials confirm theoretical concepts of deficit irrigation and have also highlighted the benefits of using a well judged 'dry-off' period (to 3 x TAM) as a simple, low risk water saving strategy. Trials cannot, however, be used to answer questions on how to manage streamflow, irrigation strategy/water demand and available storage interactions over time. There are tools available to investigate these relationships, for example, the *ACRU* agrohydrological simulation model. Evidence given in this paper and in other reports on the water status of the industry suggests that the commissioning of such an investigation and the adoption of irrigation strategies on the basis of these insights could be of great benefit to the sugar industry and result in major increases in long term profitability.

The challenge of determining and implementing effective irrigation strategies at the field level has been addressed. Robust water budgeting and yield relationships have been integrated into a simple to operate spreadsheet tool, *ZIMsched.* This version of *ZIMsched* can be used to simulate the effect of different water management strategies on water requirements and ERC yields, taking into consideration:

- irrigation system type (e.g. pivot vs furrow),
- irrigation system performance (coefficient of uniformity CU),
- soil characteristics, and the
- expected climate of the season,

so that a targeted amount of water is used on the most effective manner. The selected strategy can then be implemented using the same tool.

The validity of this tool for simulating ERC is still being checked, however, it is based on sound international research. Preliminary comparisons between simulated ERC yields and water use are in good agreement with experimental trial data collected in the lowveld of Zimbabwe. The ERC yield estimates are particularly sensitive to the duration of the different sugarcane growth periods, and care should be exercised to ensure realistic values. This is an area that needs further research. Ideally the duration of the growth periods should be related to thermal time and other environmental factors that influence crop development, for example, day-length.

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APPENDIX D: ACCOUNTING FOR UNIFORMITY OF APPLIED IRRIGATION WATER USING MULTIPLE WATER BALANCES IN *ZIMSCHED 2.0* (Ascough and Lecler, 2004)

ACCOUNTING FOR UNIFORMITY OF APPLIED IRRIGATION WATER USING MULTIPLE WATER BALANCES IN ZIMSCHED 2.0

G. W. ASCOUGH

School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal

and

N. L. LECLER

South African Sugarcane Research Institute

Corresponding author:
G. W. Ascough
Private Bag X01,
Scottsville,
3209,
South Africa
E-mail: ascoughg@ukzn.ac.za
Tel: 033-260 5490
Fax: 033-260 5818

ACCOUNTING FOR UNIFORMITY OF APPLIED IRRIGATION WATER USING MULTIPLE WATER BALANCES IN ZIMSCHED 2.0

ABSTRACT

Irrigation water is seldom applied in a completely uniform fashion. Thus parts of a field typically receive more irrigation water than other parts. As a result there is a potential reduction in yield in the portions of the field which receive deficient and/or excess water. ZIMsched 2.0 is an irrigation systems simulation model which uses three water balances to account for the impacts of the non-uniformity of irrigation water applications. In this paper the sensitivity of the water balance and crop yields simulated with ZIMsched 2.0 for a range of multiple water balance permutations was investigated. Simulations were run for the Pongola region, RSA for the period 1980 – 2000 using different irrigation uniformities, soils, scheduling options, numbers of simultaneous water balances and distribution functions to describe the spatial variability of applied water. The results showed that the simulated crop yields, drainage, runoff and seasonal irrigation efficiency were sensitive to irrigation non-uniformity represented using multiple water balances. However, using more than three simultaneous water balances to represent the non-uniformity of applied irrigation water did not produce any further significant differences in the values simulated. Using different distribution functions to describe the spatial variability of irrigation water applications for a given uniformity value also did not produce significant differences in the variables simulated. Thus, in this case study it was computationally efficient and representative to use only three water balances and the uniform distribution function to account for the spatial variability or non-uniformity of applied irrigation water.

Keywords: sugarcane, multiple water balances, irrigation scheduling, ZIMsched, irrigation systems, uniformity

1 INTRODUCTION

The application of irrigation water to a field is never uniform. This non-uniformity results in portions of the field that are over- and/or under-irrigated. Thus, there will be areas of the field that will be subjected to water shortages and areas that may be subjected to water logging. These conditions will ultimately lead to a reduction in the potential yield of the field.

The spatial distribution of water applied to a field has been represented using distribution functions such as the normal, uniform, specialised power, and log-normal distributions (Warrick, 1983; Heermann *et al.*, 1992). A planning model to determine optimal irrigation strategies which takes into account the effect of the non-uniformity of seasonal irrigation water applications on crop yield has been described by de Juan *et al.* (1996). However, a major constraint of de Juan *et al.*'s (1996) model is that the water balance was somewhat over-simplified. Li (1998) presented a similar approach to relating crop yield to irrigation uniformity, however, Li (1998) related crop yield to water deficits at particular growth stages to try and better represent water stress effects. Mantovani *et al.* (1995) not only described the development of a simple model to relate yield to irrigation amount and uniformity, which is apparently the foundation of the approaches of both de Juan *et al.* (1996) and Li (1998), but also compared this approach to results obtained by running a more process-representative but data intensive crop growth model, namely Ceres-maize (Jones and Kiniry, 1986). The inclusion of irrigation application uniformity in the growth model simulations was achieved by running the Ceres-Maize simulation model to simulate multiple units with each unit receiving a different irrigation application amount dependent on irrigation uniformity. A comparison between the simple model and the Ceres-Maize model adapted to simulate spatial variability in applied water showed similar trends but differences in absolute values (Mantovani *et al.*, 1995). The multiple water budgets approach has the advantage of better representing the dynamics of the soil water balance.

Lecler (2003) developed *ZIMsched 2.0,* a sugarcane yield and irrigation systems simulation model which uses three water balances to account for the impacts of the non-uniformity of irrigation water applications. In this paper the sensitivity of the water balance and crop yields simulated with *ZIMsched 2.0* for a range of multiple water balance permutations were investigated. These included the effects of more than three water balances and the use of various distribution functions to describe the spatial variability of water applications. Impacts on yields of estimated recoverable crystal (ERC) and the water balance for a range of scheduling options, soils and seasonal weather conditions were assessed.

2 METHODOLOGY

To account for the variation in water distribution across a field, the field was divided into 3, 5, 7, 9, 11, or 13 equal parts. The simulated depth of irrigation water applied to each portion was determined by assuming a statistical distribution for the irrigation water application and calculating the average application depth in each portion. This is illustrated for a normal distribution in Figure 1. The inputs were the uniformity (low quarter distribution uniformity (DU_{lq}), coefficient of uniformity (CU) or coefficient of variation (CV)) and the target or mean irrigation application depth. The target application depth was determined from the irrigation scheduling option used. For these simulations, fixed amount, fixed cycle and variable amount, variable cycle scheduling options were used. The fixed amount, fixed cycle scheduling option had different winter and summer irrigation application depths/cycles as are commonly used. The variable amount, variable cycle scheduling option simulated the soil being refilled to a specified level below field capacity at a soil water deficit coinciding with the planned mean irrigation application depth. This option was used to simulate an "ideal" scheduling practice. Figure 1 shows the average simulated irrigation water application depth in each zone when the field has been divided into 13 equal areas for 13 simultaneous water balances. The average irrigation application depth for each zone was calculated numerically. Figure 2 shows the average depth of simulated irrigation water applications for a specialised power distribution that has been separated into five water balances.

The *ZIMsched 2.0* irrigation systems simulation model (Lecler, 2003) was configured to simulate growing a crop of sugarcane in Pongola, KwaZulu-Natal for the period 1980 – 2000. A number of simulations were run to compare output from the different number of simultaneous water balances used and to assess the sensitivity of the model to changes in distribution type and input parameters. For the purposes of this study, it was assumed that the soils were homogeneous within the field and that the non-uniformity of irrigation water applications was constant during the period of the simulations. Variables assessed were yield of estimated recoverable crystal (ERC), application efficiency, runoff, and deep percolation. The seasonal application efficiency (SAE) was defined as:

$$\text{SAE} = \frac{\text{Accumulated seasonal actual transpiration}}{\text{Total irrigation water supplied} + \text{Rainfall}} \qquad (1)$$

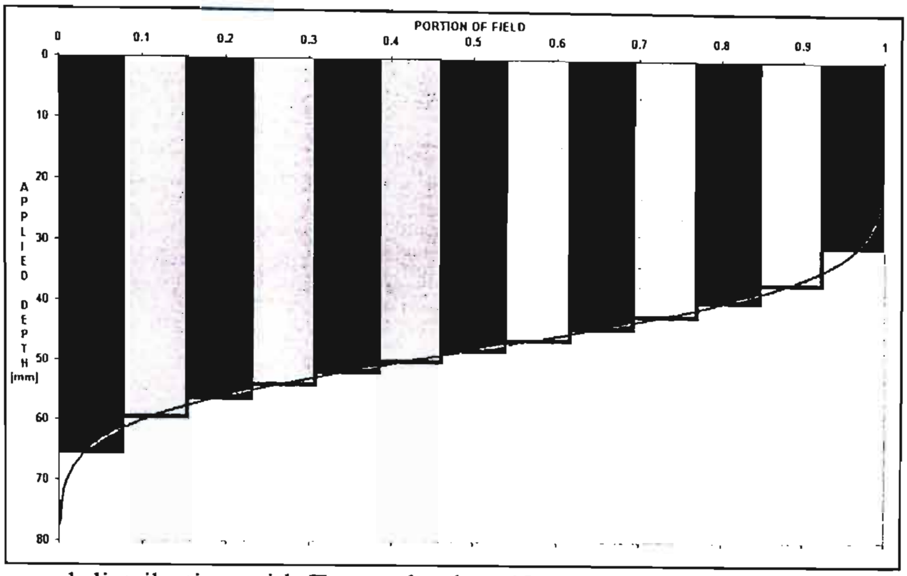

Figure 1 Normal distribution with Target depth = 48mm, DU_{lq} = 75% and average depths in each portion for 13 water balances.

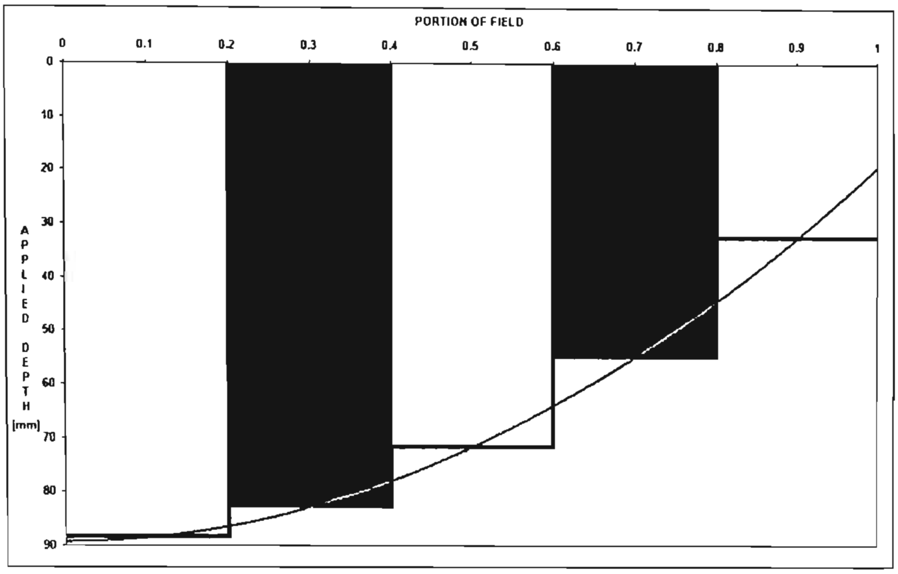

Figure 2 Specialised power distribution with Target depth = 66mm, DUlq = 60%, b exponent = 2 and average depth in each portion for 5 water balances.

Due to the large number of potential simulations that were possible by assuming different soils, irrigation uniformities, scheduling options, planting dates, or number of water balances simulated, only a reduced number of simulations were done. For the two scheduling options, the parameters shown in Table 1 were used for the simulations. Option 1 is assumed to represent ideal scheduling and Option 2 is a typical schedule used by overhead irrigators in the Pongola region.

Table 1 Scheduling options used for simulations

Option	Target depth
1. Variable cycle, variable amount	Refill to field capacity before the onset of stress less 10mm allowed for storage of rainfall
2. Fixed cycle, fixed amount	Summer: 48mm applied in 12h every 14 days Winter: 24mm applied in 6 hours every 14 days

The simulations were run for two different soil types. The properties of the clay (Cl) and sandy-clay (SaCl) soils used are shown in Table 2.

Table 2 Soil properties used for simulations (after Schulze *et al.*, 1995; Allen *et al.*, 1998)

Soil type	PWP [m/m]	DUL [m/m]	PO [m/m]	Total available moisture [mm]
Cl	0.298	0.416	0.482	94
SaCl	0.228	0.323	0.423	76

3 RESULTS AND DISCUSSION

The use of more than one water budget did have an effect on yield, drainage and runoff simulated. In Figure 3 the yields simulated for a normal distribution with $DU_{lq} = 60\%$ for 1, 3, 5, 9 and 13 water budgets are shown. Scheduling option 1 was used. The difference in yield between one water budget and three or more water budgets was significant at the 5% level. However, the difference in yield was not significantly different when using three or more than three water budgets. The average yield for one water balance is higher than that for the multiple water balances. Thus, taking uniformity into account in *ZIMsched 2.0* affected the simulated yield as stress in under- and over-irrigated areas was taken into account. It is interesting to note, that in years of high rainfall, the yield was lower than in years of less rainfall. The high rainfall in 1984 was due to flooding where 366.6mm of rain fell in three consecutive days.

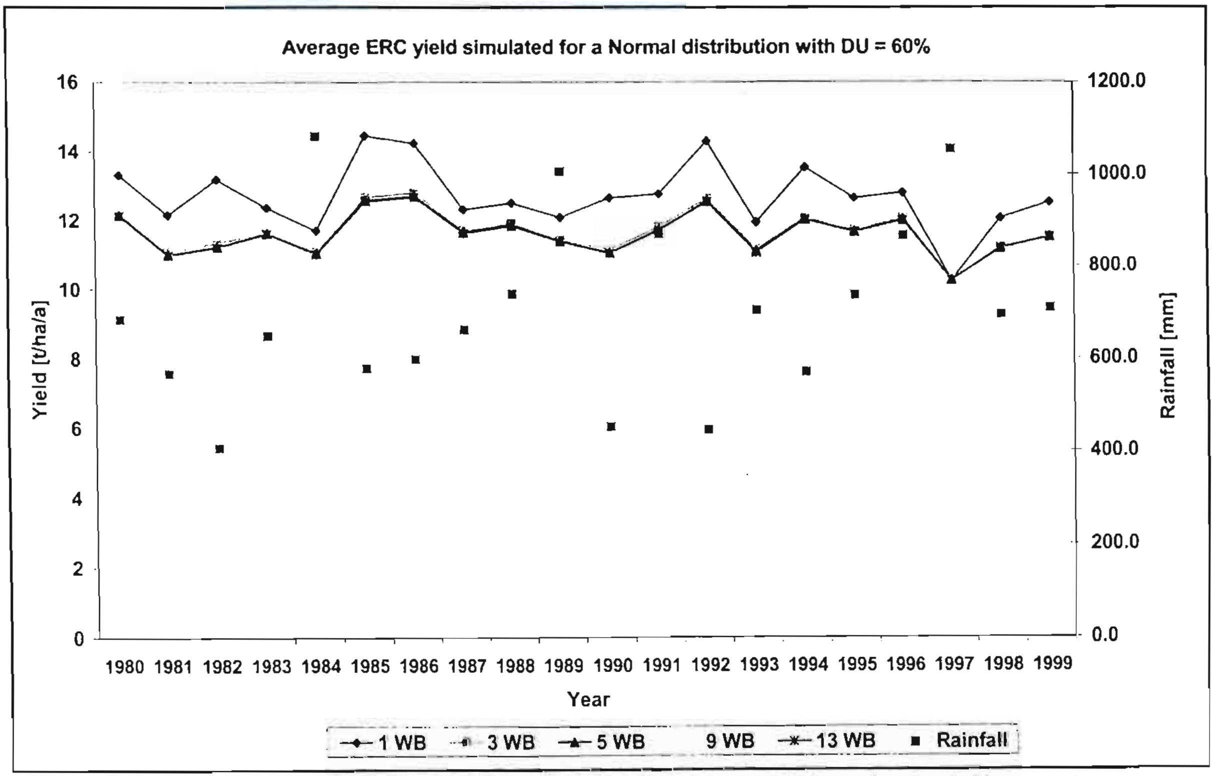

Figure 3 Simulated ERC yield for a clay soil, $DU_{lq} = 60\%$ and scheduling option 1.

In Figures 4 and 5 the average drainage and runoff simulated for normally distributed irrigation water applications with $DU_{lq} = 75\%$ and using scheduling Option 1 are shown. The difference between the average drainage and runoff simulated for one water balance versus three or more water balances was not significantly different at the 5% level. However, it can be seen that using a single water balance produces lower simulated runoff and drainage. The use of either a uniform or specialised power distribution (exponent = 2) did not produce any significant differences in the average drainage or runoff simulated over a normal distribution for the same uniformity.

In Figure 6 the average amounts of irrigation water applied using 13 water balances and scheduling Option 1 are shown. As expected, the average irrigation water applications were dependant on the amount of rainfall. The model showed increased irrigation water demand in low rainfall years and decreased demand in high rainfall years. There were small differences in the average water applied for the two specialised power distribution curves. This difference is due to the average calculated from the 13 water balances not being equal to the average of the distribution curve. Despite using an "ideal" irrigation scheduling approach, there is still potential for substantial runoff and drainage when rainfall events occur on an already wet soil. The application efficiency ranged from 52.9 to 79.5%. Years with low efficiency corresponded with high rainfall years as there was less efficient use of rainfall. In general, the efficiency was above 65% for this scheduling option. Accounting for rainfall or being able to forecast rainfall events with certainty is, therefore, likely to result in substantial improvements in seasonal irrigation application efficiencies.

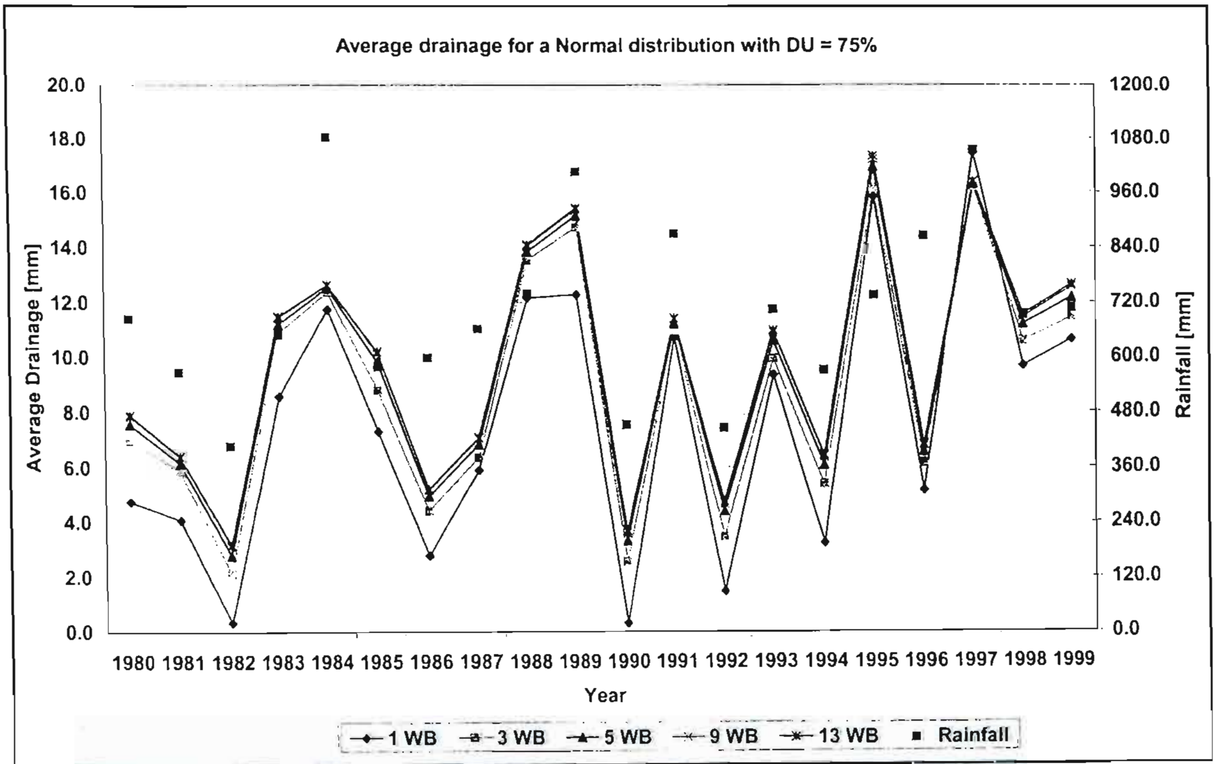

Figure 4 Average drainage simulated for a Normal Distribution with DU_{lq} = 75% for 1, 3, 5, 9 and 13 water budgets using scheduling option 1.

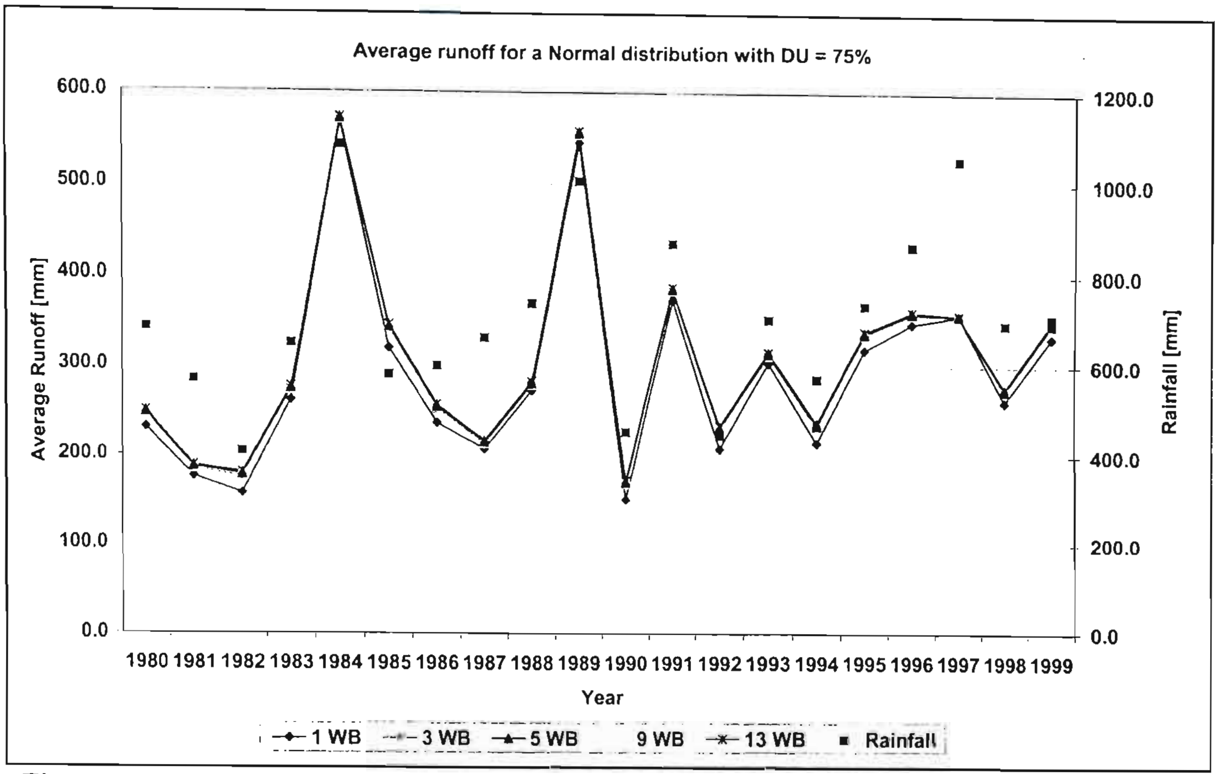

Figure 5 Average runoff simulated for a Normal Distribution with DU_{lq} = 75% for 1, 3, 5, 9 and 13 water budgets using scheduling option 1.

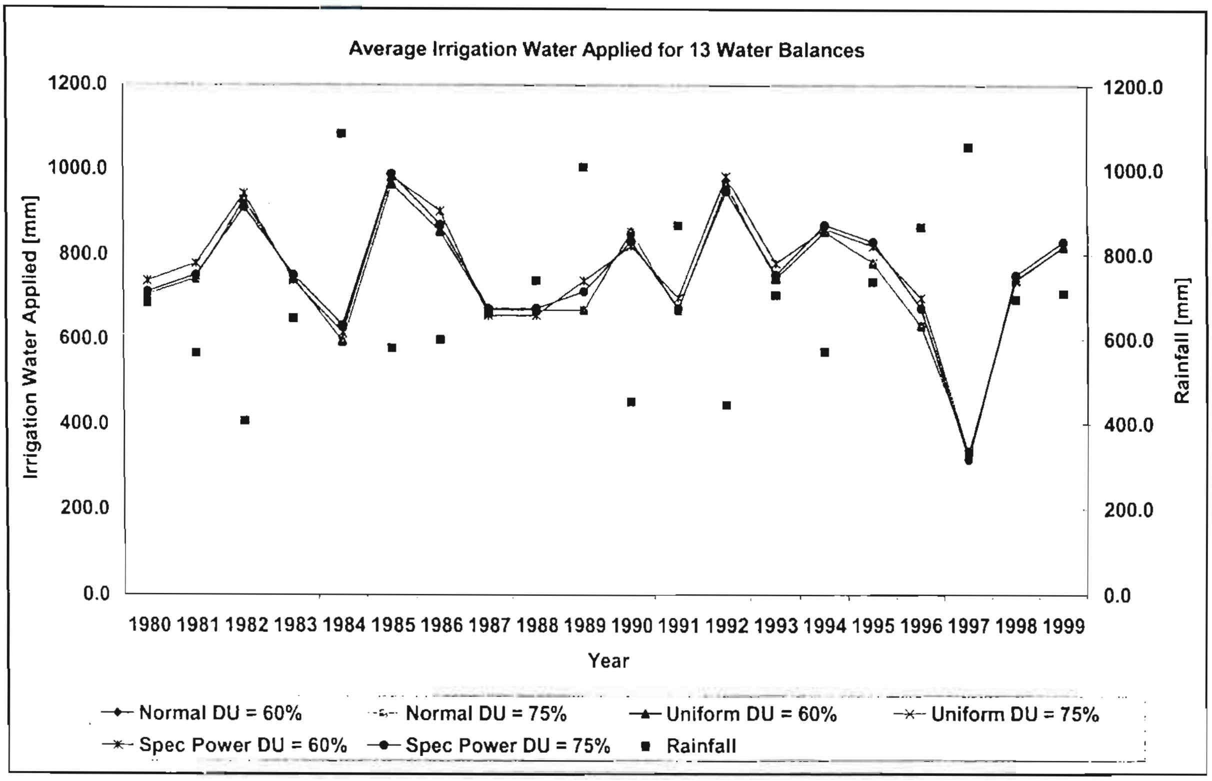

Figure 6 Average irrigation water applied using scheduling option 1 and 13 water balances.

In Figure 7 the effect of varying the soil type is shown. For a clay soil the runoff was greater than that of a sandy clay soil due to the lower infiltration rate of the clay soil. The sandy clay soil showed increased drainage due to the higher drainage rate from that type of soil. The clay soil exhibited greater total runoff and drainage losses compared to the sandy-clay soil.

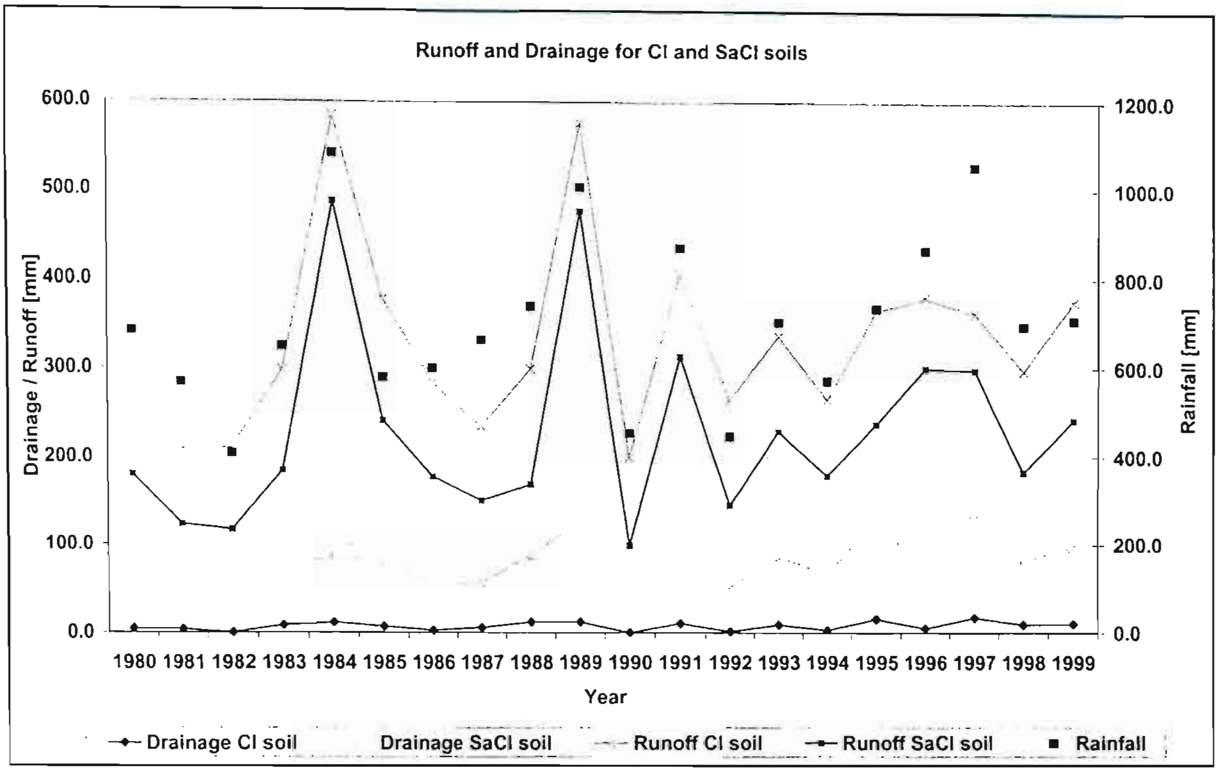

Figure 7 Runoff and drainage for Cl and SaCl soils using 13 water balances with a Normal distribution, $DU_{lq} = 60\%$ and scheduling option 1.

For scheduling Option 2 the findings were very similar. However, due to the less efficient method of applying water, more runoff, more drainage and poorer efficiency was noted. The efficiency was much lower than that of scheduling Option 1 ranging from 36.9 to 66.6%. The efficiency is lower due to the inflexibility of the scheduling option used and because it makes very inefficient use of rainfall. In scheduling Option 2 the cycle was not reset after significant rainfall events as might occur in practice. Thus these values are the lower boundary for application efficiency. The simulated drainage ranged from 12.7 to 470.3mm and the simulated runoff ranged from 221.9 to 1055.5mm. The sandy clay soil produced more drainage and less runoff than the clay soil. There was significant runoff from the clay soil, which resulted in the very poor application efficiencies.

In Figure 8 the average simulated ERC yields for 13 water balances and for the various distributions are shown. The average yields simulated were similar, with the higher uniformity of water application giving slightly higher yields. The poor performance in yield in 1997 was due to the high amount of rainfall (resulting in less radiation) and over-irrigation that took place that caused the field to be saturated for a large portion of the year. Comparing this to the 10.2 t/ha/a yield in 1997 for scheduling Option 1 (see Figure 3), shows the detrimental effect of too much water on yields.

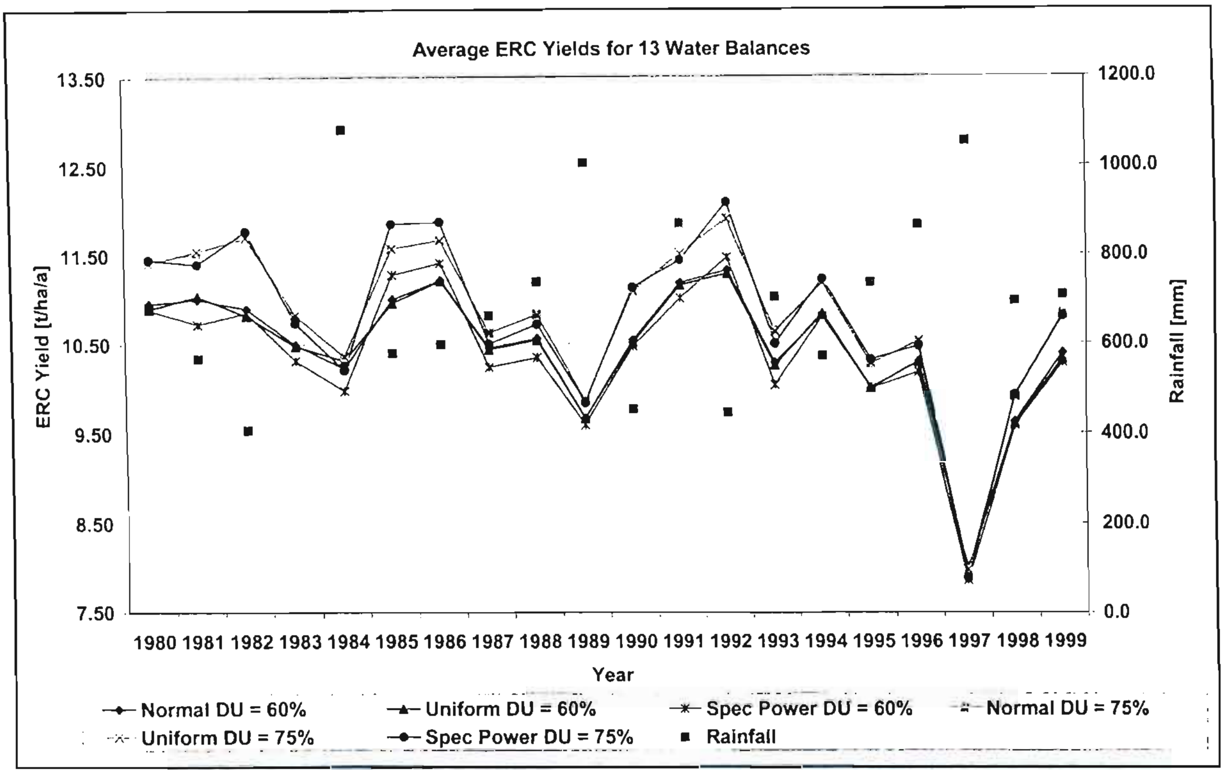

Figure 8 Average ERC yields of 13 water balances using scheduling option 2.

5 CONCLUSIONS

Accounting for uniformity of irrigation water application had an effect on simulated yields. The results from the simulations showed that there were significant differences between a lumped average simulation and simulations using multiple water balances. However, increasing the number of simultaneous water balances beyond three did not produce significant differences. Thus, division of a field into at least three portions should be considered in order to account for the effects of non-uniform irrigation water applications in simulation models.

Average simulated crop yields decreased when the field was split into multiple water balances. This shows that *ZIMsched 2.0* is sensitive to simulated over- and under-irrigation. On the other hand, the average drainage and runoff simulated were greater from the multiple water balance simulations than from the lumped simulation, as expected. The greater resolution afforded by the multiple water balances resulted in runoff and drainage which is likely to occur on the portions of the field being over-irrigated being simulated.

For the same uniformity value, the type of distribution used to describe the spatial variability of applied water did not result in significant differences in the simulated values of yield, runoff, drainage and seasonal irrigation application efficiencies. Using three water balances in *ZIMsched 2.0* was shown to be a valid approach for representing the effects of irrigation uniformity, various irrigation scheduling options, soils and climate on crop yields and the water balance.

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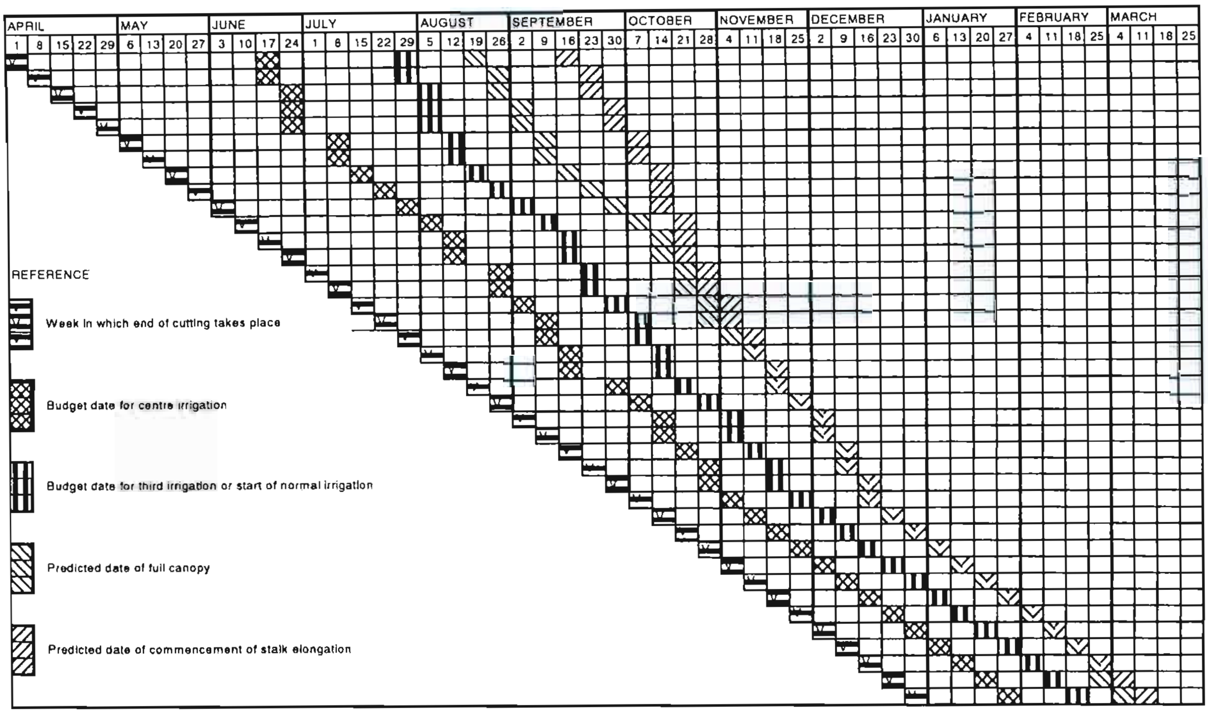
APPENDIX E: TRIANGLE ESTATE'S WATER MANAGEMENT GUIDELINES



Note:

- The aim is for the first three irrigation water applications to be equal in magnitude to the soil's TAM, thereafter, soil water depletionis calculated using a soil water budget in which A-pan evaporation data is multiplied by a factor of 1.0 in order to estimate daily evapotranspiration
- After the first three irrigation water applications, subsequent irrigation applications should be equal in magnitude to 50 % of the soil's TAM
- Rainfall less than 5 mm is ignored while rainfall and/or irrigation water applied in excess of the calculated soil water depletion is assumed lost as far as the water budget is concerned
- The crop is usually dried off prior to harvest for a period during which A-pan evaporation accumulates to a value equal to 2 to 3 times the soil's TAM value

Figure E1 Triangle Estate's water management guidelines

APPENDIX F: HIPPO VALLEY ESTATE'S WATER MANAGEMENT GUIDELINES

Table F1 Monthly crop factors which are multiplied by A-pan evaporation values in order to estimate evapotranspiration losses

	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR
1.APRIL CUT - c/f	0.2	0.2	0.2	0.3	0.7	0.8	1.0	1.0	1.0	1.0	1.0	0.0
2.MAY CUT - c/f	0.0	0.2	0.2	0.3	0.7	0.8	1.0	1.0	1.0	1.0	1.0	1.0
3.JUNE CUT - c/f	1.0	0.0	0.2	0.2	0.5	0.8	1.0	1.0	1.0	1.0	1.0	1.0
4.JULY CUT - c/f	1.0	1.0	0.0	0.2	0.2	0.3	0.6	1.0	1.0	1.0	1.0	1.0
5.AUGUST CUT - c/f	1.0	1.0	1.0	0.0	0.2	0.3	0.6	1.0	1.0	1.0	1.0	1.0
6.SEPTEMBER CUT - c/f	1.0	1.0	1.0	1.0	0.0	0.2	0.4	0.8	1.0	1.0	1.0	1.0
7.OCTOBER CUT - c/f	1.0	1.0	1.0	1.0	1.0	0.0	0.2	0.4	0.8	1.0	1.0	1.0
8.NOVEMBER CUT - c/f	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.2	0.4	0.8	1.0	1.0
9.DECEMBER CUT - c/f	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.2	0.6	1.0	1.0

Note:

- The crop is usually dried off for a period during which A-pan evaporation accumulates to 2 to 3 times the soil's total available moisture, TAM, value
- The crop factors shown in Table E1 are further modified, depending on the soil's TAM according to Equation E1 as follows:

  K_{cm} = K_{ct} (1 – 0.003(TAM-76) / 2)

  where

  K_{cm} = modified crop factor

  K_{ct} = monthly crop factor shown in Table F1

Table F2 Percentage of rainfall which is considered effective and added to the water budget

Days since previous rainfall of 5mm +	Recorded Rainfall mm				
	0 - 9	10 - 20	21 - 40	41 - 75	75+
More than 4	0%	0%	60%	80%	100%
2 - 4	0%	50%	80%	100%	100%
1	50%	70%	100%	100%	100%

APPENDIX G: MKWASINE ESTATE'S WATER MANAGEMENT GUIDELINES

Table G1 Monthly crop factors which are multiplied by A-pan evaporation values in order to estimate evapotranspiration losses

	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR
1.APRIL CUT - c/f	0.40	0.50	0.60	0.75	0.85	0.85	1.00	1.00	1.00	1.00	1.00	0.00
2.MAY CUT - c/f	0.00	0.40	0.50	0.60	0.75	0.85	1.00	1.00	1.00	1.00	1.00	1.00
3.JUNE CUT - c/f	0.85	0.00	0.40	0.50	0.75	0.85	1.00	1.00	1.00	1.00	1.00	0.85
4.JULY CUT - c/f	0.85	0.85	0.00	0.40	0.50	0.75	0.85	1.00	1.00	1.00	1.00	0.85
5.AUGUST CUT - c/f	0.85	0.85	0.85	0.00	0.40	0.50	0.75	0.85	1.00	1.00	1.00	0.85
6.SEPTEMBER CUT - c/f	0.85	0.85	0.85	0.85	0.00	0.40	0.60	0.85	1.00	1.00	1.00	0.85
7.OCTOBER CUT - c/f	0.85	0.85	0.85	0.85	0.85	0.00	0.40	0.70	1.00	1.00	1.00	0.85
8.NOVEMBER CUT - c/f	0.85	0.85	0.85	0.85	0.85	0.85	0.00	0.40	0.70	1.00	1.00	0.85

Note:

- The crop is usually dried off for a period during which A-pan evaporation accumulates to 2 to 3 times the soil's total available moisture, TAM, value
- Generally, rainfall less than 15 mm is ignored and rainfall or irrigation in excess of the calculated soil water depletion is assumed lost as far as the water budget is concerned

APPENDIX H: CHARTS AND CALENDARS FOR IRRIGATION SCHEDULING OF SUGARCANE IN THE ZIMBABWE LOWVELD (Lecler, 2003)

CHARTS AND CALENDARS FOR IRRIGATION SCHEDULING OF SUGARCANE IN THE ZIMBABWE LOWVELD

N L LECLER

Zimbabwe Sugar Association Experiment Station,
P/Bag 7006, Chiredzi, Zimbabwe
Currently at: South African Sugar Association Experiment Station,
P/Bag X02, Mount Edgecombe, 4300, South Africa
E-mail: Neil.Lecler@sugar.org.za

Abstract

Many emergent farmers growing irrigated sugarcane do not have easy access to computers. To provide such farmers with appropriate agronomic and water management decision aids, charts showing when irrigation water should be applied were produced and are described in this paper. The charts can be used with most types of irrigation systems and on all soil forms found in the sugar industry. A simple but robust methodology to determine and account for effective rainfall was also developed. The information in the irrigation scheduling charts, together with other appropriate agronomic recommendations, could help growers to derive more inclusive 'sugarcane growing' management calendars, which include fertiliser and herbicide recommendations. Although not as accurate for water management as the use of credible computer simulation models and near-real time weather data, these schedules and the methodology for accounting for rainfall, could be better suited to many growers.

Keywords: sugarcane, emergent farmers, irrigation scheduling, effective rainfall, management

Introduction

Many farmers growing irrigated sugarcane are either averse to the use of computer-based decision support tools, or do not have easy access to computers. This is particularly evident with emergent farmers. Charts showing when irrigation water should be applied have been produced to provide such farmers with appropriate water management decision aids. This paper outlines the development of these charts and gives examples of their application. The charts show the average number of days between irrigation applications for cane cut at different times during the harvest season, using different types of irrigation systems and on different soil forms. A robust methodology to determine and account for effective rainfall was also developed.

Methodology

ZIMsched 2.0, an irrigation systems simulation model (Lecler, 2000; Lecler, 2003), was used to determine the ideal intervals between irrigation water applications for various target soil water depletion levels, at different times during the growing season. Irrigation water applications were simulated to take place immediately after planting/harvesting and subsequently throughout a 12-month growing period whenever the simulated soil water depletion level reached the selected target value. The target soil water depletion levels were selected dependent on the type of irrigation system and/or soil water holding characteristics.

The results shown in this communication are for target soil water depletion levels of -50, -36 and -25 mm, corresponding, in absolute terms, to the magnitude of typical furrow, overhead sprinkler and centre pivot irrigation water applications, respectively. Long term average daily values of maximum and minimum temperatures and A-pan evaporation, recorded at the Zimbabwe Sugar Association Experiment Station (ZSAES) were used as the inputs to *ZIMsched 2.0*. The number of days between successive irrigation applications for a range of representative harvest dates were then tallied and tabulated for the growing season (cf Figure 1).

Accounting for rainfall when using the scheduling charts

Values for rainfall ranging from 3 mm to 60 mm were input to *ZIMsched 2.0* in order to simulate the resultant period of extension to the next required irrigation, at different times during the year. This period was dependent on soil and drainage characteristics, the time of year and the amount of rain. However, it was found that a rule of thumb to determine this period, was to divide the recorded rainfall by the mean daily A-pan evaporation value for the respective month during which the rainfall occurred. This rule of thumb proved fairly robust, provided the result was limited to a maximum value of six. The resulting number of days is then added to the day count between irrigation water applications, as illustrated in the following two examples.

Example 1: 20 mm of rain falls in May

Referring to Table 1, the mean daily A-pan evaporation for May is 4 mm. Dividing the 20 mm of rain by an A-pan evaporation of 4 mm yields 5. This result is not greater than 6, the maximum number of days to be added, therefore 5 days are added to the day count between successive irrigation water applications.

If the day count between irrigation applications was 10, it would change to a total of (10 + 5) = 15. If 7 days had already been counted when the rain occurred, a further 8 days (15 7 = 8) would still need to be counted before the next irrigation water application is applied. The rain has resulted in the day count between irrigations changing from 10 to 15.

Example 2: 60 mm of rain falls in March

Mean daily A-pan evaporation for March is 6 mm. Dividing 60 mm of rain by the March mean A-pan evaporation of 6 mm yields 10. This result is greater than 6, the maximum number of days to be added, therefore only 6 days are added to the day count between irrigation applications, and not 10 days.

Table 1. Mean monthly A-pan values. Values were calculated from more than 24 years of data recorded at the Zimbabwe Sugar Association Experiment Station.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
7	6	6	5	4	3	3	5	6	7	7	7

Results

The day counts between successive irrigation water applications for typical furrow, overhead sprinkler and centre pivot irrigation systems are shown in Figure 1. To illustrate the use of the charts in Figure 1, consider the following example. For a furrow irrigated field cut in late April, which takes approximately 50 mm of water per irrigation application, the grower would select the 'Furrow Irrigation Schedule' in Figure 1. After cutting, 50 mm of water would be applied within one week.

Thereafter, following the chart column headed 'May', irrigation applications would proceed as follows:

- count 78 days, apply 50 mm on day 79
- count 24 days, apply 50 mm on day 25
- count 13 days, apply 50 mm on day 14
- count 10 days, apply 50 mm on day 11, and so on.

The day count between successive irrigation water applications will eventually reduce to 7, and stay at 7, until February and March when it increases to 9. Drying off would start around 12 March.

Note: The count is re-set to one on the day following an irrigation water application, and the irrigation water is applied on the day after the day count reaches the value shown in the table. The information in the table was derived on the assumption that the crop would be cut on the first day of the month. Therefore, if a crop is cut, say, in late April, it is best to select the 'May' column. Alternatively, if a crop is cut in early April, it would be best to select the 'April' column.

The time between the initial irrigation (within one week of cutting) and the following irrigation may seem excessively long. Research at the ZSAES has, nevertheless, shown that at least 200 mm of A-pan evaporation can be accumulated between such irrigation applications with no yield losses (Nyati, -). These trial-based research results are in general agreement with what *ZIMsched 2.0* predicts, although *ZIMsched 2.0* also shows variations due to different cutting dates, canopy development rates and irrigation systems. Evaporation losses during the early phase of growth are very low, and occur mainly from the bare soil surface, especially in the winter months when crop canopy development is relatively slow. The traditional crop factors of 0.4-0.5 that have regularly been used to schedule irrigation applications during this period are often inappropriate, especially for furrow irrigation. Under furrow irrigation evapotranspiration in the early part of the growing season is relatively low, because large water applications are applied relatively infrequently and only a portion of the soil surface is wetted.

Discussion and recommendations

An accurate way to schedule irrigation water applications is to use a suitably representative and credible computer simulation model with appropriate input information / data. However, many growers are averse to the use of computers or do not have easy access to computer technology. These same growers are nevertheless under increasing pressure to improve production efficiencies in order to sustain profitability. In southern Africa they also often operate in environments where water is scarce and where there is increasing competition for existing water supplies. In order to help such farmers, many of whom over-irrigate and/or apply irrigation water in an *ad-hoc* manner, simple scheduling charts have been produced for different irrigation systems. Correct use of these charts should facilitate improved production efficiencies by the provision of better information on when to irrigate and how much water to apply. Although not as accurate as a computer simulation tool such as *ZIMsched*, the charts and 'rule-of-thumb' methodology for accounting for rainfall are, nevertheless, likely to be a significant improvement on many irrigation scheduling approaches. Whilst hopefully simple to interpret and use, they are based on sophisticated and proven water budgeting and crop growth algorithms (cf. Lecler 2003). The information in the charts can also be integrated with other appropriate agronomic recommendations to derive more inclusive management calendars for irrigated cane, which include, for example, fertiliser and herbicide recommendations. These management calendars may prove popular and valuable decision aids for many farmers, especially emergent farmers.

The development and evaluation of similar charts and management calendars for other irrigated areas in southern Africa where growers may be averse to the use of computers, is recommended.

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FURROW IRRIGATION SCHEDULE (TAM > 90 mm)

Average Time (Days) Between 50 mm Irrigation Applications for Different Cutting / Harvest Dates

Note: An initial irrigation application of approximately 50 mm must be applied within 1 week of cutting if the cane has been well dried off

Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
41	52	78	78	66	51	40	35	34	34
16	29	24	22	20	18	17	16	15	15
14	21	13	11	9	9	8	9	8	8
13	18	10	9	8	7	8	7	8	8
16	10	9	7	7	7	7	7	7	•
17	10	8	7	7	•	7	•	•	•
17	10	8	•	•	•	•	•	•	•
14	8	7	•	•	•	•	•	•	•
10	8	7	•	Feb - 8	•	•	Feb/Mar - 8	•	•
10	8	•	Feb - 8	Mar - 9	Feb/Mar - 8	•	Apr - 10	Feb/Mar - 8	Apr - 10
8	7	•	Mar - 9	Apr - 10	Apr - 11	Feb/Mar - 8	May - 13	Apr - 10	May - 13
8	7	•			May - 11	Apr - 10	Jun - 17	May - 13	Jun - 17
8	•	•	D/Off 2 Apr	D/Off 20 Apr		May - 14	Jul - 18	Jun - 17	Jul - 18
8	•	Feb/Mar - 9			D/Off 11 May	Jun - 17	Aug - 12	Jul - 18	Aug - 11
7	•							Aug - 11	Sep - 9
7	•	D/Off 12 Mar				D/Off 25 Jun	D/Off 15 Aug	Sep - 10	Oct - 8
•	•								
•	Feb - 8							D/Off 23 Sep	D/Off 26 Oct
•									
•	D/Off 15 Feb								
•									
D/Off 18 Jan									

OVERHEAD IRRIGATION SCHEDULE (TAM > 70 mm)

Average Time (Days) Between 36 mm Irrigation Applications for Different Cutting / Harvest Dates

Note: An initial irrigation application of approximately 50 mm must be applied within 1 week of cutting if the cane has been well dried off

Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
38	48	69	70	57	42	36	30	29	29
11	14	20	17	16	16	12	12	12	12
10	16	10	9	9	7	7	7	6	6
10	15	9	8	7	6	6	6	6	6
9	14	9	7	6	6	6	5	6	5
10	11	6	7	5	5	6	5	5	6
12	8	6	5	5	5	5	•	5	6
13	7	6	5	•	•	5	•	•	•
13	7	6	•	•	•	•	Feb/Mar - 6	•	•
13	7	5	•	Feb/Mar - 6	Feb/Mar - 6	•	Apr - 7	Feb/Mar - 6	Apr - 7
10	6	5	Feb/Mar - 6	Apr - 7	Apr - 7 / 6	Feb/Mar - 6	May - 10	Apr - 7	May - 10
7	6	•			May - 9	Apr - 6	Jun - 12	May - 10	Jun - 12
7	6	•	D/Off 2 Apr	D/Off 20 Apr		May - 10	Jul - 12	Jun - 12	Jul - 13
7	5	Feb/Mar - 6			D/Off 11 May	Jun - 12	Aug - 12	Jul - 13	Aug - 8
6	5							Aug - 8	Sep - 6
6	•	D/Off 12 Mar				D/Off 25 Jun	D/Off 15 Aug	Sep - 6	Oct - 6
6	•								
6	Feb - 6							D/Off 23 Sep	D/Off 26 Oct
5									
•	D/Off 15 Feb								
•									
D/Off 18 Jan									

OVERHEAD (PIVOT) IRRIGATION SCHEDULE (TAM > 60 mm)

Average Time (Days) Between 25 mm Irrigation Applications for Different Cutting / Harvest Dates

Note: An initial irrigation application of approximately 50 mm must be applied within 1 week of cutting if the cane has been well dried off

Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
30	38	53	64	52	39	33	28	28	27
7	10	13	7	8	7	5	5	5	5
6	9	11	7	6	5	4	5	4	4
•	•	11	7	5	5	•	4	•	•
•	•	6	5	5	4	Nov - 3	•	Jan - 3	Mid Jan - 3
Jun - 9	Aug - 5	5	5	5	•	•	Dec - 3	•	•
Jul - 9	Sep - 4	Sep - 4	4	Early Oct - 4	Mid Oct - 3	Feb/Mar - 4	Feb/Mar - 4	Feb/Mar - 4	Feb/Mar - 4
Aug - 5	Oct - 3	Oct - 3	•	Mid Oct - 3	•	Apr - 5	Apr - 5	Apr - 5	Apr - 5
Sep - 4	•	•	Mid Oct - 3	•	•	May - 6	May - 6	May - 6	May - 6
Oct - 3	•	Feb/Mar - 4	•	Feb/Mar - 4	Feb/Mar - 4	Jun - 10	Jun - 9	Jun - 9	Jun - 9
•	D/Off 15 Feb		Feb/Mar - 4	Apr - 6	Apr - 5		Jul - 10	Jul - 10	Jul - 10
•		D/Off 12 Mar			May - 7	D/Off 25 Jun	Aug - 7	Aug - 8	Aug - 5
D/Off 18 Jan			D/Off 2 Apr	D/Off 20 Apr				Sep - 5	Sep - 4
					D/Off 11 May		D/Off 15 Aug		Oct - 4
								D/Off 23 Sep	
									D/Off 26 Oct

Note: The **drying-off dates** shown in the scheduling Tables correspond to an accumulation of an average 270 mm of A-pan evaporation prior to harvest. This corresponds to the general ZSAES recommendation of drying off to approximately 3 x TAM. Research findings in Australia and South Africa recommend drying off for up to only 1.5 x TAM. Discrepancies may be due to the way in which TAM has been estimated in the different trials and some trials may have been influenced by the presence of a water table. Therefore, the start of drying off may need adjustment, especially if soils are shallow with TAM's <130 mm, or if one is unsure of the TAM. If a water table is present, every effort should be made to drain the field and/or reduce irrigations until the water Table has been lowered to > 1.2 m. In such cases, the dry-off period may need to be extended.

Figure 1. Irrigation scheduling charts for different types of irrigation systems. The charts were derived using *ZIMsched* and long term average weather data.