QUANTIFYING AND BENCHMARKING IRRIGATION SCHEME PERFORMANCE WITH WATER BALANCES AND PERFORMANCE INDICATORS

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Submitted in partial fulfilment of the requirements
for the degree of MSc Engineering

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2007

DISCLAIMER

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

Signed: .... Date: ....

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ACKNOWLEDGEMENTS

The author would like to express his sincere appreciation for the assistance given by the following, without whom this research would not have been possible:

- Dr NL Lecler, South African Sugarcane Research Institute (SASRI), for supervision and valuable encouragement, guidance and assistance throughout the project.
- Prof JC Smithers, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, for supervising this project and for providing focus to the research.
- Mr GW Ascough, formally from the School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, for supervision and assistance during the first year of this project.
- The managing and operating staff of the irrigation scheme that was the focus of the project, unfortunately confidentiality requirements prevents disclosing their names, but without their assistance and permission, this research would not have been possible.
- The farmers on the irrigation scheme, who also cannot be named due to confidentiality concerns, for the use of data and for vital insights into key issues within the irrigation scheme. The success of this research would not have been possible without their active participation.
- Mr D Mills, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, for help and assistance with the on-farm irrigation systems evaluations.
- The South African Sugar Research Institute (SASRI), specifically to Mr C Gers for Geographical Information System (GIS) soils data.
- The Water Research Commission (WRC) of South Africa and the South African Department of Water Affairs and Forestry (DWAF), for funding the project.
- The University of KwaZulu-Natal for post graduate scholarship and financial assistance.
- To my family and friends for their encouragement and support.

ABSTRACT

South Africa is a water scarce country. As pressure on available water resources increases, irrigation, the largest consumer of water, has to find ways of improving water use efficiency. Benchmarking in the irrigation sector has been identified as a suitable technique to implement this improvement. Benchmarking can be broadly defined as the identification and application of organisation specific best practices with the goal of improving competitiveness, performance and efficiency. A South African sugarcane irrigation scheme was identified to investigate a proposed benchmarking methodology. The scheme was unique in that electromagnetic flow meters were utilised and monitored on a daily basis. This facilitated an in depth study into irrigation water use at the scheme. The project focused on three different objectives. The first objective was to determine the losses, and consequently the efficiency, with which the irrigation scheme was able to deliver irrigation water from the water source to the farm boundary during the years 2004 and 2005. This was achieved by completing the water balance for the scheme with specified geographic and temporal boundaries. Results indicated that the scheme was very efficient with a delivery efficiency of 83.4 and 94.0 % for 2004 and 2005 respectively. These efficiencies were above the accepted South African Department of Water Affairs and Forestry (DWAF) standard of 80 %. The temporal distribution of the delivery efficiency was also investigated to identify periods within each year when inefficiencies occurred, and to better understand the nature of potential losses. It was concluded that the investigations into the temporal distributions be utilised together with the water balance approach in future studies into the performance of irrigation water delivery infrastructure at other South African irrigation schemes.

The second objective was to calculate a set of internationally applied external irrigation benchmarking indicators. External indicators from the International Water Management Institute (IWMI), the International Program for Training and Research in Irrigation and Drainage (IPTRID) and the Irrigation Training and Research Center (ITRC) were reviewed for application in a South African context. The external indicator analysis highlighted that at a scheme level, insufficient irrigation was occurring to effectively meet the irrigation demand. It was also found that the scheme infrastructure was not the limiting cause of this observation. The external indicator results highlighted the need for additional schemes for comparison purposes. The results from this component of the study also emphasized the importance of stakeholder confidentiality concerns when attempting to implement a benchmarking initiative.

The third objective was to rank individual farm performance of all the farms in the scheme, in terms of total farm sugarcane yield and seasonal irrigation water use. Farm yield and irrigated area were obtained to investigate the relationships between yield and irrigation water application. There were substantial variations in total farm yield and water use for both the 2004 and 2005 seasons, indicating much potential for improvement by many farmers relative to each other. The individual seasonal farm water use was also compared to a simulated irrigation demand, as determined with the *SAsched* irrigation systems and crop yield model. Simulation results with the *SAsched* model, using representative soils and climate data for the scheme, showed that the majority of farms were under irrigating relative to the simulated demands, especially in the late spring/early summer period. From on-farm irrigation system evaluations that were performed, it was found that irrigation system capacity constraints were not limiting irrigation applications in the majority of farms. Further research in the form of selected soil water monitoring is required to investigate these observations further.

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AED	Atmospheric evaporative demand
A_{FS}	Full reservoir surface area
ANCID	Australian National Committee on Irrigation and Drainage
ASCE	American Society of Civil Engineers'
A_{WS}	Wetted surface area
BREB	Bowen Ratio Energy Balance
C	Monthly reservoir equivalent adjustment coefficient
CI	Confidence interval
c_g	Gross to net irrigation conversion factor
CMA	Catchment Management Agency
CN	Curve Number
CU	Coefficient of Uniformity
CV	Coefficient of variation
DE%	Delivery efficiency
DU	Distribution Uniformity
DUL	Drained Upper Limit
DU_{lq}	Low quarter distribution uniformity
DWAF	Department of Water Affairs and Forestry of South Africa
$\mathbf{E_a}$	Mass transfer component of the Penman equation
$\mathbf{E_m}$	Monthly equivalent A-pan evaporation
$\mathbf{E_r}$	Reference potential evaporation
ERC	Estimated recoverable crystal
$\mathbf{E_s}$	Evaporation from the soil surface
ET	Actual evapotranspiration
$\mathbf{F_v}$	Relative water stress index
I	Total Inflow
IE	Irrigation Efficiency
IPTRID	International Program for Training and Research in Irrigation and Drainage
ITRC	Irrigation Training and Research Center
IWMI	International Water Management Institute
$K_{c\ mid}$	Crop factor value for middle stage of development
MOM	Management, Operation and Maintenance

NFA	Average total annual net farm water application
PWP	Permanent Wilting Point
RAP	Rapid Appraisal Process
RIS	Relative Irrigation Supply
R_n	Net radiation component of the Penman equation
R_w	Weekly rainfall
RWS	Relative Water Supply
SABI	South African Irrigation Institute
SAWUEF	South African Water Use Efficiency Framework
SCS	Soil Conservation Service
SGVP	Standardized Gross Value of Production
SU	Statistical Uniformity
TAW	Total Available Water
T_p	Potential transpiration
V_I	Volume of measured water inflow
V_{loss}	Volume of unaccounted for water
V_O	Volume of measured water outflow
V_R	Volume of water contribution from rainfall
V_{SE}	Volume of water lost to surface water evaporation
V_{Sest}	Estimated seepage volume
WDCR	Water Delivery Capacity Ratio
WMA	Water Management Area
WRC	Water Research Commission of South Africa
WUA	Water User Association
γ	Psychrometric "constant"
Δ	Slope of the saturation vapour pressure curve
ΔS	Change in storage

1. INTRODUCTION

South Africa is a water poor country with limited water resources which are spatially and temporally variable in their distribution. The demand for water in South Africa is ever-increasing (NWRS, 2004). The ever-increasing demand has resulted in water stressed areas in the country. Irrigated agriculture is the largest user of water of South Africa, currently estimated to utilise 62 % of the country's stored water resources (NWRS, 2004). This was revised from the previous figure of 54 % in 1999 (WRC, 1999). With increasing demands for water, and as the largest user, irrigators will have to justify their utilisation of the limited water resources. Burt *et al.* (1997) argue that irrigation water is necessary and that it should be wisely used. Quantification of irrigation systems performance is therefore needed to assess the efficient use of water by the irrigation sector.

The National Water Act in South Africa (National Water Act, 1998) states that water has to be used and managed in accordance with the national water resource strategy. This national water resource strategy aims, *inter alia*, to ensure an adequate supply of water to meet the requirements of basic human consumption and for the protection of aquatic environments, which is defined as a reserve in the act. The strategy also deals with the conservation and quality of water resources and focuses on demand management. Due to the large amount of water consumed by irrigated agriculture and the potential environmental degradation as a result of over-irrigation and drainage of poor quality water, there is considerable interest in defining the performance of irrigated systems (Clemmens and Burt, 1997). Unfortunately, irrigation performance is frequently not as efficient as it could potentially be and deficiencies can be cited at almost every level in the irrigation sector (Murray-Rust and Snellen, 1993). With examples of poor performance, and combined with the current situation in South Africa where demand exceeds supply of water in more than 50% of the 19 Water Management Areas (NWRS, 2004), irrigation is being targeted as an inefficient user of water. Therefore measurement techniques that can be used to assess the efficiency of water use at farm, irrigation project and catchment scales are required to identify these shortfalls and strategies to implement improvements need to be formulated.

Evaluating irrigation performance through benchmarking and water balances is a method of quantifying performance at a project scale (Malano, 2000; Burt, 2001). Benchmarking itself is a useful tool in the management of water (Ghazalli, 2004). An irrigation benchmarking process identifies and incorporates a number of performance indicators that describe both internal and external aspects of the project's performance (Burt, 2001). These indicators are then either compared against previous levels of performance, desired future targets or against other irrigation projects. At present, benchmarking is not a common practice in the irrigation and drainage sector

(Malano, 2000). However, it could be a technique which could facilitate and improvement in irrigation systems performance in South Africa.

The Water Research Commission of South Africa (WRC) is currently funding a research project entitled: "Standards and guidelines for improved irrigation water use efficiency from dam wall release to root zone application". The project was commissioned in April 2004 and the completion thereof is projected to be in April 2009. The objective of the project is to supply all stakeholders in the irrigation water use "supply chain" with guidelines, tools and recommendations to improve the efficiency of irrigation water distribution and use. The WRC project proposal motivates that the management of irrigation water use starts from releases at the dam wall, through river or canal conveyance, on-farm storage and distribution and in-field application up to root zone storage. However, at the time that the project was formulated, there was no standardised terminology, comparable benchmarks or generally acceptable guidelines to improve water use and irrigation efficiency. The lack of comparable benchmarks or generally acceptable guidelines needed to be urgently addressed in order to provide consistent management advice and comply with the requirements of the National Water Act (1998) regarding compulsory licensing and periodic review of licences. The project is therefore focussed on identifying possible solutions to assist in improving efficiency in the entire irrigation water "supply chain". In order to accomplish this objective, a number of smaller sub-objectives were identified such that the main objective may be achieved. One of these sub-objectives required the investigation of the potential use of benchmarking in the project. Therefore, the University of KwaZulu-Natal (UKZN) was tasked with researching the topic of benchmarking in the irrigation sector with the view of formulating and testing a possible methodology to be used as a pilot study for the larger WRC project.

The objective of this study was to develop a methodology that could be used to quantify and benchmark irrigation performance in South African irrigation schemes. The following approach was adopted to meet this objective:

1. To review literature on irrigation benchmarking used internationally, specifically the irrigation performance indicator sets and benchmarking methodologies developed by the International Water Management Institute (IWMI), the International Program for Training and Research in Irrigation and Drainage (IPTRID) and those of the Irrigation Training and Research Center (ITRC) in the United States of America.
2. To select a methodology and an appropriate set of performance indicators from the literature reviewed and apply it in a selected irrigation scheme. This methodology would need to focus on three areas, namely:

   i) applying the external indicators to the irrigation scheme as a whole,

ii) using water balances to quantify the extent of losses and consequently the efficiency of scheme water delivery, and

iii) to quantify the on-farm performance of all the farms on the scheme, and investigate individual water application trends.

3. To identify a suitable South African irrigation scheme in which the proposed methodology could be applied.
4. To apply all three aspects of the methodology and to assess the suitability and usefulness for application in other irrigation schemes identified by the larger WRC project.
5. To recommend possible changes and modifications to the methodology for application in other South African irrigation schemes.

This document consists of seven chapters. Chapter 2 contains a review of literature on the assessment of irrigation performance. The concept of using benchmarking in irrigation is introduced and the tools used to apply it are discussed. An introduction into why benchmarking is being investigated for the WRC project is also outlined. Some international irrigation benchmarking applications are also discussed and lessons to be learnt from those projects are expanded upon. The South African irrigation scheme which was selected as the study area where the proposed benchmarking methodology was applied is introduced in Chapter 3. Aspects of the scheme that are covered include types of irrigations systems currently used in the scheme, crops, scheme operation, soils and water quality. Chapter 4 contains the methodology and results of the external indicators that were applied on the study area described in Chapter 3. The water balance approach that was applied to quantify the extent of losses and consequently efficiency is outlined in Chapter 5. Chapter 6 covers the methodology and results from the individual farm analysis of all the farms in the scheme. Finally, Chapter 7 contains a discussion and conclusion of all the results that were obtained in the study and a review of the benchmarking process that was applied. Recommendations for further applications are suggested and improvements to the methodology are proposed. Appendix A, presented at the end of the document, contains a review of irrigation simulation models.

2. A REVIEW OF MEASURES OF IRRIGATION PERFORMANCE

Evaluating irrigation performance through benchmarking and Rapid Appraisal Processes (RAP) is a method of quantifying performance at a scheme scale (Malano, 2000; Burt, 2001). Benchmarking irrigation system performance using water measurement and water balances is another method of quantifying irrigation systems performance (Burt, 1999). Benchmarking itself is a useful tool in the management of water (Ghazalli, 2004). An irrigation benchmarking process identifies and incorporates a number of indicators that describe both internal and external aspects of scheme performance (Burt, 2001). These indicators are then either compared against previous levels of performance, desired future targets or with other irrigation schemes. At present, benchmarking is not a common practice in the irrigation and drainage sector (Malano, 2000).

Several international organisations have developed indicators for comparing performance of irrigated agricultural systems. Molden *et al.* (1998) from the International Water Management Institute (IWMI) developed a set of nine external indicators that they believed were capable of adequately describing system performance at a scheme level. A similar set of external indicators was developed by Malano and Burton (2001). Their set, however, included indicators describing the environmental performance of a system that was not included in the work done by Molden *et al.* (1998). Burt and Styles (1998) also developed external indicators to assess the performance of a scheme and included internal indicators to evaluate the internal processes of irrigation schemes. The indicators proposed by all of the above mentioned studies are reviewed in this chapter and the relative strengths, weaknesses and reasons for their use are also discussed.

The use of water balances to quantify irrigation performance is also covered in this chapter. The different criteria for successful water balances, such as the definition of the correct spatial and temporal boundaries, as well as the use of confidence intervals for the water balance components, are also detailed.

In order to assess the performance of irrigation systems at a scheme level, it is necessary to measure or estimate all of the components of the hydrologic water balance (Clemmens and Burt, 1997). Included in these estimates is the manner in which irrigation water is being applied, which is necessary to evaluate performance. To achieve these goals, definitions of whether the irrigation water use is beneficial and reasonable need to be established (Burt *et al.*, 1997). Existing definitions for water use are provided and possible definitions of what use is deemed to be beneficial or not in a South African perspective are discussed in the chapter.

2.1. Definition and Application of Benchmarking in Irrigation

The comparison of performance between organisations has been a common practice in the private commercial sector in the last two decades (Malano, 2000). However, in the irrigation industry, organisations have operated in an environment that has largely been isolated from stakeholder and public pressures. As competition increases for limited water resources between different economic sectors, irrigation agencies are being forced to become more accountable for their water use (Malano, 2000). This has resulted in the need for irrigation agencies to improve performance. Benchmarking has been identified as a suitable technique to implement this improvement.

Malano and Burton (2001) define benchmarking as follows:

> "Benchmarking may be defined as the identification and application of organisation specific best practices with the goal of improving competitiveness, performance and efficiency. It is a continuous process that involves (i) internal assessment of the organisation, (ii) comparing it with the best practices of more successful similar businesses in the market, (iii) determining the performance gap between current practice and best practice, and (iv) selecting best practices, tailoring them to fit the organisation and implementing them. The cycle of improvement continues."

Figure 2.1 illustrates the benchmarking process as defined above.

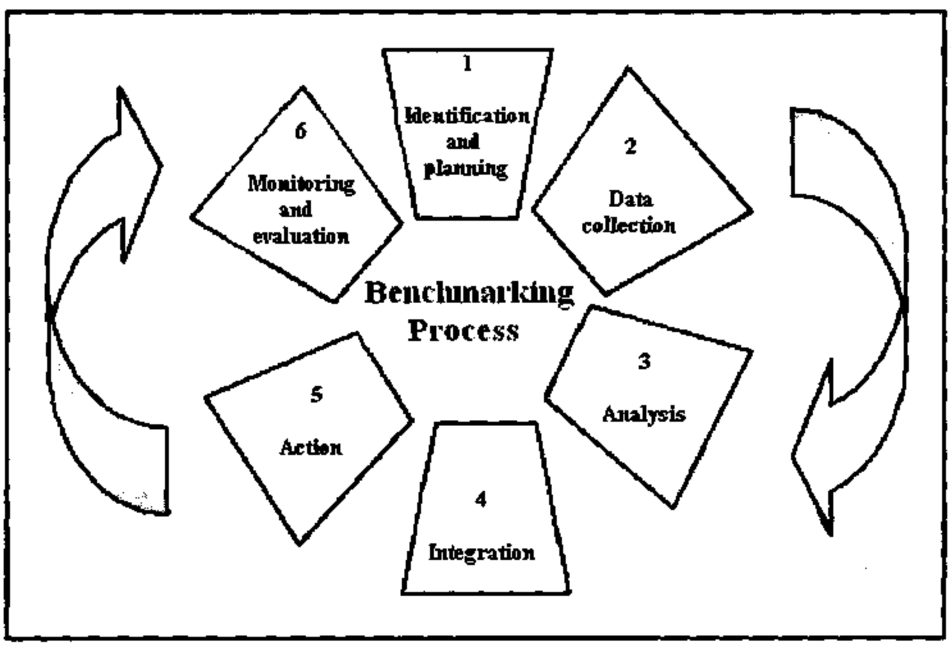

Figure 2.1 The benchmarking process (Malano and Burton, 2001).

From this definition it is evident that the main objective of benchmarking is to find and implement best management practices for an organisation (Malano, 2000). Benchmarking is also an opportunity for organisations to learn from the experiences of others. Comparison of performance between different organisations and different systems can be made. These comparisons can either be within or between different countries or regions.

There may be many reasons why an irrigation organisation may be interested in the benchmarking activity. They may be responding to a number of "drivers", some of which are listed below (Malano and Burton, 2001):

- The increasing demand on the irrigation sector to produce more food for growing populations.
- The growing pressure to effect cost savings whilst increasing the productivity and efficiency of the water resource.
- Turnover and privatisation of irrigation and drainage schemes to water users and water user associations.
- The increasing interest by the wider community for productive and efficient water use and the protection of natural environments.
- An increasing need for accountability to both government and water users in respect of water resource use and price paid for water.

Malano and Burton (2001) state that it is important to identify which drivers are forcing change within the irrigation and drainage sector. In South Africa, the National Water Act (1998) identifies the need for equitable use of water within the different sectors. It also allows for the provisions of basic water requirements for the environment and basic human consumption and this allocation is defined in the act as the "reserve". These processes are forcing irrigators in South Africa to be more transparent and accountable for their water use and are the drivers in the South African context, especially within the context of increasing demands from other water use sectors. Once the drivers have been identified, the extent and specifications of the data that will be required in the process needs to be defined. For this process, external and internal indicators are identified. It is of critical importance that the definitions of these indicators are all consistent to ensure that all the data collected is comparable (Malano and Burton, 2001).

Bos *et al.* (1994) believe that the benefit of incentives should be one of the key drivers in any performance related exercise. It is uncommon to find irrigation agencies that reward good performance and penalise poor performance. Bos *et al.* (1994) state that it is highly unlikely that irrigation managers will adopt a new performance based management framework if there are no associated benefits directly coupled with the framework.

As briefly highlighted above, benchmarking in the irrigation sector is applied through one of two techniques. The use of performance indicators that describe many aspects of project performance is one technique and the use of water balances and water measurement is another technique. However, invariably both techniques are used simultaneously. This is due to the need for water measurement and water balance computations when calculating performance indicators. The next section introduces water measurement and water balances as they are applied in an irrigation benchmarking exercise.

2.2. Water Measurement and Water Balances

All irrigation system performance assessments rely heavily on computing an accurate hydrologic water balance over the area considered (Small and Svendsen, 1992; Clemmens and Burt, 1997; Burt, 1999). Water balance approaches for assessing irrigation system performance have been widely used. Burt (1999) defines a water balance as a process that accounts for all the water volumes entering and leaving a 3-dimensional space over a specified period of time. This approach also needs to account for internal changes in water storage over the specified period of time. The 3-dimensional area to be considered could vary depending on the intent of the evaluation. In an irrigation benchmarking exercise utilising external process indicators, the scale of the evaluation could be at a project scale, but within the project scale and for internal process indicators, the water sources and destinations also need to be verified at field and farm levels. Irrigation performance indicators rely heavily on the ability to quantify the various water sources and destinations. Proper quantification of water use requires careful definition of both spatial and temporal boundaries, both laterally and vertically (Burt *et al.*, 1997), in terms of the spatial boundaries and the appropriate time scale for the temporal boundaries.

2.2.1. Defining boundaries for performance evaluation

To successfully compute a water balance, both the spatial and temporal boundaries of the evaluation need to be identified and specified (Burt, 1999). These two components are introduced and discussed in this section.

2.2.1.1. Spatial boundaries

The lateral and vertical boundaries form part of a hydrologic water balance. A typical example of a water balance can be seen together with defined boundaries in Figure 2.2. The quantitative definition of one or another water balance component, whether the source is irrigation or natural, depends on the boundaries of the region under consideration (Burt *et al.*, 1997). Often a water balance is based on geographic boundaries (Clemmens and Burt, 1997).

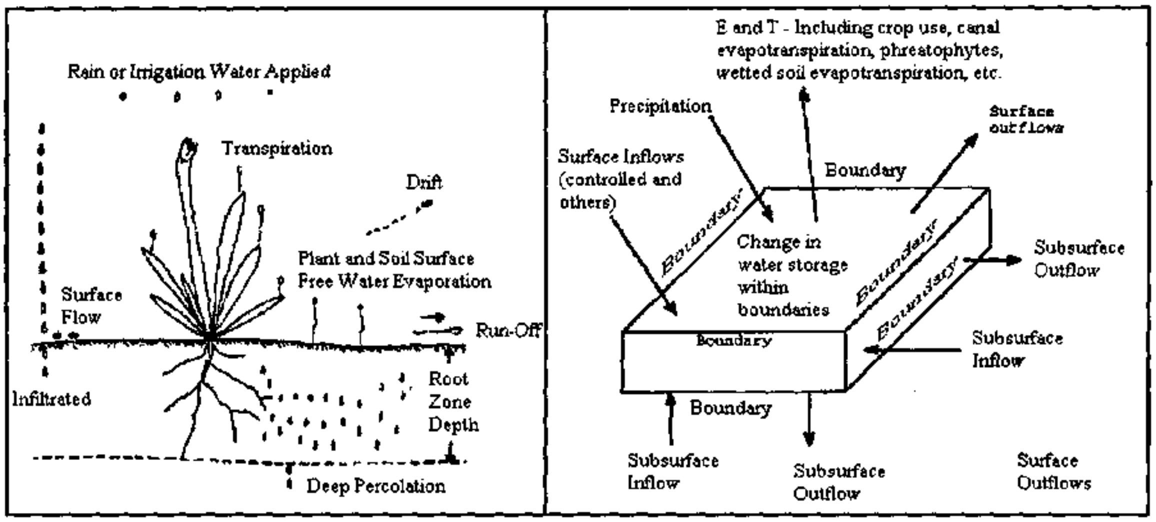

Figure 2.2 Water sources and destination diagrams with boundaries (after Burt *et al.*, 1997).

Table 2.1, presented by Burt (1999), contains a summary of the typical spatial boundaries required in an irrigation performance assessment. An important aspect highlighted in Table 2.1 is that of defining the lower spatial boundary for a district level assessment. If ground water is being extracted, or if there is a high water table, the lower boundary will be the bottom of the underground water aquifer. If there is no groundwater pumping or a high water table, the lower boundary is defined as the bottom of the root zone (Burt, 1999).

Table 2.1 Spatial boundaries of various areas (Burt, 1999)

Space	Upper boundary	Lower boundary	Horizontal boundary
Farm	Crop canopy	Bottom of root zone	Farm fields
Conveyance system	Water surface	Canal bottom	All diversions, spills, and discharge points
Water district without groundwater pumping	Crop canopy	Bottom of root zone	District
Water district with groundwater pumping	Crop canopy	Bottom of aquifer	District
Water district without groundwater pumping, but with a high water table	Crop canopy	Bottom of water aquifer that is tied into the high water table	District

Small and Svendsen (1992) also used the corresponding geographic area of an irrigation scheme to define the boundaries of performance. However, Small and Svendsen (1992) state that performance assessment boundaries can also be defined according to:

i. the functions performed by the irrigation system, and
ii. the processes involved in creating and sustaining the irrigation system during its lifetime.

These two additional criteria have importance in that they are used to differentiate responsibilities for water management in an irrigation scheme. For example, a water user association would be responsible for water management from the scheme off take to the farm boundary. From the farm boundary onwards, the water management responsibility is handed over to the farmer. These responsibilities are aligned with the space differentiated in Table 2.1. When a conveyance system is assessed, it should be noted that the boundary for functional management lies with the water user association and has nothing to do with an individual farmer. The opposite occurs when assessing a specific farm, where the water user association has no input.

2.2.1.2. Temporal boundaries

Defining the correct temporal boundaries for an assessment is as important as defining the correct spatial boundaries. All the sources and destinations of water in a water balance change from one year to another (Burt, 1999) and within a year. Therefore, the duration of an assessment, i.e. per irrigation event, per month, per season, or per year, needs to be specified accordingly.

2.2.2. Water balance parameters

The data that need to be quantified for the completion of the water balance include crop, climate and irrigation data. Burt *et al.* (1997) present the following descriptions of some of the estimates required to complete the water balance.

i. Evaporation is the conversion of liquid water to water vapour. For the purposes of an irrigation water balance, evaporation is considered to be from free water surfaces, from plant intercepted irrigation water and from the soil surface. Evaporation does not include any water that has passed through the plant. The rate of evaporation is dependant on factors such as surface area, atmospheric conditions and other soil factors. Changing irrigation frequency, irrigation method, mulching and shading are examples of how the rate of evaporation can be modified (Burt *et al.*, 1997).
ii. Transpired water is water which has passed through the plant stomata and into the atmosphere as vapour. The main influences on transpiration are atmospheric conditions and solar radiation. However, it is also dependant on evaporation, as transpiration generally

decreases as evaporation increases. Microclimate around the field or plant can also influence the amount of transpiration. Transpiration can be reduced if the root-zone soil water potential is low enough to reduce uptake by roots (Burt *et al.*, 1997).

iii. Evapotranspiration is the combined process of evaporation from the soil and wet plant surfaces and transpiration from plants. As can be assumed from the above descriptions of transpiration and evaporation, the combined evapotranspiration process is controlled or influenced by soil, crop, irrigation, and atmospheric factors. Evapotranspiration is often used instead of evaporation and transpiration because separating the evaporation and transpiration is difficult to accomplish (Burt *et al.*, 1997).

iv. Crop evapotranspiration is the actual amount of evaporation and transpiration within the cropped area of a specified field, and which is related to the growing crop only. The difference between crop evapotranspiration and (iii) is that the crop evapotranspiration excludes the addition transpiration from weeds. In irrigation applications, evapotranspiration requirements are met by rainfall and irrigation water (Burt *et al.*, 1997).

v. Infiltration is the process of water movement through the soil surface into the soil matrix. All infiltrated water is in transit and some infiltrated water can enter the plant system through the roots immediately, and some can be temporarily stored as soil water in the root zone. The stored water can reach and even exceed the field capacity of the soil. The stored water is then either used by the plant or it slowly percolates down the soil profile (Burt *et al.*, 1997).

vi. Deep percolation is infiltrated water that has moved below the root zone of the crop and is hence unavailable to the crop. When crop roots have developed fully and occupy the entire soil profile, deep percolation occurs relatively quickly. In regions of the soil profile where roots are yet to occupy (i.e. young roots developing deeper), deep percolation can be more complicated to quantify (Burt *et al.*, 1997).

vii. Runoff is surface water that leaves the specified boundaries in liquid form. Surface water that is captured and reapplied within the specified boundaries is not classified as runoff. This means that runoff from one part of a region, that is used downstream in the region is not classified as runoff, as long as both regions fall within the specified boundaries (Burt *et al.*, 1997).

In addition to the components mentioned, Fairweather *et al.* (2003) state that measurements or estimates of the following elements are also required:

- the soil water deficit before irrigation,
- effective rainfall,
- amount of irrigation water applied, and

- the leachate requirement based on the salts in the irrigation water compared with the salts stored in the root zone.

Once the different components of the water balance have been defined, they need to be partitioned into different water use categories. Partitioning of irrigation can be accomplished in two ways, namely by partitioning the water on the availability for recovery, and by determining if the water use was beneficial or not.

2.2.3. Partitioning of applied irrigation water by availability for recovery

Of the total depth of irrigation water applied, only a certain proportion of it can be recovered for future use. This is determined by whether the water was consumed or not. Burt *et al.* (1997) defined consumptive and non-consumptive uses of water as follows:

- Consumptive uses include water that either ends up in the atmosphere, or in harvested plant tissue. The atmospheric component would have originated through evaporation or transpiration processes.
- Non-consumptive uses include any other quantities of water that leave the specified boundaries. Runoff, deep percolation and canal spills are considered to be non-consumptive uses. Such water can be reapplied in other regions; however, water quality is often degraded.

2.2.4. Partitioning of applied irrigation water by beneficial use

Irrigation water can also be partitioned on the basis of whether the water was beneficially or non-beneficially used, or whether the use was reasonable or unreasonable. The following section defines each of these uses and gives examples for each.

2.2.4.1. Beneficial use

Burt *et al.* (1997) define a beneficial use as water that supports the production of crops or water that is consumed in order to achieve an agronomic objective. The two major components of beneficial water use are (i) water that is used for crop evapotranspiration, and (ii) water used to maintain or improve soil productivity. Other minor beneficial water uses might include water that is used for climate control, seedbed preparation and evapotranspiration from cover or windbreak crops. Burt *et al.* (1997) emphasise that in certain applications these minor uses can constitute a major portion of the total water use and therefore should not be ignored.

Water that is stored in the root zone should not be considered as beneficial (Burt *et al.*, 1997). Until stored water leaves the root zone for another destination it should be considered as neutral. These beneficial water uses are only applied in an irrigation water use context and water that is beneficial to others sectors (i.e. water that is not used for crop production) were not considered.

2.2.4.2. Non-beneficial uses

Water that is not beneficially used includes excess soil evaporation, evapotranspiration from vegetation other than the crop, deep percolation in excess of the salt removal requirement, excess deep percolation resulting from non-uniform application and tail water that is not recovered for further use (Burt *et al.*, 1997). Matters are complicated by the fact that it is practically difficult to distinguish what is beneficial or not. Burt *et al.* (1997) provides irrigation uniformity as an example: a small amount of non-uniformity is unavoidable, yet deep percolation due to non-uniformity is considered non-beneficial. Therefore certain non-beneficial water uses need to be considered in the context in which they are encountered.

2.2.4.3. Reasonable uses

All beneficial water uses are defined as being reasonable (Burt *et al.*, 1997). When determining whether a water use is reasonable or not, economics, uncertainties in the climate and physical limitations of the irrigation systems will all have an affect. Certain non-beneficial uses can be classed as reasonable under certain circumstances. These would occur due to the uncertainties that arise when farmers are deciding on an application depth and would include estimates of the soil water depletion, crop coefficients, leaching requirements, advance times and infiltration rates, reference evapotranspiration, measurement of the inflow rates and the potential rainfall that might occur in the near future.

2.2.4.4. Unreasonable uses

These are water uses that are neither beneficial nor reasonable. Therefore they would be uses that do not have economic, practical or any other justification that would deem them to be reasonable. Excessive deep percolation would be defined as an unreasonable irrigation water use (Burt *et al.*, 1997).

Having identified and described all the components of the water balance, it is also important that the degree of accuracy with which each of these components can be estimated is known, so that a better understanding of the results can be gained. The concept of accuracy of estimates is dealt with next.

2.2.5. Accuracy of estimates

Every measurement of a non-discrete quantity, such as a water volume, contains an element of uncertainty, regardless of the variable and method of measurement (Clemmens and Burt, 1997). This fact applies to all methods of estimating water quantities in the water balance diagrams. In a water balance, once the outflows have been subtracted from the inflows, the theoretical remainder should be the change in storage in the zone under investigation. However, Clemmens (1999) and Burt (2001) warn that each measurement used in such a methodology has an associated degree of uncertainty and this must be accounted for in the computation. In order to assess this uncertainty, confidence intervals should be assigned to all water balance data, in order to show that there are uncertainties in the data and computation techniques that have been used. Statistically speaking, a confidence interval is related to the coefficient of variation (CV). The CV of an estimated quantity is described in Equation 2.1 (Burt, 2001).

$$CV = \frac{\text{mean}}{\text{standard deviation}} \qquad (2.1)$$

The associated 95% confidence interval (CI), for a normal distribution, of the estimated quantity is described by Equation 2.2.

$$CI = \pm 2 \times CV \qquad (2.2)$$

In Equation 2.2, the CI is expressed as a fraction of the estimated value.

The accuracy of an estimated or calculated value is normally expressed as a percentage and generally the 95 % confidence interval is used to define this accuracy (Clemmens, 1999).

In terms of relating two independent estimates in a water balance calculation, the different confidence intervals for each independent variable need to be combined to determine the confidence interval of the resulting quantity. Burt (2001) state that when two or more quantities are added together, the resulting confidence interval (CI_R) is determined with Equation 2.3:

$$CI_R = \frac{\sqrt{m_1^2 CI_1^2 + m_2^2 CI_2^2 + \ldots + m_i^2 CI_i^2}}{m_1 + m_2 + \ldots + m_i} \qquad (2.3)$$

where CI_1 = confidence interval of the first quantity,

CI_2 = confidence interval of the second quantity,

CI_i	=	confidence interval of the i^{th} quantity,
m_1	=	estimated value of the first quantity,
m_2	=	estimated value of the second quantity, and
m_i	=	estimated value of the i^{th} quantity.

Burt (2001) continued by stating that when two or more independent quantities are multiplied together, the confidence interval of the result (CI_R), is determined with Equation 2.4:

$$CI_R = \sqrt{CI_1^2 + CI_2^2 + ... + CI_i^2 + \frac{CI_1^2 \cdot CI_2^2 \cdot ... \cdot CI_i^2}{i^2}} \tag{2.4}$$

where	CI_1	=	confidence interval of the first quantity,
	CI_2	=	confidence interval of the second quantity,
	CI_i	=	confidence interval of the i^{th} quantity, and
	i	=	number of independent quantities.

The variations in discharge measurement accuracy and therefore the errors that occur in the measured volumes can be categorized as either systematic or random.

To conclude the matter of accuracy and confidence intervals in irrigation, a level of 5 - 10 % accuracy is generally sufficient (Burt, 2001). This level of accuracy is assumed to be sufficient because the problems that are often encountered in irrigation schemes are typically so obvious that it is unnecessary to strive for extreme accuracy when attempting to identify areas for improvement (Burt, 2001). In terms of efficiency from a South African perspective, van der Stoep *et al.* (2005) state that DWAF officials consider an efficiency (ratio of water outflow to inflow) of 80 % to be acceptable in terms of irrigation scheme water supply. Therefore this value needs to be considered in conjunction with the accuracy when determining the efficiency of irrigation scheme water supply in South Africa.

The next section describes a rapid appraisal process methodology which is one of the benchmarking tools presently being used internationally.

2.3. Rapid Appraisal Process (RAP)

The Irrigation Training and Research Center (ITRC) in the USA has been promoting the use of RAP and similar techniques for the past 15 years (Burt *et al.*, 1995, cited by Burt and Styles, 1998).

The main reason for conducting a RAP is to identify what can be done to improve irrigation scheme performance. Burt (2001) provided the following definition of a rapid appraisal process:

> "The Rapid Appraisal Process (RAP) for irrigation schemes is a 1-2 week process of collection and analysis of data both in the office and in the field. The process examines external inputs such as water supplies, and outputs such as water destinations (evapotranspiration, surface runoff, etc.). It provides a systematic examination of the hardware and processes used to convey and distribute water internally to all levels within the scheme (from the source to the fields). External indicators and internal indicators are developed to provide (i) a baseline of information for comparison against future performance after modernisation, (ii) benchmarking for comparison against other irrigation schemes, and (iii) a basis for making specific recommendations for modernisation and improvement of water delivery service."

A RAP can provide valuable information about many different aspects of irrigation scheme design and management. However, this can only be done if the RAP is executed properly and by qualified personnel (Burt, 2001). For a RAP to be successful, the process requires (i) evaluators with training in irrigation, (ii) evaluators with specific training in RAP techniques, and (iii) follow-up support and critique for the evaluators when they begin and after the have completed their investigation (Burt, 2001).

Burt (2001) states that the first step in a RAP consists of a prior request for information from the irrigation scheme authorities. This information would typically include cropped areas, flow rates into the scheme, weather data, budgets and staffing. These data then need to be organised by the evaluators. Missing information and perceptions of how the irrigation scheme functions are gained by individual interviews with the scheme managers. An investigation of the scheme then commences. This includes travelling down and through canal networks, observing methods and hardware used for water control, and talking to operators and farmers about the service that the scheme delivers. This systematic information gathering and diagnosis of the scheme can highlight many aspects of the scheme engineering and operation. The data collection process can be time consuming, as delays are normally due to locating the data in the organisations records. However, if the data does not exist, spending additional time at the scheme will not create the data (Burt, 2001).

As stated in the definition, the RAP requires the computation of internal and external performance indicators. Burt (2001) emphasises that the results from external indicators provide little or no guidance as to what must be done to improve performance in an irrigation scheme. However, internal indicators are necessary to understand the processes used within an irrigation scheme, the level of water delivery service throughout the scheme and, when combined with the external indicators, they can be used to formulate a plan that will improve overall performance. Bos *et al.* (1994) believe that it is unlikely that there will be sufficient time and resources to adequately assess all aspects of scheme performance simultaneously and to only investigate one aspect of an irrigation scheme would be unwise or even misleading. Therefore, because the RAP attempts to investigate the entire scheme, it overcomes the problem of being misled by one component only (Burt, 2001).

2.4. External Performance Indicators

One approach to the comparisons between systems and benchmarking process is to compare the outputs and impacts on irrigated agriculture. External indicators are used to relate outputs from a system derived from the inputs into that system (Molden *et al.*, 1998). Various irrigation and drainage institutes around the world have devised sets of external indicators for irrigation scheme comparison. Burt and Styles (1998) investigated external performance indicators in order to determine if modern water control and management practices in irrigation make a positive difference in performance. In research done by IWMI, Molden *et al.* (1998) developed nine external performance indicators for comparing performance of irrigated agricultural systems. The International Programme for Technology and Research in Irrigation and Drainage (IPTRID) has also performed extensive research on the subject (Malano and Burton, 2001). The RAP developed by Burt (2001) is another technique by which external performance can be monitored.

The institutions mentioned above all rely on a comprehensive data capturing exercise and then an evaluation of the performance indicators in a spreadsheet. This type of framework is the same as those used by both Burt (2001) and Malano and Burton (2001). The frameworks consist of production data and irrigation data that are combined to produce performance indicators that can be used for assessment (Degirmenci *et al.*, 2003).

Bos *et al.* (1994) point out that it is important for a chosen set of performance indicators to remain in focus with the objectives established by a specific irrigation scheme. It is highly improbable and unwise for managers to utilise every performance indicator described in this section. Specific conditions and objectives will lead to managers selecting relevant indicators that would be of benefit to their systems. According to Bos *et al.* (1994), the addition of certain specific conditions in a system may warrant the development of additional indicators to describe a particular situation.

The external indicators derived by the studies reviewed can be divided into four different categories, *viz.* agricultural output indicators, water supply indicators, economic indicators and environmental indicators. The following sub-sections contain a description of each of the four categories.

2.4.1. Agricultural output performance indicators

The agricultural output performance indicators that were reviewed are presented in Table 2.2.

Table 2.2 Summary of agricultural output indicators

No.	Indicator Name	Indicator Equation	IWMI	ITRC	IPTRID	RAP
1	Total annual value of agricultural production (US \$)	$\frac{\text{Total annual tonnage of each crop}}{\text{Crop market price}}$			x	
2	Output per cropped area (US \$.ha^{-1})	$\frac{\text{Production}}{\text{Irrigated cropped area}}$	x	x	x	x
3	Output per unit command area (US \$.ha^{-1})	$\frac{\text{Production}}{\text{Command area}}$	x	x	x	x
4	Output per unit irrigation supply (US \$.m^{-3})	$\frac{\text{Production}}{\text{Diverted irrigation supply}}$	x	x	x	x
5	Output per unit water consumed (US \$.m^{-3})	$\frac{\text{Production}}{\text{Volume of water consumed by crop ET}}$	x	x	x	x
6	Achieved production factor	$\frac{\text{Production with irrigation}}{\text{Production without irrigation}}$		x		
7	Potential production factor	$\frac{\text{Potential production with irrigation}}{\text{Production with irrigation}}$		x		

As it can be seen from Table 2.2, Molden *et al.* (1998) (IWMI), Burt and Styles (1998) (ITRC), Malano and Burton (2001) (IPTRID) and Burt (2001) (RAP) all suggest the use of Indicators 2, 3, 4, and 5. These four indicators, which were first proposed by Molden *et al.* (1998), relate agricultural output to land and water units and provide the basis for comparison of irrigated agricultural performance. The result of these four indicators must be viewed in context to the region in which they were applied. Where water is a more constraining resource compared to land, output per unit water may be more important than output per unit land. The reverse would apply if land were more constrained (Molden *et al.*, 1998). The volume of water consumed by ET is for the crops only. It does not include canal evaporation, nor does it include flows to sinks and pollution (Molden *et al.*, 1998).

Burt and Styles (1998) questioned whether it is possible to compare production between different irrigation schemes. This is because production is dependant on many different variables besides irrigation. For this reason Molden *et al.* (1998) developed the Standardized Gross Value of

Production (SGVP) for cross-system comparison, as there are differences in local prices at different locations throughout the world. To compute the SGVP, as shown in Equation 2.5, equivalent yield is calculated based on local prices of crops grown, compared to the local price of the predominant, locally grown, internationally traded base crop. This equivalent production is then valued at world prices (Molden *et al.*, 1998).

$$SGVP = \left(\sum_{i=1}^{crops} A_i Y_i \frac{P_i}{P_b} \right) P_{world} \tag{2.5}$$

where

Y_i	=	yield of crop i (tons.ha^{-1}),
P_i	=	local price of crop i (local currency),
P_{world}	=	the value of the base crop traded at world prices (US \$),
A_i	=	area cropped with crop i (ha),
P_b	=	local price of the base crop (local currency), and
Crops	=	number of different crops grown in the scheme.

The SGVP is not net value added. Molden *et al.* (1998) provide the following two reasons for this. Firstly, it is far easier to compute because many of the deductions needed to get from gross to net value added are susceptible to distortions (subsidies, taxes, credit) or they are very difficult to measure (family labour costs, opportunity cost of land and water). Secondly, 'yield' (output per unit land) is also a gross indicator and is unqualified by indications of input levels, soil type, or even variety.

Burt and Styles (1998) proposed that the real goal in assessing the production in a region is to determine what opportunities still exist in an irrigation scheme for improved production. Indicators 6 and 7 in Table 2.2 give an indication of how much irrigation has improved production in a region. They also indicate whether there is any potential for increased production (Burt and Styles, 1998). Burt and Styles (1998) did not calculate Indicators 6 and 7 as they were only proposed after the analysis component of their research was reached. However, they state that the data for Indicator 6 would be relatively simple to obtain and the data for Indicator 7 can be estimated from the abundance of crop research work that has been conducted around the world. These two indicators fit the definition of a true performance indicator because they include both the actual value and a target value (Bos *et al.*, 1994). They allow evaluators to quickly assess the magnitude of deviation in a given region from benchmark production values.

English *et al.* (2002) believe that as competition increases for limited resources, irrigators will tend to optimise their return in terms of water used and not in terms of yield attained. Indicator 4, which calculates the return per cubic meter of irrigation water supplied, would give an indication of the optimisation that English *et al.* (2002) described. Such an indicator could become important in a benchmarking exercise because it would give an indication as to how well irrigation utilises water compared to other industries in the same region.

2.4.2. Water supply performance indicators

It is important to understand the efficiency of water supply to irrigation schemes. This section describes external indicators that provide insight into the water supply status of irrigation schemes. It continues on from the previous section and is a summary of work done by Molden *et al.*, (1998), Burt and Styles (1998), Burt (2001) and Malano and Burton (2001). Table 2.3 summarises the water supply performance indicators.

Table 2.3 Summary of water supply indicators

No.	Indicator Name	Indicator Equation	IWMI	ITRC	IPTRID	RAP
8	Total annual volume of irrigation water delivery (m^3)	Total annual volume of irrigation water delivery			x	
9	Relative Water Supply (RWS)	$\frac{\text{Total water supply}}{\text{Crop demand}}$	x	x	x	x
10	Relative Irrigation Supply (RIS)	$\frac{\text{Irrigation supply}}{\text{Irrigation demand}}$	x	x	x	x
11	Irrigation Efficiency % (IE)	$\frac{\text{Volume of irrig. water beneficially used}}{\text{Volume of irrig. water applied} - \Delta\text{ storage of irrig. water}}$		x		x
12	Water Delivery Capacity Ratio (WDCR)	$\frac{\text{Canal capacity to deliver water at system head}}{\text{Peak consumptive demand}}$	x	x	x	x
13	Annual irrigation water supply per unit command area ($m^3.ha^{-1}$)	$\frac{\text{Total annual volume of irrigation supply}}{\text{Command area}}$			x	
14	Annual irrigation water supply per unit irrigated area ($m^3.ha^{-1}$)	$\frac{\text{Total annual volume of irrigation supply}}{\text{Total annual irrigated crop area}}$			x	
15	Security of entitlement supply	$\frac{\text{System water entitlement}}{\text{10 year minimum water availability flow pattern}}$			x	x

Levine (1982) first presented the Relative Water Supply (RWS), which is an external indicator as shown as Indicator 9 in Table 2.3. Relative Irrigation Supply (RIS) was developed by Perry (1996) and is referenced as Indicator 10 in Table 2.3. In these two indicators, the crop demand is defined as the potential crop ET, or the ET under well-watered conditions. For rice, deep percolation and seepage are included (Molden *et al.*, 1998). The total water supply of the scheme is the volume of all surface diversions plus net groundwater draft plus rainfall, but excluding recirculation of internal drainage within the scheme. The irrigation demand is the crop demand less effective rainfall and the irrigation supply is the volume of surface diversions plus net groundwater draft. Rain and recirculated drainage water are excluded from the irrigation supply (Molden *et al.*, 1998).

Molden *et al.* (1998) used Indicators 9 and 10 to describe the basic water status in irrigation schemes. Both RWS and RIS relate the water supply to the water demand. They are an indication of whether there is sufficient water in the scheme as well as how closely supply and demand are matched. When irrigation and rainfall meet the water requirements RIS is near unity. Molden *et al.* (1998) caution against the interpretation of RWS and RIS, as they need to be viewed in the context to which they were applied. For example, an irrigated area upstream in a scheme may divert large amounts of water for ease of management and supply. This excess water would then serve as a source for downstream users. In such a case, the resulting higher upstream RWS indicates appropriate use. Also a lower value may indicate that deficit irrigation is being practiced and that farmers are maximising their returns on available water. Lorite *et al.* (2004) computed annual RIS and RWS value for four seasons in irrigation districts in Spain and concluded that the indicators are directly affected by rainfall. Their results showed greater variation in the drier years. The rainfall, and in particular effective rainfall, is a subjective issue. It is difficult to estimate exactly what portion of the total annual rainfall can be classed as effective (Kloezen and Garces-Restrepo, 1998).

Malano and Burton (2001) and Burt (2001) also use RWS and RIS as two of their external indicators. They were computed on an annual basis. Burt and Styles (1998) state that RWS and RIS do not consider the timing of the water availability, nor the corresponding crop and soil requirements. They state that RWS and RIS do not provide significant value in that they provide a snapshot view of the water available. However they recommend the use of "dry season" and "wet season" indicators together with the annual value presented by Molden *et al.* (1998). This is because the dry season and wet season indicators may have completely different values that would be masked if only an annual value was used.

Burt and Styles (1998) state that the American Society of Civil Engineers' (ASCE) Irrigation Efficiency (IE), shown as Indicator 11, gives a much more detailed description of water destinations than both RIS and RWS. The numerator in Indicator 11 represents the total volume (beneficial and non-beneficial uses) of irrigation water that leaves the specified boundaries (Burt *et al.*, 1997). The IE equation must also be applied within a specific time. In the context of benchmarking, IE would be applied on an annual basis (Burt and Styles, 1998). If computed according to the ASCE guidelines, IE considers the amounts, timing and usage of water. The ASCE guidelines also define what usage of water is considered to be beneficial or not, as well as whether the equation has been computed within the correctly specified boundaries. Burt *et al.* (1997) describe in detail what is considered to be beneficial and non-beneficial water use. According to Burt and Styles (1998), when irrigation efficiency is properly understood and defined then double accounting of water and unwarranted expansion of production area are avoided.

The Water Delivery Capacity Ratio (WDCR), Indicator 12, gives an indication of the extent to which the irrigation infrastructure is constraining the cropping intensity in the command area (Molden *et al.*, 1998). This is achieved by comparing the canal conveyance capacity to the peak consumptive demands. Values greater than 1 indicate that the canal capacity is not a constraint to meeting crop water demands. An advantage of having a WDCR greater than 1 is that it indicates additional capacity that will allow for more flexible water deliveries (Molden *et al.*, 1998). The peak consumptive demand is defined as the peak crop irrigation requirement for a monthly period and is expressed as a flow rate at the head of the irrigation system (Molden *et al.*, 1998). Burt and Styles (1998) did not agree with this definition of peak demand because it included the rainfall component of the ET and therefore does not give an indication of the actual irrigation requirements. Therefore, they suggest the denominator be changed to "Peak *irrigation water* consumptive demand". Malano and Burton (2001) agree with Burt and Styles (1998) in that the peak consumptive demand refers to the demand from irrigation water only.

Malano and Burton (2001) included Indictors 13 and 14, water supply per unit command area and water supply per unit irrigated area respectively, in their set of external indicators as another measure for assessing water distribution in irrigation schemes. Different regions with similar climate and cropping patterns should exhibit values in the same region if performance is adequate. Malano and Burton (2001) and Burt (2001) both included Indicator 15, which is a measure of how frequently the irrigation organisation is capable of supplying the established water entitlements. It can be seen as an indicator that can be used to possibly assess whether or not water entitlements have been properly allocated in a particular irrigation scheme or catchment.

2.4.3. Financial performance indicators

As with all other types of investments, irrigation policy makers are interested in the return on investments made. Along the same lines, researchers would like to be able to recommend systems that yield acceptable returns within the environment to which they were applied (Molden *et al.*, 1998). Table 2.4 summarises the different financial performance indicators.

Table 2.4 Summary of financial performance indicators

No.	Indicator Name	Indicator Equation	IWMI	ITRC	IPTRID	RAP
16	Gross return on investment (%)	$\frac{\text{Production}}{\text{Cost of irrigation infrastructure}}$	x	x		
17	Cost recovery ratio	$\frac{\text{Revenue collected from water users}}{\text{Total MOM cost}}$	x	x	x	x
18	Maintenance cost to revenue ratio	$\frac{\text{Total maintenance expenditure}}{\text{Revenue collected from water users}}$			x	x
19	Total MOM cost per unit command area (US $\$.ha^{-1}$)	$\frac{\text{Total MOM expenditure}}{\text{Command area}}$			x	x
20	Total cost per person employed (US $\$.person^{-1}$)	$\frac{\text{Total cost of MOM personnel}}{\text{Number of MOM personnel employed}}$			x	x
21	Revenue collection performance	$\frac{\text{Revenue collected from water users}}{\text{Total service revenue due}}$			x	x
22	Staffing numbers per unit command area (persons.ha^{-1})	$\frac{\text{Number of MOM personnel employed}}{\text{Command area}}$			x	x
23	Average revenue per m^3 of water supplied (US $\$.m^{-3}$)	$\frac{\text{Revenue collected from water users}}{\text{Total annual volume of water delivery to users}}$			x	x

The term MOM in Table 2.4 refers to the total Management, Operation and Maintenance cost associated with an irrigation scheme. Indicator 16 in Table 4.3 is termed the "Gross return on investment", and helps provide researchers and policy makers in decision-making. In order to calculate this indicator, the cost of the irrigation infrastructure needs to be determined. This term considers the cost of the water delivery system referenced to the same year as the SGVP. It focuses more on the water delivery structure so that it will be possible to analyse differences between various systems. Types of delivery systems include structured, automated, and lined and unlined canal sections. The infrastructure related to river diversions, storage, and drainage were not included because of the desire to be able to compare different methods of water delivery (Molden *et al.*, 1998). The diversion and storage works infrastructure costs were also excluded because they often serve other non-irrigation purposes as well (Molden *et al.*, 1998).

Burt and Styles (1998), who investigated 18 different irrigation schemes from around the world, state that it can be difficult to accurately determine the cost of irrigation infrastructure. Many irrigation schemes have been constructed over decades of time and accurate records of costs are often not available. Molden *et al.* (1998) encountered the same problem in some of their case studies when they applied their set of indicators to 27 schemes around the world. As a solution they estimated the current cost of construction per hectare prevailing in those countries that did not have reliable construction costs.

Molden *et al.* (1998) refer to Indicator 17, presented in Table 2.4, as "Financial self-sufficiency". Burt (2001) and Burt and Styles (1998) prefer to refer to it as "Percentage of O & M collected". Malano and Burton (2001) defined it as the "Cost recovery ratio". Indicator 17 is an indication of the percentage of the MOM expenditures which are generated locally. Government subsidies for MOM would result in a low financial self-sufficiency, whereas schemes where farmers pay the majority of MOM costs would have a high self-sufficiency. Indicator 17 only yields information on MOM expenditure, not the MOM requirement. Therefore a high value of self-sufficiency may not indicate a sustainable system, as the MOM expenditures might be too low to meet the actual maintenance needs (Molden *et al.*, 1998).

2.4.4. Environmental performance indicators

A summary of the environmental performance indicators is given in Table 2.5. Molden *et al.* (1998) and Burt and Styles (1998) had no indicators that described the performance of a system from an environmental perspective. The main reason behind computing these environmental indicators is to establish how the irrigation systems impact on the environment and whether they are sustainable or not (Malano and Burton, 2001).

Table 2.5 Summary of environmental performance indicators

No.	Indicator Name	Indicator Equation	IWMI	ITRC	IPTRID	RAP
24	Water quality: Salinity ($dS.m^{-1}$)	$\frac{\text{Electrical conductivity of irrigation water inflow}}{\text{Electrical conductivity of drainage water}}$			x	x
25	Water Quality: Biological ($mg.liter^{-1}$)	$\frac{\text{Biological load of irrigation water inflow}}{\text{Biological load of drainage water}}$			x	x
26	Water Quality: Chemical ($mg.liter^{-1}$)	$\frac{\text{Chemical load of irrigation water inflow}}{\text{Chemical load of drainage water}}$			x	x
27	Average depth to water table (m)	Average depth to water table			x	x
28	Change in water table depth over time (m)	Change in water table depth over time			x	x
29	Salt balance (-)	$\frac{\text{Salt content of irrigation water inflow}}{\text{Salt content of irrigation drainage water}}$			x	x

Each of these indicators is calculated on an annual basis and the value is an average of a number of monthly readings. The number of readings will be dictated by the magnitude and frequency of any fluctuations (Malano and Burton, 2001). The data for the biological and chemical load, and for the electrical conductivity, need to be converted to a volumetric value. This is accomplished by combining the readings with the total measured annual values for both irrigation water inflow and drainage (Burt, 2001). The determination of such environmental indicators is important due to the increasing concern in the quality of drainage water (Bos *et al.*, 1994).

Monitoring the depth of the water table, and any changes that may occur, is important for the following three reasons. Firstly, if irrigation water is supplied from ground reserves only, continual mining of the resource will lead to an increase in depth and therefore an increase in pumping costs. This increase in cost affects the feasibility of such a practice (Bos *et al.*, 1994). The second reason is that in arid and semi-arid regions, a high water table could result in salt accumulation in the root zone. This could lead to yield reductions, or even total abandonment of agriculture in the affected areas. The final reason is that in humid and sub-humid regions, any permanent rise in the water table could also cause yield reductions and may limit the number of workable days (Bos *et al.*, 1994).

It should be noted that no references to potential environmental pollution resulting from incorrect application of pesticides were found in the external indicator sets that were reviewed.

2.5. Internal Performance Indicators

Burt (2001) listed a number of internal indicators that were used in the RAP that he described. The internal indicators proposed by Burt and Styles (1998) also attempt to provide insight into the internal mechanisms within an irrigation scheme. One of the objectives of the irrigation performance research that Burt and Styles (1998) conducted was to identify specific actions that could be taken to ensure irrigation schemes reap the benefits of their investments. They concluded that it was insufficient to only examine the inputs and outputs of an irrigation scheme. In order to improve performance it is necessary to understand internal mechanisms and provide selective enhancement to those troublesome areas.

In order to illustrate how the internal indicators proposed by Burt and Styles (1998) function, consider the internal indicator labelled by them as "Indicator I-1: Actual service to individual fields". This internal indicator has four sub-indicators incorporated into it and they are shown in Table 2.6. Each of the sub-indicators has a maximum potential value of 4 (best case), and a minimum of 0 (worst case). In order to determine the value of the internal indicator, Burt and Styles (1998) use the following procedure:

1. A relative weighting factor is applied to each sub-indicator value. The weighting factors are only relative to each other within the indicator group. It does not matter whether the maximum value is 4 or 2, what is of importance are the relative values of the sub-indicators within the group.
2. The weighted sub-indicator values are summed together.

3. The final value is adjusted based on a worst case value of 0 and a best case value of 10.

The process can be illustrated if sample values are applied to the internal indicator in Table 2.6. If within a certain irrigation scheme, the evaluator assigned a ranking criterion of 2 to each of the four sub-indicators, the sum of the weighted values would equal 22. The maximum value for this indicator given the ranking criteria and the weighting factors is 44. When adjusted, this indicator (Actual service to individual fields) therefore scores five out of a possible ten.

Table 2.6 An example of an Internal Process Indicator: Actual service to individual fields (Burt and Styles, 1998)

No.	Sub-Indicator	Ranking Criteria	Wt
1-1A	Measurement of volumes to field	4 - Excellent measurement and control devices, properly operated and recorded. 3 - Reasonable meas. & control devices, avg. operation 2 - Meas. of volumes and flows - useful but poor. 1 - Meas. of flows, reasonably well. 0 - No measurement of volumes or flows.	1
1-1B	Flexibility to field	4 - Unlimited freq., rate, duration, but arranged by farmer within a few days. 3 - Fixed freq., rate, or duration, but arranged. 2 - Dictated rotation, but matches approx. crop need. 1 - Rotation, but uncertain. 0 - No rules.	2
1-1C	Reliability to field (incl. weeks avail. vs. week needed)	4 - Water always arrives with freq., rate, and duration promised. Volume is known. 3 - A few days delay occasionally, but v. reliable in rate and duration. Volume is known. 2 - Volume s unknown at field, but water arrives when about as needed and in the right amounts. 1 - Volume is unknown at field. Deliveries are fairly unreliable < 50% of the time. 0 - Unreliable freq., rate, duration, more than 50% of the time; volume is unknown.	4
1-1D	Apparent equity	4 - It appears that fields throughout the scheme and within tertiary units all receive the same type of water. 3 - Areas of the scheme receive the same amounts, but within an area it is somewhat inequitable. 2 - Areas of the scheme receive somewhat different amounts (unintentionally), but within an area it is equitable. 1 - It appears to be somewhat inequitable both between areas and within areas. 0 - Appears to be quite inequitable (differences more than 100%) throughout scheme.	4

Burt and Styles (1998) stress that no single internal indicator is capable of describing a scheme on its own. However, if the internal indicators are reviewed as a whole and then combined with results from certain external indicators, insight about the design, operation, and management of an irrigation scheme can be gained. Many of the internal indicators described by Burt and Styles (1998) deal with the equity, reliability and the adequacy of the irrigation supply. Equity is a measure of how fairly water is distributed among the different users. Adequacy is defined as being the capacity of an irrigation system to meet the demands of the farmers (Murray-Rust and Snellen, 1993). These latter authors define the reliability of an irrigation system as an indication of the quality of service as it considers both the reliability of discharges (quantity) and the reliability of the deliveries (timing). A system with good adequacy, equity and reliability would result in a more flexible supply to enable the farmer to grow crops efficiently and economically (Cross, 2000). Therefore, these three factors need to be investigated in order to gauge whether there is opportunity for improvement.

The WRC project for which this research was undertaken is described next.

2.6. South African Water Use Efficiency Framework (SAWUEF)

At the time of this study, the WRC was funding an irrigation research project entitled "Standards and guidelines for improved irrigation water use efficiency from dam wall release to root zone application". One of the objectives of this project is to quantify and establish typical or representative current levels of efficiency from dam wall release to root zone application on a selection of South African irrigation schemes (Ascough *et al.*, 2004). Another of the objectives is to improve these typical or representative efficiencies by proposing best managements practices which are practical and achievable. In order to establish the typical or representative efficiency levels, the framework presented in Figure 2.3 was proposed. The framework is intended to account for conveyance, distribution, surface storage, application soil storage and return flow efficiencies. At the time of this study, the framework proposed in Figure 2.3 was adopted. By the end of the project, the framework shown in Figure 2.3 might change and therefore should not be interpreted as the final framework.

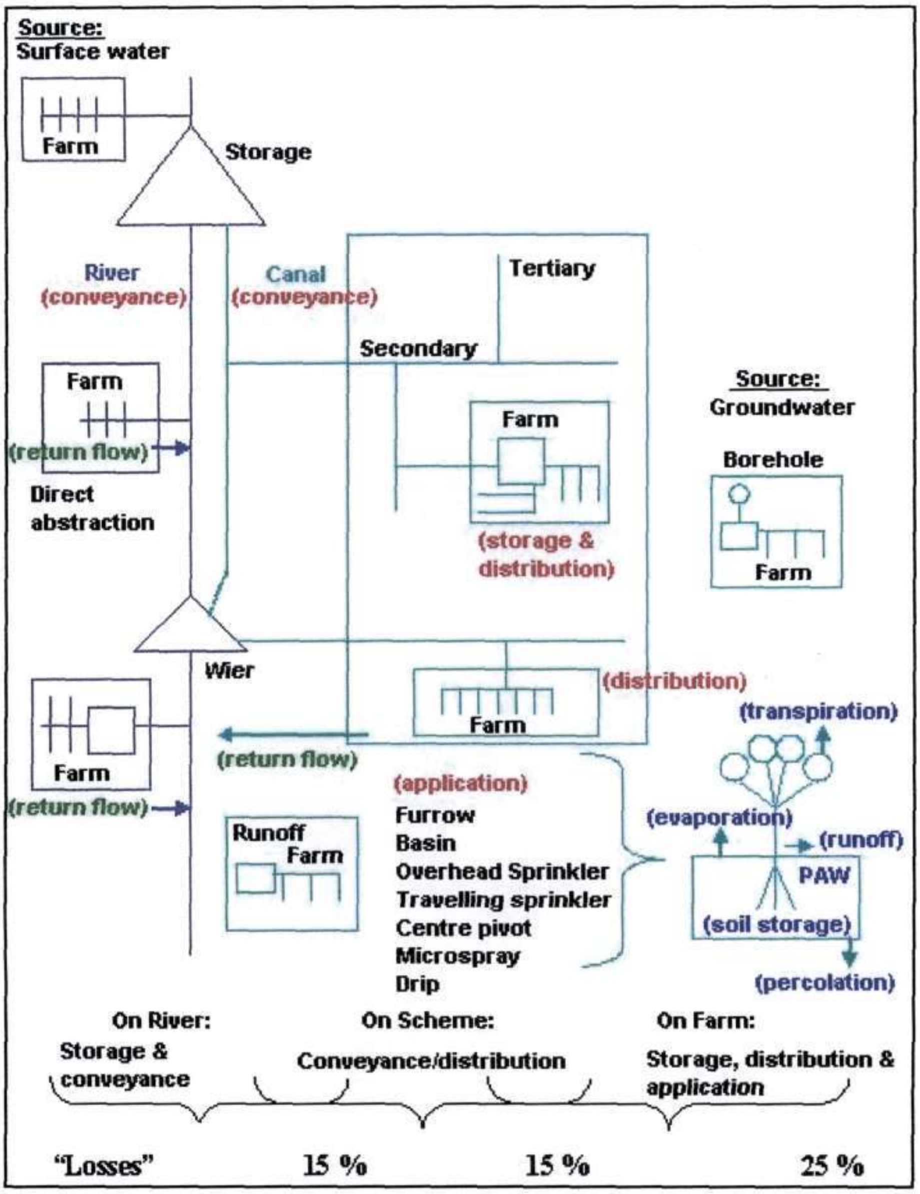

Figure 2.3 Schematic showing all possible scenarios to assess water use efficiency (Ascough *et al.*, 2004).

Figure 2.3 contains all the possible scenarios of irrigation water supply that occur in South Africa. The project objectives required that each of these different scenarios be investigated to ensure that guidelines can be provided to benefit all stakeholders in the South African irrigation environment. One of the specific objectives of the project is to evaluate and implement tools to quantify (directly and/or indirectly) conveyance, distribution, surface storage, application, soil storage and return-flow variables and factors on selected irrigation schemes. Therefore, a methodology that could be developed to quantify some of these components would be beneficial for the project to attain its objectives. Benchmarking, as it has been introduced in this chapter, was identified as a method of achieving some of the objectives of the WRC efficiency project.

In addition to the WRC project, there is also potential to apply a benchmarking methodology to water management in general in South Africa. The NWRS (2004) and the National Water Act (1998) describes the multilevel participatory water management structure that has been proposed for water management in South Africa. The country has been divided into 19 water management areas (WMA). Water management in each WMA will be the responsibility of a Catchment Management Agency (CMA). Within each of the WMA there will also be groups of water users represented by a Water User Association (WUA). The multilevel management approached can then be described as water users being managed and operated by their corresponding WUA; the CMA will then be responsible for managing the different WUA's; and finally the 19 different CMA's will report to the national Department of Water Affairs and Forestry (DWAF). There is great potential for benchmarking at various different levels within this type of structure. A WUA could provide a benchmarking service for all its water users. A CMA can then provide the same type of service for all the WUA in its WMA. Finally, DWAF would provide the final benchmarking services for each of the 19 CMA's in South Africa. The performance indicators used in each case will be different and derived from stakeholder requirements at each level. Therefore, whilst the main goal of this research was specifically for the WRC efficiency project, there is a larger potential application for benchmarking in South Africa. This concept will be discussed further in this document.

Prior to the implementation of any project, it is necessary to investigate similar applications with the goal of learning from the experiences gained in other projects. A benchmarking project has been implemented in Australia which has been operational for a number of years. The next section introduces the Australian irrigation benchmarking project and discusses what was found to be necessary for the success of the project.

2.7. Australian Benchmarking Initiative

The Australian National Committee on Irrigation and Drainage (ANCID) has been running a benchmarking program on most of their irrigation water provider systems since 1997 (Malano, 2000). The motivation for driving the benchmarking initiative in Australia was a result of the transfer of government owned and operated irrigation schemes to private and semi-private organisations which are more service orientated (Alexander, 2000). The ANCID benchmarking process focuses on six areas of the system performance, namely: (i) operational aspects, (ii) environmental aspects, (iii) customers, (iv) financial aspects, (v) social aspects, and (vi) water access arrangements (ANCID, 2004). The operational aspects of the process include indicators to quantify the following areas (Fairweather *et al.*, 2003):

- the volume of water delivered,
- the basis of delivery in terms of total entitlements and available resources,
- the water delivery efficiency,
- the extent of volumetric metering of customer water supplies, and
- the extent of water trading between different users.

The initial report in the 1997/1998 season contained 15 indicators and this number had increased to 69 indicators by the 2002/2003 season (Fairweather *et al.*, 2003; ANCID, 2004). ANCID has divided these 69 indicators into three indicator categories to provide a useful framework for benchmarking in the future (Alexander and Potter, 2004). ANCID describe the three different categories, presented below, as "Tier 1, 2 and 3" indicators (Alexander and Potter, 2004).

- Tier 1, General irrigation water provider statistics ("Who we are?").

These indicators describe the key base statistics of the different water providers in the industry. They provide a general overview of each provider and further increase the level of information captured about the Australian irrigation industry. Examples of such indicators would include irrigated area, crop types, length and size of the system, water quality, water supply and application system.

- Tier 2, Performance reporting ("How we interact?").

Tier 2 indicators assess specific external or internal regulatory/compliance/promotional needs and can be released to the public in general. Examples of such indicators would include changes in water table levels, proportion of supply points, metered system conveyance efficiency, water trading and system reliability.

- Tier 3, Confidential internal business performance benchmarking ("How we improve"?).

This set of indicators specifically targets what needs to be done in order to improve irrigation water provider businesses. The improvement is aimed at both an individual and collective level. Tier 3 indicators are aimed at a high level are confidential. Only the participating water provider knows how they compare with other service providers (Hydro Environmental, 2002, cited by Alexander and Potter, 2004). The categories that these indicators would focus on include customer service, infrastructure performance, compliance and financial performance.

ANCID and the irrigation industry in Australia have accepted the benchmarking of irrigation water provider businesses (Alexander and Potter, 2004). The Australian benchmarking exercise highlighted several key issues that should be taken into account when initiating a benchmarking process (Malano, 2000). Firstly, stakeholder participation and ownership is vital as this draws support for the benchmarking activity. All stakeholders will have to agree on a common set of performance assessment criteria which will enable the initial goal of benchmarking to be achieved, i.e. adopting and achieving best management practices. The second point, some of which have already been identified, is that of drivers. There must be clear incentives for organisations to become involved in the process. The last key aspect presented by Malano (2000) is related to data quality and availability. Most of the irrigation and drainage providers in Australia gather data on the key aspects of their service. However, because this data was always intended to be used internally, the different providers often did not use the same format to collect and store their information. Therefore, any organisations intending to join a benchmarking study would be required to adhere to established specifications and protocols (IPTRID Secretariat, 2000). This fact actually served as a catalyst for some of the schemes in the Australian benchmarking initiative to improve the quantity and quality of the data they collected (Malano, 2000).

The importance of boundaries was highlighted in Section 2.2.1. In an irrigation benchmarking exercise utilising external process indicators, the scale of the evaluation is at a project scale, but within that scale, for internal process indicators, water sources and destinations at field and farm level need to be verified as well. Figure 2.4 shows the functional and geographic boundaries of the ANCID benchmarking project as illustrated by Alexander and Potter (2004).

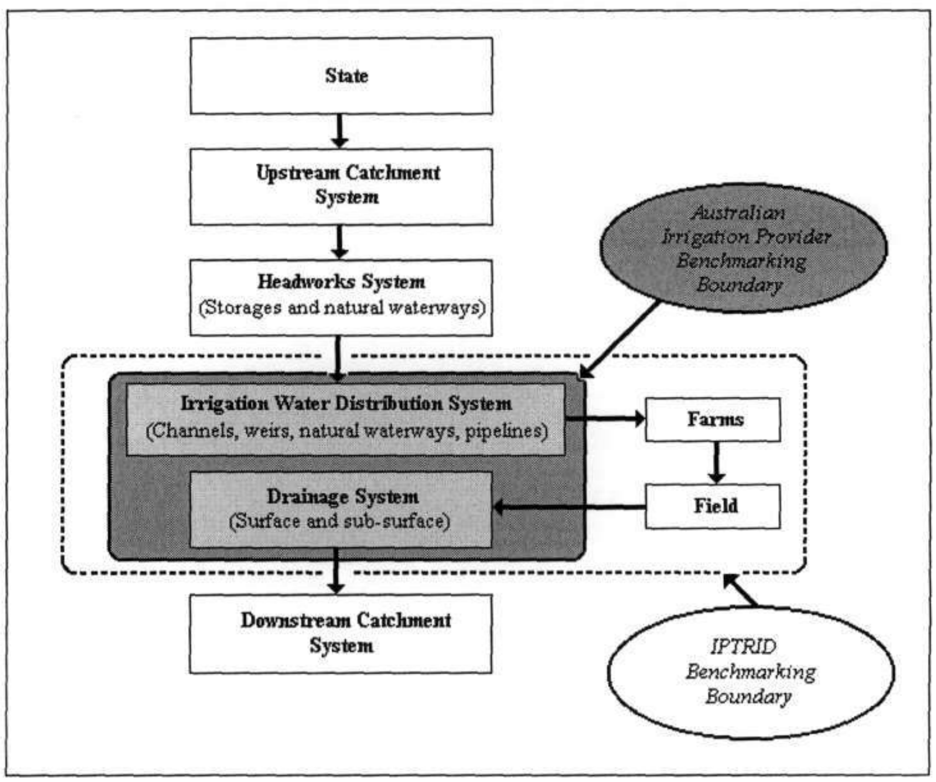

Figure 2.4 Functions of irrigation water supply businesses (after Alexander and Potter, 2004).

ANCID benchmark only the business aspects of an irrigation water service provider and do not include farm and field scale performance. . In Australia, quantifying performance at a farm and field level is achieved through their "*Water Use Efficiency Framework*" developed by Fairweather *et al.* (2003). The functional boundaries for the IPTRID external indicators that were used in the IPTRID benchmarking project are also included in Figure 2.5. The IPTRID functional boundaries include farm and field scales. If benchmarking were to be applied in a South African context, these functional boundaries would have to be defined and agreed upon by stakeholders and water managers at the different levels within the multilevel participatory water management structure.

2.8. Chapter Discussion and Conclusions

The benchmarking process relies on the calculation of external and internal indicators. External indicators relate the inputs and outputs of an irrigation project to each other. The external indicators cover four aspects of performance. These are the agricultural output, water supply, financial aspects and environmental aspects of the project performance. The problem associated with external indicators is that they give no indication as to the internal processes within a project. It was emphasised that external indicators provide little or no guidance as to what must be done to improve performance in an irrigation project. Therefore, internal indicators were developed to try to understand the processes used within an irrigation project and also the level of water delivery service throughout the project. When these internal indicators are combined with the external indicators, they can be used to formulate a plan that will improve overall performance. These plans can then be compared between different systems in an attempt to identify and formulate best management practices.

Assessing scheme performance by completing the water balance over specified geographic and temporal boundaries is also a method to quantify performance. The water balance approach was introduced in detail and all the elements required to complete a water balance were discussed. These elements included accuracy of estimates, confidence intervals and determining the change in storage over the temporal boundaries. The use of water balances is suited to determining scheme delivery efficiencies and storage efficiencies of balancing dams in irrigation schemes.

Computing performance indicators and utilising the water balance approach requires accurate estimation of the components of the hydrologic water balance. For these estimates to be made, boundaries needed to be identified. As mentioned, external performance indicators relate inputs to outputs for irrigation projects, and should only be applied at a project level scale. Irrigation water destinations also need to be categorised in order for evaluators to determine whether the use of water was warranted or not. For this purpose, definitions of what use is considered beneficial and reasonable need to be established. This chapter contained these definitions of beneficial use. However, because environmental conditions vary between projects, these definitions of beneficial use need to change accordingly. This is another area in which stakeholder participation is required. The concept of internal indicators that was described can be adopted to analyse performance at both a field and farm scale. However, they do not consider water destinations in the same manner as the external indicators and therefore do not require estimates of those destinations.

It is postulated that the computation of internal indicators via the RAP methodology would not be a useful exercise in assessing scheme performance in this study. The fact that RAP evaluators need specific training and experience in implementing the RAP methodologies, meant that it would not be possible for the author to use such a technique. This is particularly relevant to the internal indicators which are a qualitative investigation into internal aspects of scheme operation. However, the computations of the external indicators are quantitative, and therefore more straightforward, and are not susceptible to the bias introduced by an untrained and inexperienced evaluator. The main advantage of the RAP is the efficient gathering of data at the scheme and the emphasis placed on not wasting time by attempting to acquire data that is not readily available.

Another aspect that was discussed in this chapter was the scale of the assessment when using the performance indicators described. The context in which the external indicators are presented was that they would be applied at a project or irrigation scheme scale. The merits of applying at this scale are that comparisons between schemes are possible. However, the indicators could also be applied at a farm scale within an individual scheme and therefore provide possible benefits to individual farmers within a particular scheme. The possibilities for establishing best management practices at a farm scale as a result of identifying the best performers then become achievable. Therefore, parts of this study will focus on applying some of the external performance indicators at a farm scale as well.

It can be concluded there is a growing need for an improvement in irrigation and drainage performance. It was also highlighted that the participatory management approach that has been proposed, and at the time of writing has started to be implemented in South Africa could benefit, i.e. improve water use and the management thereof, from a benchmarking approach at the different management levels. In order to achieve improved performance, benchmarking with performance indicators and water balances have been identified and are currently being practiced globally by many irrigation and drainage service providers. The main function of a benchmarking process is to identify and adopt best management practices for an organisation. These can be achieved either by internal comparisons within one organisation or by comparing performance externally between similar organisations. In the Australian benchmarking initiative, a few key elements were identified that would ensure the success of the project. The first of these was that stakeholder participation was vital. In order for the best management practices to be successful, there should be clear incentives, such as a potential for increased profits, to secure stakeholder support. The second point was to do with drivers. There should be a clear reason, even before the incentives, to become involved in a benchmarking process. Some of the possible drivers were included in this review. The last important point was that in the data collection and analysis stage of a benchmarking process, the stakeholders should all adhere to established specifications and protocols. These three points were of great importance as they were lessons that were learnt through the application of other benchmarking projects. It is felt that the satisfaction of these three criteria is of great importance in this research and that they should be a priority in the formulation of a suitable methodology. It was also emphasised that it is also important for any chosen set of performance indicators to remain in focus with the objectives established by a specific irrigation project. It is unlikely that all of the indicators described in this chapter would be needed to assess every scheme. With stakeholder support, an indicator set that best describes participating projects and their potential pitfalls should be developed. The suitable indicator set, as supported by stakeholders, should be implemented in conjunction with the three points needed for implementing a successful benchmarking project.

In conclusion, a comprehensive overview of irrigation performance assessment literature has been presented. Each different method of assessment has its own associated benefits and these have been discussed. From the results of this review, it was proposed that a combination approach, where water balances and external indicators would be used in conjunction with one another, to assess irrigation scheme performance at both project and farm scales. However, in order to assess the effectiveness of the proposed approach, a suitable irrigation scheme first needed to be identified. The South African scheme that was selected for this purpose is introduced in Chapter 3.

3. STUDY AREA

This chapter introduces the irrigation scheme which was used as a study area for the research that was undertaken in the project. Bos *et al.* (1994) suggested that the performance assessment criteria should remain in focus with the specific issues that need to be dealt with at individual irrigation schemes. Malano and Burton (2001) also stressed the importance of discovering which drivers influence an irrigation scheme to utilise a benchmarking approach, before embarking on the benchmarking process. Coupled with these two issues, was the point raised by Bos *et al.* (1994) which stressed the importance of incentives, such as improved efficiency and performance, that need to be evident in the project objectives in order to increase stakeholder awareness and ensure successful participation. Without prior detailed knowledge of an irrigation scheme, it would not be possible to identify the drivers that would promote an awareness of performance, nor would it be possible to create the incentives required to get stakeholder acceptance.

The structure of this chapter consists of four different sections. In the first section, the scheme is introduced from a technical perspective and includes a technical description of the scheme infrastructure, the daily operation of the scheme and the areas of irrigated land supplied by the scheme. The second section includes a general description of soil types, water quality, and the predominating on-farm irrigation systems and the irrigation management practices. The third section uses information presented in the first two sections that identified the key issues in the scheme that needed the detailed investigation of this study.

3.1. Scheme Introduction

The irrigation scheme selected for this study was situated in the KwaZulu-Natal province in South Africa. Sugarcane was the only crop grown in the scheme. In total the scheme had a scheduled area, i.e. the area registered for water use with the Department of Water Affairs and Forestry (DWAF), of 3 400 ha. The scheduled area was allocated a permissible water use volume of 11 800 cubic meters per ha per annum. There were 36 farms in the scheme for which this scheduled area was applicable. The actual irrigated area and the scheduled area in the scheme were not the same. According to data obtained directly from the farmers and scheme managers, the actual irrigated area was approximately 4 100 ha, but this varied slightly from year to year depending on what portion of the land was fallow. The command area, which was the area that can be irrigated before the scheme infrastructure capacity becomes limiting, was 5 500 ha. When the scheme was first commissioned, some of the farmers chose to extend their water allocations and decided to use less water on slightly more land. This caused the actual irrigated area to be larger than the scheduled area.

Overhead dragline and surface drip irrigation were the two types of irrigation systems that predominated in the study area. A portion of the area was also under subsurface drip irrigation. Expressed as a percentage of the total irrigated area, the overhead dragline systems accounted for 67 % of the area and drip irrigation was practiced on the remaining 33 % of the total irrigated area. There was no surface flood irrigation or centre pivot irrigation practiced in the scheme.

Due to the sensitivity of the potential results that could arise out of any investigation on performance and efficiency, the research team was requested by scheme management to enter into a confidentiality agreement. The agreement stipulated that no information which could potentially reveal the name and location of the scheme should be divulged in the study. As such, a locality map and detailed description of the location of the scheme could not be included in this document. However, a detailed schematic which illustrates the scheme layout is presented to provide the reader with an understanding of the infrastructural layout of the scheme and the operation thereof.

3.2. Scheme Infrastructure and Operation

Figure 3.1 is a schematic representation of the irrigation scheme and shows the location of the scheme balancing dams, canals and water meters relative to each another. As shown in Figure 3.1, the specific location of water meters in scheme enabled an analysis for five independent sections. A description of the balancing dams, canals and water meters that is presented in Section 3.2.2. Figure 3.1 needs to be analysed in conjunction with the technical description of the scheme operation which is covered in the next sub-section.

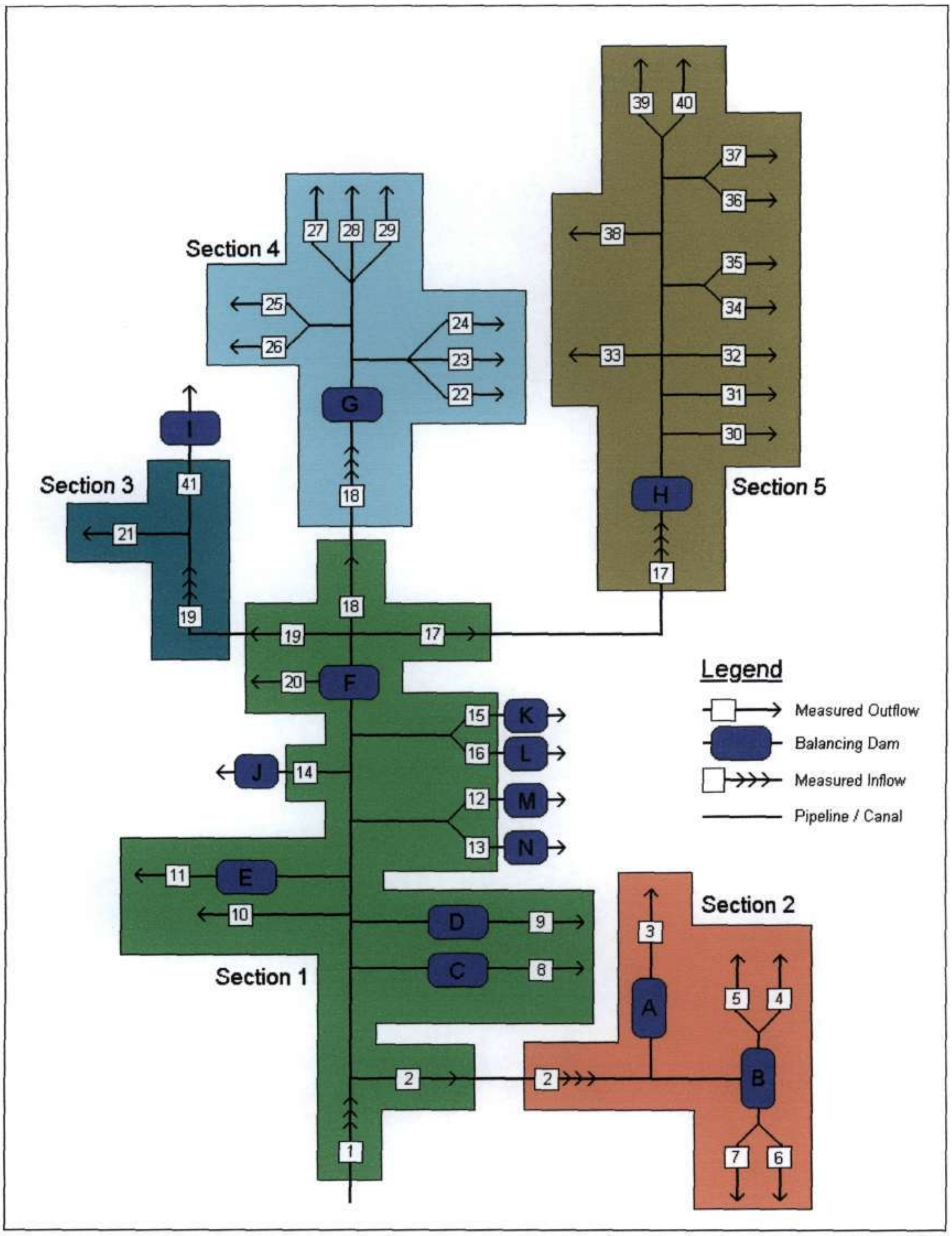

Figure 3.1 Schematic layout of the selected irrigation scheme.

3.2.1. Technical description of operation

The scheme management consisted of a scheme manager and approximately ten other staff members who were responsible for delivering water to the edge of the farm boundaries. This responsibility entailed daily management, operation and general maintenance duties. Once the water arrived at the farm boundaries, the responsibility for water management lay with the farmers themselves.

Water for irrigation purposes at the scheme was extracted out of a major river in the area. However, the scheme could not be classed as a classic run-of-river scheme and relied on the presence of a large reservoir upstream of the scheme. This reservoir ensured a reliable supply of water to the scheme during dry periods. However, irrigators were not the only water users, and there were other industrial and domestic users in the catchment. Therefore, in practice, during past severe water shortages irrigators had their water allocation reduced because they had the lowest assurance of supply.

Irrigation water for the scheme was released from the upstream reservoir, and upon arriving at the scheme intake works, was pumped from the river into a main canal which conveyed water into the center of the scheme. The canal ultimately spilled into a large balancing dam, Dam F in Figure 3.1. Farmers in the scheme abstracted water for irrigation either directly from the canal or from one of the many balancing dams on the scheme. This can be observed in Figure 3.1. Details of the canal and different balancing dams in the scheme is provided in Section 3.2.2.

In order to estimate short term, *viz* 1 week, irrigation water demands in the scheme, farmers were required to estimate what their water use would be a week in advance and place a water order with the scheme manager on a Tuesday morning. The scheme management then used their experience, together with knowledge of water currently stored in the scheme balancing dams, and placed an order with the upstream reservoir on Thursday. The water order was further broken down into daily volumes so that the release from the reservoir would correspond with the scheme pumping schedule at the river. Water for the scheme was released from the reservoir from Friday night onwards. The released water started to arrive at the scheme pump station on Monday morning. Therefore, the travel time from the upstream reservoir to the scheme was approximately 60 hours. The whole ordering process then repeated itself with farmers placing another order on Tuesday for the next week. According to the scheme manager, significant rainfall caused interruptions in the ordering process, and if rainfall occurred after an order had been placed, the order was cancelled by the scheme manager.

Water management and billing in the scheme was achieved by metering water use at forty strategic points in the scheme. These water meters were monitored daily and consequently water use in the scheme could be calculated on a daily basis. The water meters, which were electromagnetic flow meters, with a claimed accuracy of ± 0.5 % on a cumulative volume (Flowmetrix, 2006), were essential in the management and billing of water use. Thirty-six water meters measured water flowing onto individual farms. The other four meters were used to measure water movement within the scheme delivery infrastructure. The scheme also made use of several balancing dams which were used to ensure a flexible and reliable water supply to the farms. The use of accurate water meters also meant that farmers were charged for water on a volumetric basis. This was not typical in South Africa where in many irrigation schemes farmers paid according to scheduled area. Paying for the actual volume of water used provided an incentive to use water more efficiently.

The maintenance of the water delivery infrastructure in the scheme was excellent. The scheme was shutdown for 3-6 weeks in July for a comprehensive maintenance schedule. The canal would be emptied and examined for leaks. Should leaks be found, they were patched with an elastic polymer. All electrics and pumps in the scheme were also checked and serviced and, if necessary, completely overhauled during this period. Major structural repairs were also carried out on canals, balancing dams and pump stations if required. These maintenance procedures helped to alleviate disruptions in water supply to the scheme during other times of the year and thus ensured a reliable and efficient water supply to the farms in the scheme.

3.2.2. Technical description of infrastructure

The scheme consisted of a section of canal and several balancing dams. As already described, the level of water measurement was also comprehensive. This section describes the canal, the balancing dams, and the water meters used in the scheme.

3.2.2.1. Canal

The main canal in the scheme was 9.14 km long and consisted of ten different sections. The different sections were connected to each other by ten underground siphons. The total combined length of the canal and the siphons was 11.90 km. The canal was cement lined and of a parabolic shape. The top width was 3.0 meters with a corresponding depth of 1.78 meters. The canal had a slope of 1:2000 and could convey just over 3 $m^3.s^{-1}$ when full. A photograph of the main canal is shown in Figure 3.2. An interesting feature that can be observed in Figure 3.1 is the presence of drainage chutes that prevented runoff, from the irrigated lands above the canal, from actually entering the canal. These drainage chutes had benefits related to improved water quality and prevention of excess sediments building up in the canal as a result of runoff into the canal. The drainage contours and chutes thus helped ensure that the only water that enters the canal is that which was pumped in from the river and any rainfall that fell directly onto the canal. This enabled the accurate computation of a water balance which is described in Section 5.1.

Figure 3.2 Section of the main canal, with drainage chute in the background.

A further feature that is highlighted in Figure 3.2 is the location of the water quality testing point for the scheme, marked by the small white signboard in the foreground of the photograph. A water sample was taken every two weeks at this location and is tested for physical, organic and chemical impurities. More detail on water quality is provided in Section 3.3

3.2.2.2. Balancing dams

The scheme relied on balancing dams for the temporary storage of water within the scheme. The presence of these dams ensured a flexible and reliable water supply to the farms. The scheme management had responsibility for managing the water level in some of the balancing dams, while farmers managed the level of the remaining dams. The decision on who took responsibility for management the level was as follows. If scheme management were responsible for ensuring that a particular dam always had sufficient water in it, then the dam was classed as their responsibility. If the farmer managed the level of a dam without input from scheme management, then the dam would be the sole responsibility of that particular farmer. In total, there were seventeen balancing dams on the scheme. The cumulative volume of the balancing dams on the scheme was approximately 800 000 m^3. A photograph of a typical balancing dam that was present in the scheme is shown in Figure 3.3.

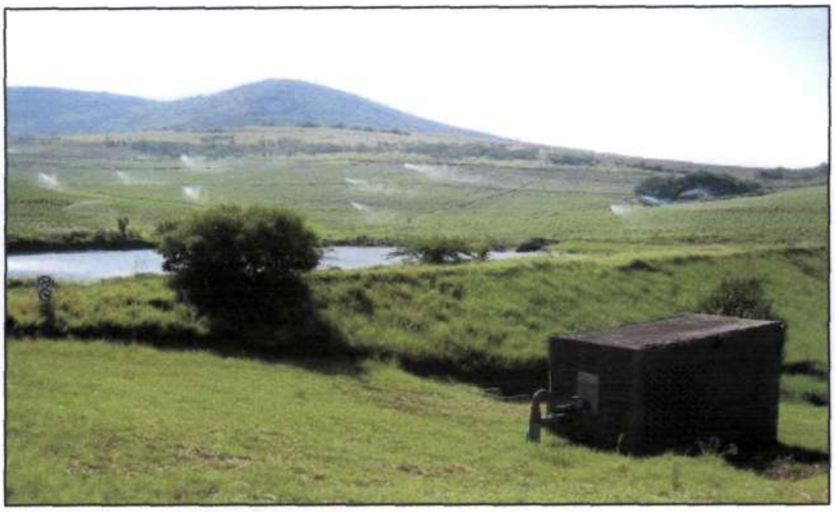

Figure 3.3 Typical balancing dam in the study area.

The volumes of all the balancing dams within the geographic boundaries for each of the five different sections that were shown in Figure 3.1 are presented in Table 3.1. The listed volumes were used to determine the change in water storage in the scheme over the evaluation period, as well as to estimate the daily seepage from each of the dams. These calculations are described in detail in the methodology presented in Chapter 5. All of the balancing dams that are listed in Table 3.1 were earthen walled, unlined dams.

Table 3.1 Characteristics of balancing dams in the scheme

Label in Figure 3.1	Surface Area (ha)	Storage Capacity (m^3)	Location (Figure 3.1)
A	0.42	20 000	Section 2
B	2.00	100 000	Section 2
C	0.92	25 000	Section 1
D	1.00	30 000	Section 1
E	0.35	15 000	Section 1
F	10.64	420 000	Section 1
G	1.25	40 000	Section 4
H	1.8	60 000	Section 5

3.2.2.3. Water metering

As shown in Figure 3.1, there were 40 water meters in the scheme. There was one mechanical impeller meter, and the remainder were all electromagnetic flow meters. The meters were manufactured by the South African company Flowmetrix™. Each of the meters was read on a daily basis, and the water usage for each meter was entered by scheme management into a Microsoft

Excel spreadsheet that was developed specifically for water management purposes. Some of the meters were located at pump stations with power consumption (kWh) meters. At these locations, the power consumption reading was combined with the pump capacity to estimate the volume of water pumped. The estimated volume was used to check for any possible gross errors in the electromagnetic flow meter readings. According to Flowmetrix (2006), the meters did not need to be recalibrated after installation. However, the larger meters at the scheme were checked every two years to confirm their accuracy.

3.3. General Scheme Information

In this section, soil types, water quality and on-farm irrigation systems and management is introduced.

3.3.1. Soils

The distribution of the soil parent material within the scheme is shown in Figure 3.4. The geographical layout of the scheme infrastructure can also be seen in Figure 3.4. Schmidt (2001) reported on the soil parent material and soil form in the study area. Much of the work presented in this section emanates from the investigation by Schmidt (2001). Table 3.2 contains information on soil form and parent material.

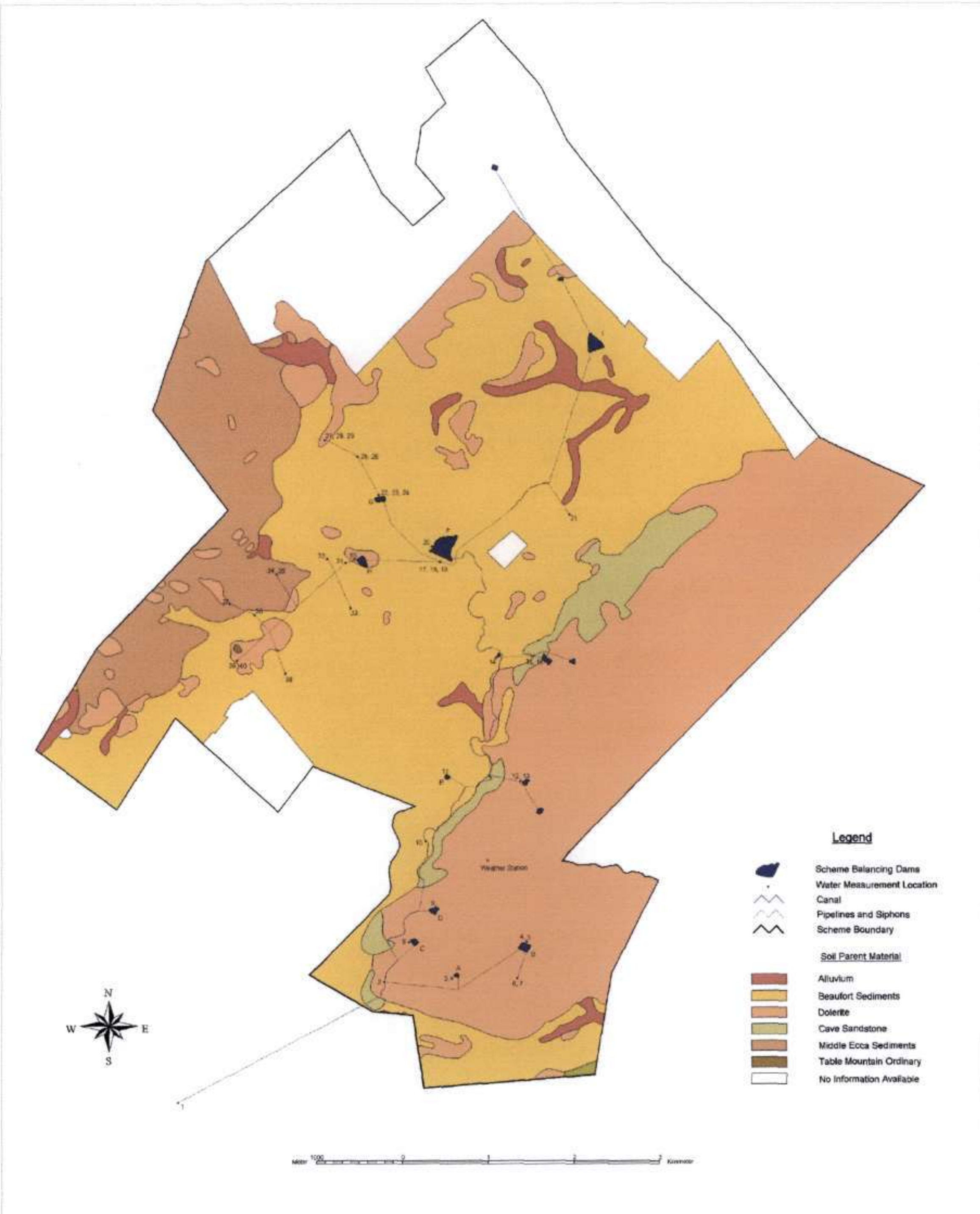

Figure 3.4 Distribution of soil parent materials in the study area (after SASRI, 2005a).

The percentages of soil parent material and soil form are summarised in Table 3.2. There is no relationship between the Soil Parent Material and the Soil Form data presented in Table 3.2. From Figure 3.4 and Table 3.2 it can be seen that the soils more suitable for irrigation were located on the North-West and South-East sides of the scheme, with the relatively poorer soils in between.

Table 3.2 Soil form and soil parent material distribution in study area (after Schmidt, 2001)

Soil Parent Material	Irrigation Suitability Class*	% Area	Soil Form	Irrigation Suitability Class*	% Area
Alluvium	1 - 2	5.1 %	Swartland	3	34.2 %
Tarkastad Sediments	3	52.9 %	Oakleaf	1	13.8 %
Clarens Sandstone	1 -2	1.9 %	Mayo	1-2	13.6 %
Dolerite	1	24.6 %	Bonheim	1-2	12.6 %
Vryheid Sediments	2	15.6 %	Glenrosa	2	11.4 %
Tugela Schist	1 -2	0.1 %	Mispah	No Data	5.7 %
			Valsrivier	No Data	3.1 %
			Arcadia	No Data	2.2 %
			Milkwood	No Data	1.1 %
			Westleigh	No Data	0.9 %
			Inhoek	No Data	0.6 %
			Shortlands	No Data	0.5 %
			Clovelly	No Data	0.1 %

* Class 1: Few limitations for irrigation purposes

Class 2: Moderate limitations for irrigation purposes

Class 3: Severe limitations - marginal irrigation soil

From Table 3.2 it is evident that five soil forms, namely the Swartland, Oakleaf, Mayo, Bonheim and Glenrosa forms, made up approximately 85.6 % of the total area. Schmidt (2001) classified each of these five soil forms into a category that described its suitability for irrigation purposes Schmidt (2001) stated that the Swartland form, which makes up 34.2 % of the area, had severe limitations in terms of poor water holding capacities and salinity hazards, and that exceptionally good irrigation management was needed to ensure water contents in the soil were at the correct levels for optimum crop production, and to prevent excess salts building up in the soil profile. The Swartland form was also prone to sodicity problems, especially if poor quality irrigation water was utilised. The Oakleaf form was the best of the five dominant soil forms with few limitations when used for irrigation. Table 3.2 shows that the Oakleaf form occurred on 13.8 % of the study area. The remaining three dominant soil forms, *viz* the Mayo, Bonheim and Glenrosa forms, were found on 37.6 % of the area and were considered to have few to moderate limitations in terms of use with irrigation.

Schmidt (2001) stressed that the information provided by the analysis of the soil parent material and soil form could only be used as a broad interpretation of any trends that may occur within the scheme. The soil information presented in Figure 3.4 and Table 3.2 was based on total farm area. In the study area, between 40 and 80 % of the total farm area was typically used for cultivation. In addition, farmers tended to cultivate those portions of the farm with better soils, and therefore Schmidt (2001) stated that the information presented should be considered as a worst case scenario.

In conclusion, it is recognised that a large proportion of the soils in the study area are difficult to manage from an irrigation point of view. Schmidt (2001) stated that the reasons for the difficult management include low soil moisture storages and moderate to poor infiltration and drainage on certain soils. Schmidt (2001) continued and stated that these complications were compounded when conventional dragline irrigation systems were used. Soils with low moisture storage capacities required frequent applications of small amounts of water to avoid water logging and excessive deep percolation, and conventional dragline systems were incapable of achieving this in practice. Schmidt (2001) also warned of potential decreased yields due to high sodicity and poor internal drainage on some of the soils.

3.3.2. Water Quality

A water quality sample was taken approximately every 2 weeks at the scheme. The samples are taken either from the river intake, or at the location on the main canal as depicted in Figure 3.2. As previously mentioned, the sample is tested for physical, organic and chemical impurities. Based on the quality of the water, the sample was classified as either A, B, C or D class water. Schmidt (2001) reported that the A class was the best and was considered to be suitable for irrigation of sugarcane. The B and C classes were considered to be moderate to poor quality water and were deemed to be unsuitable for the irrigation of sugarcane on the soils that occurred in the study area due to salinity and/or sodicity hazards. Any water that fell within the D class was considered to be completely unsuitable under normal irrigation practices due to excessive salinity and/or sodicity concentrations.

Water quality samples were first taken in October 1995, and up until the sample taken in February 2006, a total of 130 water samples had been analysed. The frequency of sampling was supposed to be one sample per month. Figure 3.5 shows the percentage of these samples that fell into the different water quality classes.

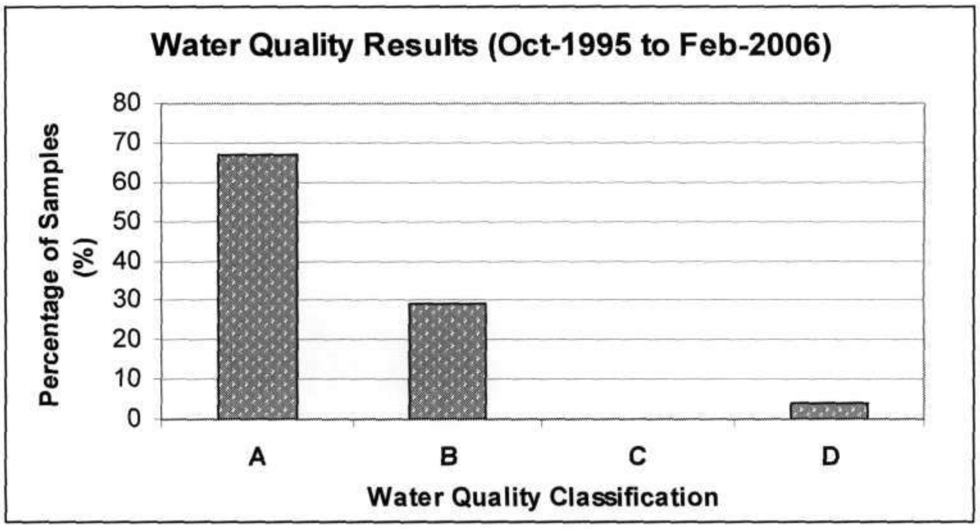

Figure 3.5 Water quality sample results for the period October 1995 to February 2006.

Figure 3.5 shows that 67 % of the water samples consisted of A class water. A further 29 % of the samples were B class water, and the remaining 4 % of the samples fell into the D category. The results show that the majority of water used for irrigation at the scheme was good. However, 33 % of the water supplied to the scheme required special management to prevent possible salinity and sodicity problems from developing in the soil. The water quality problem could be further exacerbated in areas with marginal soils. The conclusion that can be drawn was that the combination of poor water quality and marginal irrigation soils may have been a contributing factor in areas of the scheme where low crop yields occurred.

3.3.3. On-farm irrigation systems and management

Much of the irrigation management in the scheme relied on the presence of an automatic weather station located within the scheme boundary as shown in Figure 3.4. Many of the farms in the scheme relied on the automatic weather station to provide an estimate of crop water use in the area. The crop water use estimate was used both for the ordering of water, described in Section 3.1, and in the scheduling of irrigation applications. Scheduling by means of direct soil water measurement was not practiced on any of the farms within the scheme. However, many of the farms utilised a water balance, also referred to as a "profit-loss" approach, to irrigation water management. The drying-off process that was needed in sugarcane to increase stalk sucrose concentration and quality was also practiced by all the farmers on the scheme. The specific length of the dry-off process was dependant on soil type, the harvest date of the crop, and whether ripening chemicals were used to aid the dry off process, and consequently varied from farm to farm.

A number of the farms in the scheme also had maintenance programmes whereby irrigation equipment was monitored and replaced when necessary.

3.4. Key Issues in Study Area

There were many water management issues within the larger catchment in which the scheme was situated. These issues impacted on the scheme and this section describes some of these issues. Schmidt and Ashburner (2001) reported that the catchment was fully utilised in terms of water supply. Consequently, Schmidt and Ashburner (2001) stated that competition for water in the catchment was high and that DWAF had put a moratorium on the granting of any further irrigation permits. Irrigated agriculture was the largest user of water in the catchment and was allocated approximately 75 % of the utilisable water resources (Schmidt and Ashburner, 2001). Therefore, with the high level of competition for water in the catchment, and with irrigators being the largest users of water, there was considerable interest in the improvement of efficiency of irrigation in the catchment as a water conservation and demand management strategy in order to improve water supply on a catchment scale.

Another potential issue that was investigated by Schmidt (2001) was the relationship between irrigation water application and sugarcane yield in the catchment. Schmidt (2001) found that farmers in the scheme, and other schemes in the catchment, typically used 35 to 45 % of their total annual allocation. This equated to between 450 and 550 $mm.ha^{-1}$ per annum. The average irrigation demand, as calculated by the South African Sugarcane Research Institute for the design of the scheme, was 760 $mm.ha^{-1}$ per annum. The low annual application rates have been hypothesised to make a large contribution to the lower than expected sugarcane yield being obtained by farmers in the scheme. Factors which contributed to the low application rates in the scheme were attributed by Schmidt (2001) to shallow soils, which had low total available moistures, and the conventional dragline systems which were not suitable for the soil. Schmidt (2001) concluded that in order to increase the application amount, the conventional dragline systems would have to be substituted with systems that could apply a small amount of water more frequently, such as drip irrigation. However, Schmidt (2001) stated that often poor cash flow prevented farmers from converting to such systems.

3.5. Discussion and Conclusion for Study Area

An irrigation scheme with excellent water management practices had been identified as a study area in which to implement a pilot study into benchmarking irrigation water use at both scheme and farm scales. A brief introduction into the scheme management, soils, water quality, irrigated and scheduled areas, and the types and management of irrigation systems have been presented in this chapter.

Previous studies in the area have focussed on existing and potential soil related problems, possible causes for low rates of water application and on how crop yields in the scheme could be improved. These studies provide valuable information and recommended a holistic approach to seek solutions, rather than focus on specific areas alone. The excellent water metering records at the scheme enable an investigation of how efficiently the scheme was capable of delivering water to the farm boundary. The water meter records can also be used to determine the trends in the seasonal application of water on all the farms in the scheme. Such an exercise could highlight favourable practices which are evident on certain farms, and lacking on others and which improve the understanding of water use in the scheme. As noted previously, competition for water in the catchment is high and irrigators, who use the majority of the water, need to justify and prove that they are using water efficiently and effectively. What is perceived as being a high allocation of water to irrigators has been the focus of much debate. However, what is not included in these discussions is the quantification of losses that occur from when irrigation water is released from the reservoir until it reaches the farm boundary. These losses, some of which are unavoidable, need to be quantified so that more objective and informed water management decisions can be made. Therefore, quantifying water uses and losses in the scheme, including the unavoidable losses, would be of value to the scheme management in order to justify the water allocation of the irrigators.

The three different methodologies of analysing scheme performance at the scheme will be described. The first aspect was to take information available at the scheme and apply the traditional benchmarking approach with external indicators, as discussed in Chapter 2. This aspect is covered in Chapter 4. The analysis of the scheme delivery performance, which determines how efficient the scheme is in delivering water to the farm boundary, is the focus of Chapter 5. Chapter 6 contains the analysis of irrigation trends and performance from the farm boundary onwards, and provides further insight into some of the key issues that are introduced in this chapter. Each of the next three chapters contains both the methodology and results for each of the three separate aspects.

4. ASSESSING SCHEME PERFORMANCE WITH EXTERNAL PERFORMANCE INDICATORS

The external indicators reviewed in Chapter 2 were developed by recognised international irrigation organisations. Molden *et al.* (1998), Burt and Styles (1998), Burt (2001) and Malano and Burton (2001) all presented indicators which were used to describe four different aspects of irrigation scheme performance, i.e. agricultural output, water supply, financial performance and environmental performance. From the objectives specified by the larger WRC irrigation efficiency project, the computation of a set of these external indicators, in line with those calculated internationally, was required to test the suitability of the indicators in a South African context. Therefore, it was decided to compute as many of the reviewed external indicators as possible. The anticipated result from such an approach was to assess if the external indicators were of beneficial value when computed on a selection of South African irrigation schemes as part of a benchmarking exercise. The methods to calculate the set of external indicators are described in this chapter. The potential usefulness of external indicators and recommendations on how the use of external indicators could be improved, especially in the context of the larger WRC irrigation efficiency project, are also presented.

4.1. Methodology

The methodology for computing the external indicators was based on evaluating the inputs required for each indicator, and then either assessing the availability of the required inputs, or if the inputs could be estimated from existing data. In addition, confidentiality requirements that were stipulated by the scheme management meant that certain indicators could not be computed. The methodology that is presented in this section covers both those indicators which could be calculated, and those which could not be presented as a consequence of the confidentiality agreement with the scheme management. Each of these two categories are dealt with in a separate section within this chapter.

4.1.1. External indicators utilised in the study

The set of external indicators that could be calculated for the studied irrigation scheme are summarised in Table 4.1. A discussion of each indicator and how the data inputs were obtained and calculated are contained in the list presented after Table 4.1.

Table 4.1 External indicator set utilised in the study

	Indicator No.	Indicator Name	Indicator Equation
Agricultural Output Indicators	1	Total annual value of agricultural production (R)	(Total annual tonnage of each crop) * (Crop market price)
	2	Output per cropped area ($R.ha^{-1}$)	$\frac{\text{Production}}{\text{Irrigated cropped area}}$
	3	Output per unit command area ($R.ha^{-1}$)	$\frac{\text{Production}}{\text{Command area}}$
	4	Output per unit irrigation supply ($R.m^{-3}$)	$\frac{\text{Production}}{\text{Diverted irrigation supply}}$
	5	Output per unit water consumed ($R.m^{-3}$)	$\frac{\text{Production}}{\text{Volume of water consumed by crop ET}}$
Water Supply Indicators	6	Total annual volume of irrigation water delivery (m^3)	Total annual volume of irrigation water delivery
	7	Relative Water Supply (RWS)	$\frac{\text{Total water supply}}{\text{Crop demand}}$
	8	Relative Irrigation Supply (RIS)	$\frac{\text{Irrigation supply}}{\text{Irrigation demand}}$
	9	Water Delivery Capacity ratio (WDCR)	$\frac{\text{Canal capacity to deliver water at system head}}{\text{Peak consumptive demand}}$
	10	Annual irrigation water supply per unit command area ($m^3.ha^{-1}$)	$\frac{\text{Total annual volume of irrigation supply}}{\text{Command area}}$
	11	Annual irrigation water supply per unit irrigated area ($m^3.ha^{-1}$)	$\frac{\text{Total annual volume of irrigation supply}}{\text{Total annual irrigated crop area}}$

4.1.1.1. Total annual value of agricultural production (R)

The total annual value of agricultural production was an indicator which was recommended by all four of the international irrigation organisations referred to in Chapter 2. It would have been ideal to use the recommendation of Molden *et al.* (1998) and attempt to compute the standardised gross value of production (SGVP), instead of a total unstandardised value of production. The results from this study could then be compared with results from other studies at both a national and international scale. The SGVP equation required a base crop to be selected. The base crop was defined as the predominantly grown crop that is traded on the international market. Due to the fact that only sugarcane was grown in the scheme, it was the only option available for the base crop. However, unlike other crops traditionally grown in irrigation schemes, the farmer would receive income based on the product of total biomass and sucrose percentage. The sucrose is then further processed in a mill and sold on national or international markets as refined sugar. Hence it would have been difficult to determine the portion of the international sugar price that a farmer would typically have obtained for a specific crop. For these reasons, it was decided to calculate the unstandardised value of production for the scheme. This required biomass, sucrose percentage and local crop price information. The average amount of sucrose contained in the total biomass of sugarcane for the entire scheme was 13.28 % and 12.75 % for the 2004 and 2005 seasons respectively (Armitage, 2006). The total biomass production in the scheme was 198 741 tons and 209 532 tons for 2004 and 2005 respectively. As previously highlighted, to estimate the value on which the scheme farmers would be paid, the sucrose percentage was multiplied by the total biomass obtained from the scheme farmers. The local sucrose prices for the 2004 and 2005 seasons were R1297.19 and R1389.80 per ton respectively (Armitage, 2006).

4.1.1.2. Output per cropped area ($R.ha^{-1}$)

The cropped area was the total irrigated area of all the farms on the scheme. The total irrigated areas for the 2004 and 2005 seasons were 3 721 and 3 778 ha respectively. The total annual value of agricultural production obtained was divided by the cropped area.

4.1.1.3. Output per unit command area ($R.ha^{-1}$)

The output per unit command area was calculated in a similar manner to the output per cropped area with the total command area used in place of the irrigated area. The total command area of the scheme was 5 500 hectares. The total annual value of agricultural production obtained was divided by the command area.

4.1.1.4. Output per unit irrigation supply ($R.m^{-3}$)

The total output per unit irrigation supply was calculated by dividing the total annual value of agricultural production by the diverted irrigation supply.

4.1.1.5. Output per unit water consumed ($R.m^{-3}$)

The output per unit water consumed was calculated by dividing the total annual value of agricultural production by the volume of water transpired from the crop, estimated from ET. The methodology of how the evapotranspiration was calculated is described in detail in Chapter 6. The *SAsched* irrigation simulation model was used for the purpose (Lecler, 2004). A description of the *SAsched* model is provided in Appendix A.

4.1.1.6. Total annual volume of irrigation water delivery

The total annual volume of water delivery was obtained from the historical water use records compiled by the scheme management. The total annual volume is defined as the volume of water that was delivered to the farm boundary for irrigation purposes and thus excluded the losses that occurred in the scheme delivery infrastructure. This external indicator was meant to be an indication of the extent of the scheme and the water volume that is supplied. This type of indicator is similar to the ANCID tier 1 indicator. These indicators were described by Alexander and Potter (2004) as a general irrigation scheme statistic, and are intended to provide a general overview of each irrigation scheme in a benchmarking exercise.

4.1.1.7. Relative Water Supply (RWS)

The relative water supply is defined as the total water supply divided by the crop demand. The total water supply is defined by Levine (1982) as the total rainfall plus diverted irrigation supply. The crop demand was determined with a modified version of the *SAsched* crop simulation model, which is a combination of two other models, namely *SAsched*, developed by Lecler (2004) and *ZIMsched 2.0*, developed by Lecler (2003). Details of these two models can be found in Appendix A, which contains a review of suitable crop simulation models to determine sugarcane crop and irrigation water demands in South Africa. More detail on the simulation of crop ET and irrigation water demands is provided in the on-farm analysis in Chapter 6.

4.1.1.8. Relative Irrigation Supply (RIS)

The relative irrigation supply was calculated in the manner suggested by Molden *et al.* (1998). The irrigation supply was the volume of water entering the scheme at Point 1 in Figure 3.1, and the irrigation demand was determined with the modified version of the *SAsched* model. If the irrigation demand and the irrigation supply are equal, the RIS would be near unity and indicate a favourable situation. If the RIS is less than one, a situation of under irrigation is occurring, with the irrigation demand not being met by the irrigation supply.

4.1.1.9. Water Delivery Capacity Ratio (WDCR)

The WCDR was calculated using the guidelines provided by Molden *et al.* (1998). The month with the highest simulated irrigation demand was used to determine whether the maximum discharge in the canal had sufficient capacity to meet the peak requirement. The peak irrigation demand was converted into a flow rate and then compared to the maximum flow capacity of the canal. It should be noted that this methodology required an estimation of the daily duration of flow in the canal. For example, if it was assumed that the canal was operated for twenty four hours a day, instead of ten, which may have been the case in reality, the results provided by WCDR would be incorrect. The assumption made for the study area was that the canal could be operated for a maximum of sixteen hours a day. The reason for the reduction in pumping hours was that scheme management preferred not to pump water when the Eskom power tariffs were at their highest in the mornings and evenings.

4.1.1.10. Annual irrigation water supply per unit command area ($m^3.ha^{-1}$)

The annual irrigation water supply per unit command area was calculated by dividing the total diverted irrigation supply by the total command area. This indicator is used in conjunction with the results from the annual water supply per unit irrigated area to determine if land or water is constraining in the irrigation scheme. If the annual irrigation water supply per unit command area is larger than the annual irrigation water supply per unit irrigated area it indicates that the entire command area in not being irrigated. Therefore, the area of suitable irrigable land is constraining. The reasons for it being a constraint could be that the land is not suitable for irrigation from a physical basis (i.e. poor soils), or that financial constraints prevent farmers from developing the land.

4.1.1.11. Annual irrigation water supply per unit irrigated area ($m^3.ha^{-1}$)

The annual irrigation water supply per unit irrigated area was calculated by dividing the total diverted irrigation supply by the total irrigated area.

The data requirements and the methods for computing each of the external indicators listed in Table 4.1 have been introduced and discussed. The results from applying the external indicators listed in Table 4.1 are presented next.

4.2. Results

The results which were obtained from the external indicators that were computed for both the 2004 and 2005 calendar years are contained in Table 4.2. A discussion of the results presented in Table 4.2 follows.

Table 4.2 Results for calculated external indicators

Indicator No.	Indicator Name	2004	2005
1	Total annual value of agricultural production (R)	34,236,482.46	37,128,965.63
2	Output per cropped area (R.ha^{-1})	9,200.88	9,827.68
3	Output per unit command area (R.ha^{-1})	6,224.81	6,750.72
4	Output per unit irrigation supply (R.m^{-3})	2.17	2.43
5	Output per unit water consumed (R.m^{-3})	0.76	0.83
6	Total annual volume of irrigation water supply (m^{3})	15,757,900	15,284,660
7	Relative Water Supply (RWS)	1.16	0.97
8	Relative Irrigation Supply (RIS)	0.61	0.58
9	Water Delivery Capacity ratio (WDCR)	1.08	0.95
10	Irrigation water supply per unit command area (m^{3}.ha^{-1})	2,865	2,779
11	Irrigation water supply per unit irrigated area (m^{3}.ha^{-1})	4,235	4,046

It can be seen from Table 4.2 that the production indicators, Indicators 1 to 5, show that production was better in 2005 than in 2004. The better production was a result of significantly higher biomass combined with a higher sucrose price. The higher level of production was then carried trough in all the indicators that utilised it as an input. The level of production in 2005 would have been even greater if the average amount of sucrose contained in the total biomass had been the same as that of the 2004 year.

When analysed in conjunction with each other, the results of Indicator 7 and 8 reveal an interesting observation. Both RWS and RIS relate water supply and demand and give an indication of how closely supply and demand are matched (Molden *et al.*, 1998). The RWS for 2004 and 2005 is 1.16 and 0.97 respectively. A RWS of greater than one indicates that the total water application, i.e. irrigation plus total rainfall is meeting crop demand at a temporal timescale of one year. However, ideally the RWS should be significantly higher than one to account for the variable nature of rainfall that may be occurring. For example, if relatively few significant rainfall events comprise a large proportion of the total annual rainfall, it is unlikely that the rainfall from these large events will all be beneficially used, because the majority of it would be lost to surface runoff and deep percolation. Therefore, when just analysing the annual value for RWS, such rainfall events would not be accounted for and it could be incorrectly assumed that crop demand is being met. The annual rainfall values for the scheme for 2004 and 2005 were 994.5 mm and 788.5 mm respectively. A large proton of this rainfall fell within the summer season and therefore only a portion of it would have been effective. It is at this point when the values yielded by RIS become invaluable. If the RWS was close to unity and the RIS was also close to unity it would imply that the majority of rainfall was effective and that the extra water provided by irrigation was sufficient. However, if the RWS is close to unity and the RIS is significantly below unity, it would imply that the majority of rainfall was not effective and that irrigation demand was not being matched by irrigation supply. The results from the study area show that the RIS values are 0.61 and 0.58 for 2004 and 2005 respectively. This indicates that an insufficient amount of water was being applied at a scheme scale. This would have negative effects on yield and could be a contributing factor to the current yields being below expected yields.

The water delivery capacity ratio indicates that the scheme water delivery infrastructure is not a constraint to meeting the irrigation water demands. The values were 1.08 and 0.95 for 2004 and 2005 respectively. These values for WDCR were determined based on the command area of 5 500 ha and a maximum pumping duration of sixteen hours a day. In 2004 the canal capacity may not have been constraining and in 2005 the capacity may have had a slight negative effect. However, as highlighted in Chapter 3, the actual irrigated area was less than the command area and therefore the peak demand would have been considerably less and the WDCR would have indicated an even more favourable scenario with a water capacity delivery ratio of 1.44 and 1.27 for 2004 and 2005 respectively. Therefore, it can be concluded that during the peak demand months of 2004 (December) and 2005 (September), the scheme infrastructure was not constraining the application of irrigation water. However, if the actual irrigated area had to be increased to the command area, the risk of not supplying water during peak periods would increase.

The results for the Indicators 1 to 6 and 10 to 11 in Table 4.3 do not provide much useful information unless viewed in conjunction with results from other irrigation schemes. The benchmarking process, as defined by Malano and Burton (2001), requires the results and practices of an organisation to be compared with those of a more successful similar business in the market. While it may be possible to investigate performance within an organisation, the time period of investigation would have to be extended to beyond the two year time frame that was used in this instance. As previously mentioned, the larger WRC project aims to apply these external indicators to a wide range of irrigation schemes within South Africa. The results presented in Table 4.3 could then be viewed in perspective and an indication of performance, relative to other schemes in the country, can be gained.

Due to the sensitivity of certain of the indicators that were reviewed in Chapter 2, not all the external indicators were calculated. Certain of the indicators discussed were also not relevant and therefore did not need to be determined. The next section is a summary of the indicators that were not calculated and a discussion of why they were excluded.

4.3. External indicators not utilised in study

According to Bos *et al.* (1994) it is not necessary to compute a complete range of indicators for each individual scheme as certain indicators might not be relevant in certain irrigation schemes. The set of indicators that were not calculated in this study are presented in Table 4.3. A discussion of why the external indicators in listed in Table 4.2 were rejected follows.

Table 4.3 External indicator set not utilised in the study

	Indicator No.	Indicator Name	Indicator Equation
Financial Performance Indicators	1	Gross return on investment (%)	$\frac{\text{SGVP}}{\text{Cost of irrigation infrastructure}}$
	2	Cost recovery ratio	$\frac{\text{Revenue collected from water users}}{\text{Total MOM cost}}$
	3	Maintenance cost to revenue ratio	$\frac{\text{Total maintenance expenditure}}{\text{Revenue collected from water users}}$
	4	Total MOM cost per unit command area (US $.ha^{-1})	$\frac{\text{Total MOM expenditure}}{\text{Command area}}$
	5	Total cost per person employed (US $.person^{-1})	$\frac{\text{Total cost of MOM personnel}}{\text{Number of MOM personnel employed}}$
	6	Revenue collection performance	$\frac{\text{Revenue collected from water users}}{\text{Total service revenue due}}$
	7	Staffing numbers per unit command area (persons.ha^{-1})	$\frac{\text{Number of MOM personnel employed}}{\text{Command area}}$
	8	Average revenue per m^3 of water supplied (US $.m^{-3})	$\frac{\text{Revenue collected from water users}}{\text{Total annual volume of water delivery to users}}$
Environmental Performance Indicators	9	Water quality: Salinity (dS.m^{-1})	$\frac{\text{Electrical conductivity of irrigation water inflow}}{\text{Electrical conductivity of drainage water}}$
	10	Water Quality: Biological (mg.liter^{-1})	$\frac{\text{Biological load of irrigation water inflow}}{\text{Biological load of drainage water}}$
	11	Water Quality: Chemical (mg.liter^{-1})	$\frac{\text{Chemical load of irrigation water inflow}}{\text{Chemical load of drainage water}}$
	12	Average depth to water table (m)	Average depth to water table
	13	Change in water table depth over time (m)	Change in water table depth over time
	14	Salt balance (tonnes)	$\frac{\text{Salt content of irrigation water inflow}}{\text{Salt content of irrigation drainage water}}$

The scheme did not utilise groundwater for irrigation water purposes and thus the environmental indicators (12 and 13 in Table 4.3) were not computed. However, the importance of these two indicators in an irrigation scheme which utilises groundwater for irrigation is significant, and therefore should be measured and calculated where appropriate. These views are supported by Bos *et al.* (1994), Burt (2001) and Malano and Burton (2001), as discussed in Chapter 2.

The second significant point relating to the study area was that subsurface drainage was generally not used in the scheme, although a small portion uses surface drains to assist in removing excess water out of the root zone. With no significant use of subsurface drainage, it was difficult to assess representative water quality of drainage water for the scheme. The water quality of the irrigation water inflow is measured and monitored on a biweekly basis, as presented and discussed in Chapter 3. Therefore, if drainage was to be implemented in future, the water quality of the resulting drainage water should be measured and the saline, biological and chemical properties of the drainage water should be compared to that of the inflow water by calculating Indicators 9, 10 and 11 presented in Table 4.3. The external indicator which compares the salt load of the drainage water to that of the inflow water, labelled "Salt Balance" in Table 4.3, was also not calculated due to the absence of drainage in the scheme. It could be possible to take water samples in some of the larger natural drainage paths originating in the scheme to get some indication of the differences in water quality between the drainage and inflow water.

The confidentiality agreement, which was required by the stakeholders in the scheme, stipulated that no information concerning the running costs of the scheme could be divulged during the study. This requirement had to be unconditionally accepted in order for the historical water use records to be released to this study which meant that the financial performance indicators (1 - 8) listed in Table 4.3 could not be calculated. However, the Australian benchmarking initiative, which utilised the three tier approach to performance reporting as discussed in Chapter 2, could and should be adopted if the benchmarking approach with external indicators is adopted for South African irrigation schemes. This consideration is covered in more detail in the discussion and conclusions section at the end of this chapter and could be a way to protect confidential stakeholder information, while ensuring they still benefit from being involved.

4.4. Chapter Discussion and Conclusions

Some of the external indicators that were calculated provided valuable information regarding the existing situation in the scheme. The RIS and RWS provided insight into the nature of water application and it was shown that irrigation demands were not adequately met. The WDCR was also calculated. The RWS, RIS and WDCR were used in conjunction to conclude that the scheme infrastructure was not the cause of irrigation demands not being satisfied. At a scheme level, the farmers appeared to be applying insufficient water to meet irrigation demand. This confirms the findings by Schmidt (2001), that farmers were not applying enough irrigation water. Schmidt (2001) had observed that constraining farm economics, theft of irrigation equipment, not irrigating at night due to security issues and irrigations systems incapable of frequently applying small irrigation amounts were the main contributing factors for the low observed values. It was noted that the RIS and RWS did not give an indication of what period of the year the irrigation demand is not being satisfied. This prevents a temporal analysis to determine the period within the irrigation season that the under irrigation may be occurring. This will be analysed in more detail in Chapter 6 when the individual farm water application trends are analysed. It was expected that many of the calculated indicators would have yielded a much greater benefit if more irrigation schemes had been used in the analysis. For example, the output per cropped area, output per command area, output per irrigation water supply and output per water consumed, would have been more valuable if there had been other schemes in the analysis with which to compare and benchmark results. The use of these indicators is recommended for the larger WRC efficiency project where a number of schemes should be used to establish guidelines for best practice. It was unfortunate that the SGVP could not be calculated in the study area due the reasons already highlighted. However, the potential use of the SGVP, as described by Molden *et al.* (1998) is recommended for further investigation within other irrigation schemes in South Africa within the WRC project. In schemes where it is not obvious which crop to select as the base crop for the calculation of SGVP, the base crop could be determined by conducting a sensitivity analysis, considering the entire range of crops grown on any particular scheme together with their respective market values.

The selected scheme had no subsurface drainage and therefore the quality of the drainage water was not sampled. The inflow water was sampled at a frequency which is suitable for the calculation of the environmental external performance indicators described. It is recommended that if drainage systems are installed in the future, that the quality of water emanating from these systems be sampled and compared to the quality of the inflow water. Such procedures would provide insight into leaching requirements, as well as potential soil salinity or sodicity problems.

The scheme management were also unwilling to release information pertaining to the running costs of the scheme and other sensitive financial information. This was not unreasonable, given the issues that are currently present in the catchment. This was an issue which could be encountered when benchmarking other irrigation schemes. As a solution to the problem of the release of sensitive information, the Australian approach with three different tiers of indicators, each with its own confidentiality class, is suggested. For instance, only the scheme management would be able to see results from the financial performance of the scheme in relation to others, and such information would not be available to anyone except the stakeholders involved. For such an initiative to be a success, a South African equivalent of the ANCID approach to confidentiality would be required to actively pursue the concept of irrigation benchmarking with external indicators in South Africa.

The following chapter presents the methodology and results that were obtained by analysing the scheme delivery performance with multiple water balances.

5. ASSESSING SCHEME WATER DELIVERY PERFORMANCE WITH WATER BALANCES

The level of water monitoring within the scheme was excellent and historical daily water use data was available for analysis. Thus the scheme delivery infrastructure could be analysed to determine the efficiency with which the scheme was able to deliver irrigation water to the farm boundaries. The principle used to assess the scheme delivery performance was based on computing several independent water balances for the different sections of the study area.

A water balance approach requires the quantification of all water sources and destinations within the area of interest. Therefore, all of these water sources and destinations, and how they were quantified in the study area, are presented. The water sources and destinations that are included in the water balances need to be quantified and also categorized into accountable, beneficial, reasonable or avoidable classes. Descriptions of these categories and how the water was partitioned for this study are also described.

The chapter contains three main sections. The first section includes the principles and methods of, estimation and application of the water balance. The second section presents results that were obtained by utilising the water balance approach described in the first section. The third section is a discussion and conclusion on the effectiveness of the water balance approach as a method of analysing water delivery performance in the scheme.

5.1. Methodology

The different components of the water balance and how they were categorised and estimated is described here.

5.1.1. Water balance approach

As discussed in Chapter 2, all irrigation system performance assessments rely heavily on computing an accurate hydrologic water balance over the area considered (Small and Svendsen, 1992; Clemmens and Burt, 1997; Burt, 1999) and water balance approaches for assessing irrigation system performance have been widely used. Therefore, the water balance approach was selected as an appropriate method to assess the delivery performance of each of the four analysable different sections identified and introduced in Chapter 3, and illustrated schematically in Figure 3.1. The availability of data from an automatic weather station to estimate evaporation from surface water and the contribution by rainfall also enabled the water balance approach to be utilised. The following quantities of the water balance were available:

- measured water inflow to the scheme, and
- measured water outflow onto farms in the scheme.

The following components of the water balance needed to be estimated from information collected at the scheme:

- surface water evaporation from balancing dams and canals,
- seepage from balancing dams on the scheme,
- contribution of rainfall to the balancing dams and canals, and
- change in storage of the balancing dams on the scheme.

The remaining component of the water balance was deemed as unaccounted water and could be attributed to canal seepage, pipeline leaks, water management errors, dam and canal spills, errors in measurement and excessive seepage from balancing dams which were not accounted for in the water balance. The volume of water that was unaccounted for, V_{Loss}, was determined with Equation 5.1:

$$V_{Loss} = (V_I + V_R) - (V_O + V_{SE} + V_{Sest}) \tag{5.1}$$

where V_{Loss} = volume of unaccounted for water (m^3),
V_I = volume of measured water inflow (m^3),
V_O = volume of measured water outflow (m^3),
V_R = volume of water contribution from rainfall (m^3),
V_{SE} = volume of water lost to surface water evaporation (m^3), and
V_{Sest} = estimated seepage volume (m^3).

In addition to the volume of unaccounted for water, it was also possible to determine the delivery efficiency of each section of the scheme. The delivery efficiency ($DE_{\%}$) was determined using Equation 5.2:

$$DE_{\%} = \frac{V_O \pm \Delta S}{(V_I + V_R)} \times 100\% \tag{5.2}$$

where $DE_{\%}$ = delivery efficiency of the section (%),
V_I = volume of measured water inflow (m^3),
V_O = volume of measured water outflow (m^3),
V_R = volume of water contribution from rainfall (m^3), and

ΔS = change in storage over the considered temporal boundaries (m^3).

The scheme delivery efficiency quantifies the extent of losses that occur from the irrigation water source to the edge of the farm boundary. Depending on the location of water meters within a section of the scheme, the section delivery efficiency could either have been a combination of the canal conveyance and balancing dam storage efficiency, or in other cases, it would only be comprised of balancing dam storage efficiency. Once the delivery efficiency had been determined for all the sections of the scheme, the values were compared against the recommended norm of 80 % suggested by van der Stoep *et al.* (2005). The norm of 80 % applies to beneficial outflow water relative to inflow water. If 80 % of all inflow water could be beneficially accounted for, then the infrastructure would be classed as operating efficiently.

The following sub-sections describe how the geographic and temporal boundaries were defined for the scheme delivery infrastructure, and how each of the components of the water balance were determined to facilitate the computation of the scheme delivery efficiency.

5.1.2. Geographic and temporal boundaries

Geographic and temporal boundaries for the water balance approach needed to be specified. The spatial and temporal boundaries for the assessment were based on recommendations provided by Burt (1999), as discussed in Chapter 2. The 3-dimensional geographical boundaries for the scheme delivery infrastructure are presented in Table 5.1.

Table 5.1 Geographic boundaries used in the water balance for the scheme delivery infrastructure

Space	Upper boundary	Lower boundary	Horizontal boundary
Scheme Delivery Infrastructure	Water Surface	Bottoms of canal and balancing dams	All diversions, spills, and discharge points

In terms of the temporal boundaries of the assessment, the water balance was computed for the years 2004 and 2005 calendar years. The years were divided into individual weeks and the daily water use measurements recorded by scheme management were then accumulated into weekly totals for each of the 40 water meters on the scheme. The weekly totals were then used to compute the water balance for four of the five sections.

In addition to quantifying the components and boundaries of the water balance, it was necessary to classify each component in terms of whether the water loss or use is accountable, beneficial, reasonable or avoidable. Criteria for classifying the components into these different categories were presented in Chapter 2. The following list partitions the components of the water balance used to assess scheme delivery performance in the study area.

- Accountable water use within the water delivery infrastructure

Water use that could be accounted for in the scheme was water that passed though any one of the forty water meters in the scheme.

- Unaccountable water use within the water delivery infrastructure

Unaccountable water use includes losses and inputs that could not be directly measured. These include:

- surface water evaporation from balancing dams and canals,
- water seepage and leaks from balancing dams, canals and pipelines,
- water spills from balancing dams and canals,
- contribution of rainfall to balancing dams and canals,
- surface water runoff entering balancing dams and canals,
- water lost or gained through inaccurate or faulty water meters, and
- illegal abstractions.

These water losses and additions could then be further subdivided into categories based on assumptions of whether the losses are beneficial, consumptive and reasonable. The criteria for these categories were defined by Burt *et al.* (1997), discussed in Section 2.2.5. Of the losses listed above, water evaporation from balancing dams and canals was classified as a non-beneficial, reasonable and unavoidable loss. Acceptable levels of balancing dam and canal seepage were also classed as non-consumptive, non-beneficial, reasonable and unavoidable losses. Burt *et al.* (1997) defined excessive seepage and evaporation as an unreasonable loss of water and therefore should be avoided or minimised. Water spills due to mismanagement of irrigation infrastructure was classed as a non-consumptive, non-beneficial, unreasonable and avoidable loss of water. The same applied to illegal abstractions, as those can be policed. Each of the components needed to be estimated and the following sections cover the methodologies that were applied to determine surface water evaporation, dam seepage, contribution by direct rainfall and change in storage.

5.1.3. Estimating surface water evaporation

Prior to the estimation of surface water evaporation from the balancing dams and the canals, an estimate of the atmospheric evaporative demand was required. The lack of reliable A-pan data resulted in the evaporative demand being simulated with the Penman combination equation for the estimation of daily A-pan equivalent evaporation. The general Penman Equation is described by Equation 5.3 (Penman, 1948).

$$E_r = \frac{\Delta/\gamma \cdot R_n + E_a}{\Delta/\gamma + 1} \tag{5.3}$$

where E_r = reference potential evaporation (mm),

R_n = net radiation component of the Penman equation,

E_a = mass transfer component of the Penman equation,

Δ = slope of the saturation vapour pressure curve, and

γ = psychrometric "constant".

Equation 5.3 combines the two fundamental approaches used to estimate E_r. These are the mass transfer method and the energy budget approach. The use of this method to determine equivalent daily A-pan evaporation was facilitated by the automatic weather station at the scheme and the use of the *ACRU* model (Schulze, 1995), which has the Penman combination algorithms coded as an option in the model. The accumulated equivalent daily A-pan evaporation was then multiplied by an adjustment coefficient to obtain reservoir, i.e. balancing dam, evaporation equivalent. The adjustment coefficients were obtained from regional monthly coefficients developed for South Africa as shown in Figure 5.1 (Schulze *et al.*, 1995). The equivalent daily evaporation values were then accumulated into weekly totals for both of the years under consideration.

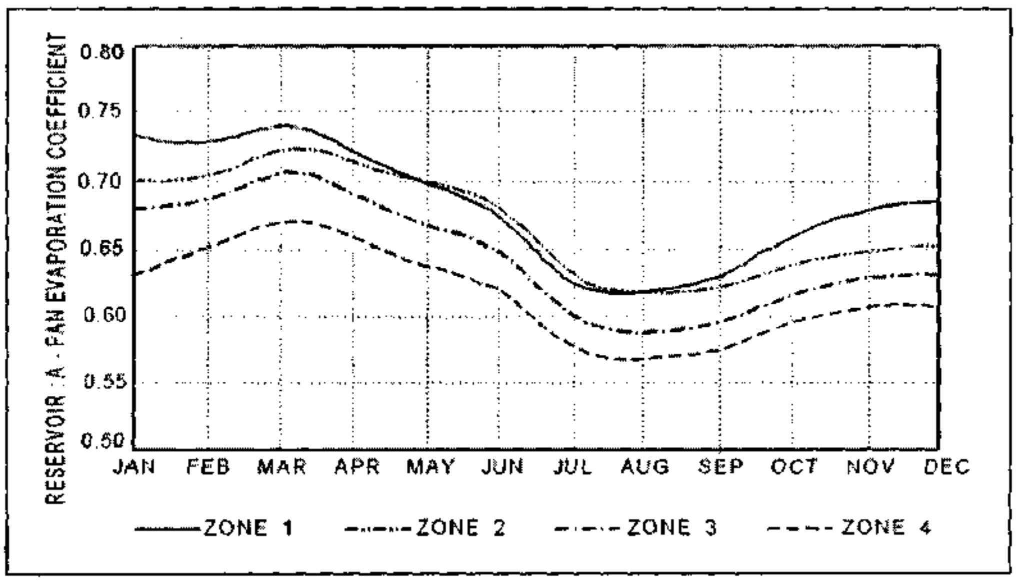

Figure 5.1 Monthly adjustment coefficients to A-pan equivalent evaporation to obtain reservoir evaporation equivalents for different zones in southern Africa (Schulze *et al.*, 1995).

The study area was situated in Zone 3, which was required in the interpretation of Figure 5.1. The four different zones found in southern Africa can be observed in Figure 5.2. The resulting monthly adjustment coefficients that were used are presented in Table 5.2.

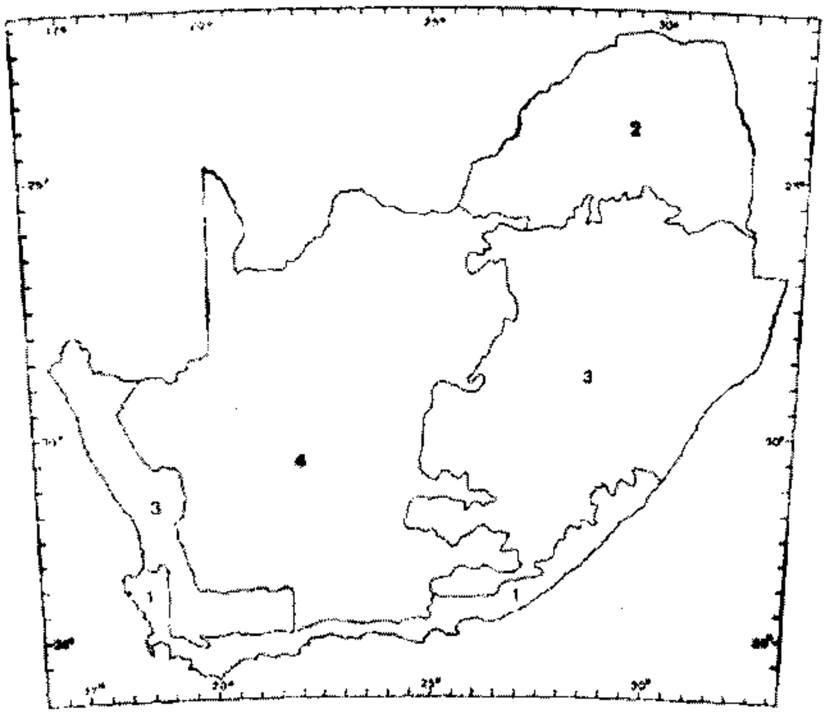

Figure 5.2 Zones of similar A-pan : S-tank relationships (Schulze and Kunz, 1995).

Table 5.2 Monthly adjustment coefficients used to determine reservoir equivalent evaporation from equivalent A-pan evaporation

Month	Adjustment Coefficient
January	0.68
February	0.69
March	0.71
April	0.69
May	0.67
June	0.65
July	0.60
August	0.58
September	0.59
October	0.62
November	0.63
December	0.64

In order to determine the monthly volume of water lost (V_{SE}, in cubic meters) due to surface water evaporation from the balancing dams and the canals in the scheme, Equation 5.4 was utilised.

$$V_{SE} = \frac{A_{WS} \cdot C \cdot E_m}{10} \tag{5.4}$$

where V_{SE} = volume of water lost due to surface water evaporation per month ($m^3.month^{-1}$),

A_{WS} = wetted surface area (ha),

C = monthly reservoir equivalent adjustment coefficient (*viz* Table 5.2), and

E_m = monthly equivalent A-pan evaporation as calculated with the Penman combination equation for estimating daily equivalent A-pan evaporation ($mm.month^{-1}$).

Equation 5.4 required an estimate of the wetted surface area. In the study area, the level of the balancing dams was not monitored on a daily basis. The water level in the canal was also not measured and recorded. Therefore, in applying Equation 5.4, assumptions regarding the actual wetted surface area of the balancing dams and canals were made in this study. These assumptions regarding the water levels surface water evaporation are presented below:

i.) *Evaporation occurred from the full supply surface area of balancing dams.* Although this assumption was not technically correct because the balancing dam levels did fluctuate daily, the dams were generally kept fairly full to ensure a reliable water supply to farms. The surface area was also captured with a Geographical Positioning System (GPS) when the dams were full, so a range of surface areas was not obtained for each balancing dam. No surface area to volume ratios for the balancing dams were available

ii.) *Evaporation occurs from the canal for 100 % of the time under investigation.* In the operation of the scheme the canal is not always full of water. Furthermore, the different sections are independent of each other due to the location of sieves and siphons. Therefore, one section could be full of stagnant water, whilst another section could be completely empty. Once pumping is initiated, the entire canal will contain water. The duration of the periods for which the canal is full or not is not recorded by scheme management, therefore such information could not be used to improve the quality of the evaporation estimate.

iii) *Evaporation was assumed to occur from the wetted surface area of the canal when the canal is at 100 % of full depth.* This would result in an over-estimate of surface water evaporation from the canal. However, it was assumed that the loss due to surface water evaporation was small in comparison to the inflow and that the assumption was acceptable in the circumstances.

Whilst these assumptions do have shortcomings, as highlighted in the discussion of each assumption, given the availability of data no improved estimates could be made. As a recommendation for further research on the performance of the scheme delivery, dam and canal levels should be recorded on a daily basis to assist in computing the evaporation component of the water balance.

5.1.4. Estimating an approximate reservoir and canal seepage

Reservoir and canal seepage are the most difficult components of the water balance to quantify (ANCID, 2000). Traditionally, once all the other components have been determined, i.e. pumped inflows and outflows, surface water evaporation, change in storage and addition by rainfall; the remaining water volume is assumed to be lost via seepage from dams and canals. This method of determining seepage, described as the inflow-outflow method by ANCID (2000), is useful for estimating seepage for long canal sections and reservoirs over a long term.

However, another method to estimate seepage from reservoirs is described by Schulze *et al.* (1995). This method assumes that daily seepage from an earth-walled and unlined reservoir may be estimated as equivalent to 0.0006 multiplied by the storage capacity of the reservoir. This is equivalent to the reservoir draining completely as a result of seepage in a time period of five years, had there been no other inflows or outflows into or from the reservoir in that period. However this method is rather a rule of thumb than an exact science, therefore the results obtained with such a calculation should be viewed in perspective. However, it was decided that reservoir seepage should be estimated with the relationship provided by Schulze *et al.* (1995) with an appropriate confidence interval. The farmers and scheme managers at the scheme were not able to provide insight into the level of reservoir seepage. Some farmers felt that the volume of seepage was excessive, whilst scheme managers disagreed and thought reservoir seepage was not substantial. As such, this investigation into the level of losses was meant to provide clarity on such issues. Therefore, the volume of unaccounted for water as described by Equation 5.1, includes canal seepage and excessive reservoir seepage that was not accounted for in the approximate estimate provided by Schulze *et al.* (1995). It is important to note that the context the Schulze *et al.* (1995) method is for catchment scale water resources assessments not for individual seepage analyses. However, obtaining accurate estimates of reservoir and canal seepage from literature was difficult and it is likely that the results from literature would be case specific and would be unlikely to improve the accuracy of these results in any case.

5.1.5. Estimating contribution from direct rainfall

The contribution from direct rainfall was included in the water balance. Daily rainfall records were obtained from the automatic weather station for the two years under consideration. The contribution as a result from rainfall was obtained by multiplying the cumulative depth of weekly rainfall with the full surface area of the balancing dams and canals. Equation 5.5 was used to determine the volume contribution due to rainfall, V_R, in each section.

$$V_R = \frac{A_{FS} \cdot R_w}{10} \tag{5.5}$$

where V_R = accumulated weekly volume rainfall (m^3),

A_{FS} = full surface area (ha), and

R_w = weekly rainfall (mm).

It must be noted that the estimate for the contribution of rainfall into the geographic boundaries would be a conservative estimate. Runoff as a result of rainfall on the areas surrounding some of the balancing dams, as well as run-off from the areas immediately above the canal would result in more inflow into the scheme delivery infrastructure. The extra inflow could potentially be a cause of inconsistent results. It was particularly pertinent for Balancing Dam F, which had a contributing catchment area of 1.5 square kilometres. During a year, the estimated runoff from this area is in the order of 135 000 $m^3.year^{-1}$ (Midgley and Pitman, 1969; cited by Schulze and Smithers, 1995), which is substantial relative to the annual scheme irrigation water passing through the dam.

5.1.6. Estimating change in storage

As mentioned previously, balancing dam levels were not recorded at the scheme. Therefore, the change in storage within the scheme delivery infrastructure had to be estimated for each year of investigation for each of the five sections in the scheme. From communication with the scheme management and observation of the scheme in operation, it was assumed that the change in storage within any section during any period would be negligible. This assumption was based on the scheme management preferring to keep balancing dams full, rather than empty, in order to ensure a reliable and equitable water supply to all the farms in the scheme. In addition to this assumption, it is worth noting that the volume of water temporarily stored and passing through any of the balancing dams on the scheme far exceeded the actual volume of the dam over the duration of a year. This observation, combined with a small error in the estimate of actual storage makes the initial assumption reasonable. This point will be further discussed in the results of the scheme delivery performance assessment. Even though the change in storage was assumed to be negligible at the scheme, it was decided to calculate the delivery efficiency for three different scenarios. The first scenario was for a change in storage of -100 %. This situation would mean that the dams were full at the beginning of the analysis and were empty at the end. This would result in increased scheme delivery efficiency because the outflow term would be increased by the storage capacity in the section. The second scenario would be for a 0 % change in storage and consequently would not have an effect on the scheme delivery efficiency. The third scenario would be for a change in storage of +100 %. This would have been caused by the balancing dams being empty at the beginning of the analysis and full at the end. Such a situation would decrease the scheme delivery efficiency because the inflow term would be increased by the storage capacity in the section.

5.1.7. Accuracy and confidence intervals

It was established in Chapter 2 that every estimate of an unknown quantity contains an element of uncertainty. It was recommended by Burt (2001) and Clemmens (1999) that each component of a water balance be assigned an associated confidence interval to account for the element of inherent uncertainty. The confidence interval of the water balance results could then be computed by applying Equations 2.3 and 2.4. The confidence intervals of the water balance parameters were estimated from the examples provided by Burt and Styles (1998) and from using the confidence intervals provided by the water meter manufacturers, Flowmetrix™. Thus the confidence intervals used for each of the parameters and the computed confidence intervals could be determined and are contained in the water balance results for each of the different scheme sections in Section 5.2.

5.1.8. Water balance trends graphs

Water balance trends graphs were produced in order to understand water use patterns within each section. Weekly totals of inflow and outflow, as measured by the water meters, were graphed to develop relative water use trends for the two years under consideration. The water balance trend graphs depicted five different aspects of water use in each section. Firstly, the relative weekly inflow and outflow in each section was plotted on the graph. In an ideal situation, these two graphs would track each other in an identical fashion, thus indicating that outflow and inflow are matched. The second two graphs showed the relative cumulative inflow and outflow in the section, and as a result of the cumulative nature of the graphs, they would increase with time and water use during the period under consideration. The graphs were relative in that the weekly values were expressed relative to the highest weekly volume (for the weekly graphs case) and relative to the total cumulative volume (for the cumulative graph case). The result is that the values never exceeded unity. If the weekly inflow and outflow graphs were equivalent, the relative cumulative weekly inflow and outflow would do the same. However, in less than ideal situations, the weekly inflow and the weekly outflow may not be equal thus causing the relative cumulative inflow graphs to diverge or converge, depending on whether there was a net loss or gain during the week. As an example to illustrate how these graphs were used, a hypothetical situation is considered where, for a period of two weeks, the weekly inflow significantly exceeded the weekly outflow as result of, for example, gross water meter inaccuracies or the loss of a large amount of water from the canals or balancing dams due to spillage. The weekly inflow and outflow graphs would not be equal, and the result would be that the relative cumulative graphs would suddenly diverge, indicating the loss. A second case might be a consistent loss or gain in the section. This situation would show the weekly inflow and outflow graphs roughly tracking each other, but they may have had slight inconsistencies over the total period. The result would be that the cumulative graphs would slowly converge or diverge, depending on whether a net loss or gain was occurring.

The last aspect that was included on the graphs was weekly rainfall, plotted on a second axis. This was used to understand the rate of water use during different seasons. For example, if substantial rainfall had occurred, the result would be that no irrigation water would be required, and water use would decrease in the section. However, if water use did not decrease after periods of significant rainfall, it would indicate that the farmers were not making use of effective rainfall and were therefore being inefficient. The water balance trends graphs are shown in the following section on results.

5.2. Results

The methodology described was applied to four of the sections in the scheme, and the corresponding results are presented in this section. Included are the water balance results, presented in table format, and the water balance trends graphs which were used as an aid to interpret the results of the water balance. The results for the entire scheme as a whole are also presented, thus providing an indication of how the scheme performed as a whole.

5.2.1. Results for section 1

Section 1 of the scheme is supplied with water from the main intake pumps at the river. A schematic of Section 1 is depicted in Figure 5.3. The volume of water entering the section from the pumps is metered by Water Meter 1, as can be seen from Figure 5.3. Section 1 of the scheme included four balancing dams and 9.143 km of cement lined canal. There were fourteen water meters that measured water exiting Section 1 onto the farms and into the other sections. The location of these meters in relation to the balancing dams can also be seen in Figure 5.3. The results for the 2004 and 2005 water balance for Section 1 are presented in Table 5.3. The significance of the results shown in Table 5.3 needs to be analysed in conjunction with the water balance trends graph shown in Figure 5.4.

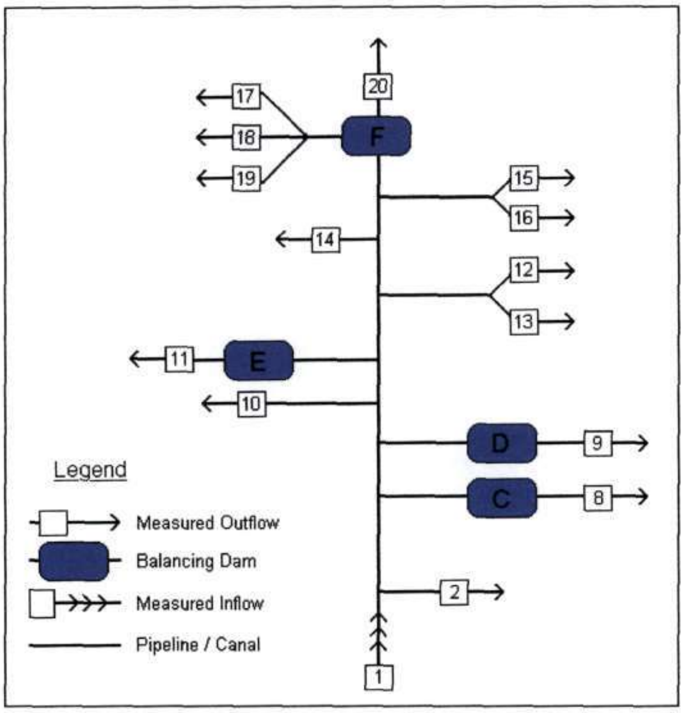

Figure 5.3 Schematic of Section 1 of the study area.

Table 5.3 Water balance results for Section 1 for 2004 and 2005

Water Balance Component	2004 (m^3)	% I (%)	2005 (m^3)	% I (%)	2004+2005 (m^3)	% I (%)	CI (%) Min	CI (%) Max
Pumped Inflow	15 757 900	99.0	15 284 660	99.2	31 042 560	99.1	-1.0	1.0
Rainfall Volume	156 967	1.0	123 627	0.8	280 594	0.9	-50.0	50.0
TOTAL INFLOW (I)	15 914 867	-	15 408 287	-	31 323 154	-	-1.1	1.1
Pumped Outflow	14 283 783	89.8	14 889 028	96.6	29 172 811	93.1	-1.0	1.0
Losses	1 631 084	10.2	519 259	3.4	2 150 343	6.9	-1.1	1.1
LOSSES DETAIL:								
Dam Seepage	115 986	0.7	113 478	0.7	229 464	0.7	-30.0	30.0
Surface Evap	164 601	1.0	154 341	1.0	318 942	1.0	-30.0	30.0
Unaccounted	1 350 497	8.5	251 440	1.7	1 601 937	5.2	-5.0	5.0

EFFICIENCY					
Storage	522 549 m^3			CI (%)	
	-100 % ΔS	0 % ΔS	+100 % ΔS	Min	Max
2004	86.5 %	89.8 %	93.1 %	-5.0	5.0
2005	93.2 %	96.6 %	100.0 %	-5.0	5.0
2004 + 2005	91.4 %	93.1 %	94.8 %	-5.0	5.0

The results in Table 5.3 indicate that in 2004 Section 1 had a delivery efficiency of between 86.5 % and 93.1 %, depending on the change in storage that actually occurred between the beginning and the end of the year. In 2005, the efficiency improved to range between 93.2 % and 100.0 %. However, the water balance results give no indication of why the efficiencies improved. Figure 5.4, which is a graph showing the relative weekly inflows and outflows from Section 1, and the relative accumulated inflow and outflow from Section 1, were used to investigate water use trends for 2004 and 2005. The weekly rainfall was also included in Figure 5.4 to assist with the understanding of the rate of irrigation water consumption within Section 1.

It should be noted that the water contribution as a result of rain falling directly on the canal and balancing dams, and the loss of water due to surface water evaporation, are approximately equal. Therefore the effect of surface water evaporation was effectively negated. It should also be noted that the loss due to surface water evaporation and the contribution due to rainfall comprise a small percentage of the total volume of water moving through the section. To illustrate this point, in 2004 the difference between surface water evaporation and the contribution from rainfall was a net loss of 7 630 m^3. Expressed as a percentage of the metered inflow into the section, the net loss was a mere 0.0485 %.

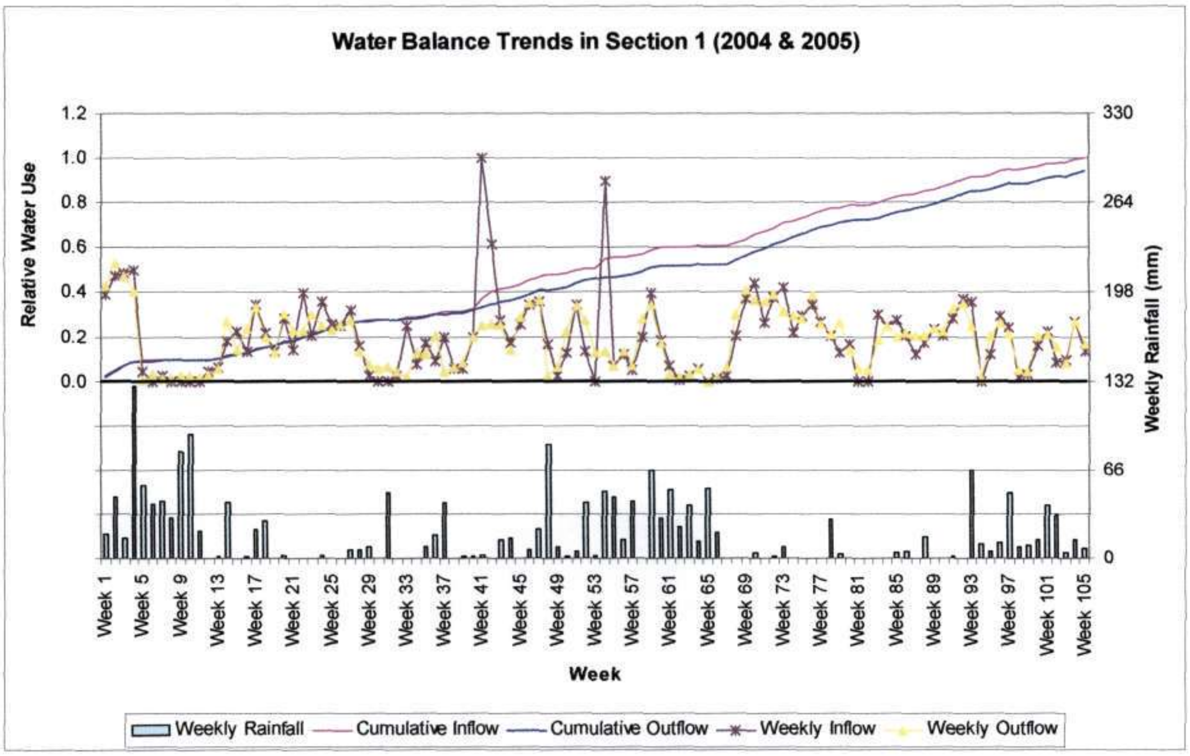

Figure 5.4 Relative weekly water balance trend results (primary y-axis) and weekly rainfall (secondary y-axis) in Section 1 for 2004 and 2005, commencing 1st January 2004.

Figure 5.4 highlights a number of water use trends and events that occurred in the 2004 and 2005 years. The first is that there were three weekly inflows that seemed to be significantly larger than all the other weekly inflow readings. These three weekly inflows occurred during week 41, 42 and 54. The result of these three inflows caused the cumulative inflow and outflow trends to diverge. Before week 41, the relative cumulative inflows and outflows were similar. Further investigation into these three inflow events revealed that the water meter at the river, which records the inflow into the section, was faulty during these three periods, and the water bailiff estimated the inflow volume. The usages which were estimated for each of the three weeks exceed the pump station capacity and are obviously incorrect. However, the error in estimation was not detected and the result was carried through the water management system and the scheme was ultimately charged by DWAF for water that was not actually used.

These three incorrect inflow values also decreased the apparent efficiency of the section and reflected negatively in the water balance, as shown previously in Table 5.3. When the data (inflow and outflow components) from Weeks 41 and 42 were excluded from the water balance analysis the efficiency for the 2004 year ranged between 95.8 and 103.2 %. When Week 54 was excluded from the analysis, the 2005 efficiency results were between 100.1 and 107.3 %. An efficiency of larger than 100 % indicates that more outflow than inflow occurred, even when considering a favourable change in storage. The reason for this inconsistency could be attributed to deep percolation and runoff losses, which occur on the farms as a result of incorrect irrigation practices, re-entering the defined geographic boundaries without being accounted for in the water balance. The contribution of runoff due to rainfall was also not accounted for, and this could also result in additional inflows into the section. Possible measurement errors could also be a cause of inconsistent results.

Figure 5.4 also shows a substantial decrease in water use during and after periods of significant rainfall. The gradient of the relative cumulative water use shows this trend by a decrease in gradient. The graph also shows higher water use in the summer periods when compared to the winter periods, once again, due to the changing gradient of the relative cumulative water use trend.

5.2.2. Results for section 2

A schematic of Section 2 is shown in Figure 5.5. The volume of water entering into section 2 is metered by Water Meter 2, as shown in Figures 3.1 and 5.5. Water exits the section via one of five water meters. There are also 2 balancing dams in Section 2. The volume entering each dam was unknown and therefore the storage efficiency of each dam could not be determined independently and consequently only the delivery efficiency for the whole section was determined.

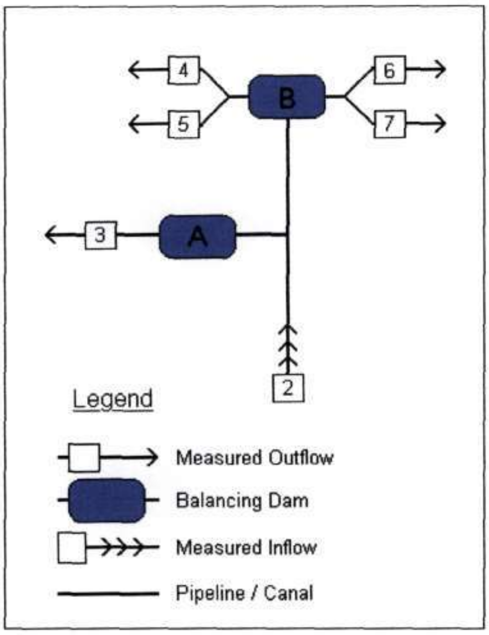

Figure 5.5 Schematic of Section 2 of the study area.

Table 5.4 contains the results of the water balance that was completed for Section 2. The water balance trend graph is presented in Figure 5.6.

Table 5.4 Water balance results for Section 2 for 2004 and 2005

	2004 (m^3)	% I (%)	2005 (m^3)	% I (%)	2004+2005 (m^3)	% I (%)	CI (%)	
							Min	Max
Pumped Inflow	1 380 379	98.3	1 331 495	98.6	2 711 874	98.4	-1.0	1.0
Rainfall Volume	24 268	1.7	19 058	1.4	43 326	1.6	-50.0	50.0
TOTAL INFLOW (I)	1 404 647	-	1 350 553	-	2 755 200	-	-1.1	1.1
Pumped Outflow	1 197 292	85.2	1 427 897	105.7	2 625 189	95.3	-1.0	1.0
Losses	207 355	14.8	-77 344	-5.7	130 011	4.7	-1.1	1.1
LOSSES DETAIL:								
Dam Seepage	26 640	1.9	26 136	1.9	52 776	1.9	-30.0	30.0
Surface Evap	25 448	1.8	23 862	1.8	49 310	1.8	-30.0	30.0
Unaccounted	155 267	11.1	-127 342	9.4	27 925	1.0	-5.0	5.0

EFFICIENCY					
Storage	120 000 m^3			CI (%)	
	-100 % ΔS	0 % ΔS	+100 % ΔS	Min	Max
2004	76.7	85.2	93.7	-5.0	5.0
2005	96.8	105.7	114.6	-5.0	5.0
2004 + 2005	90.8	95.2	99.6	-5	5

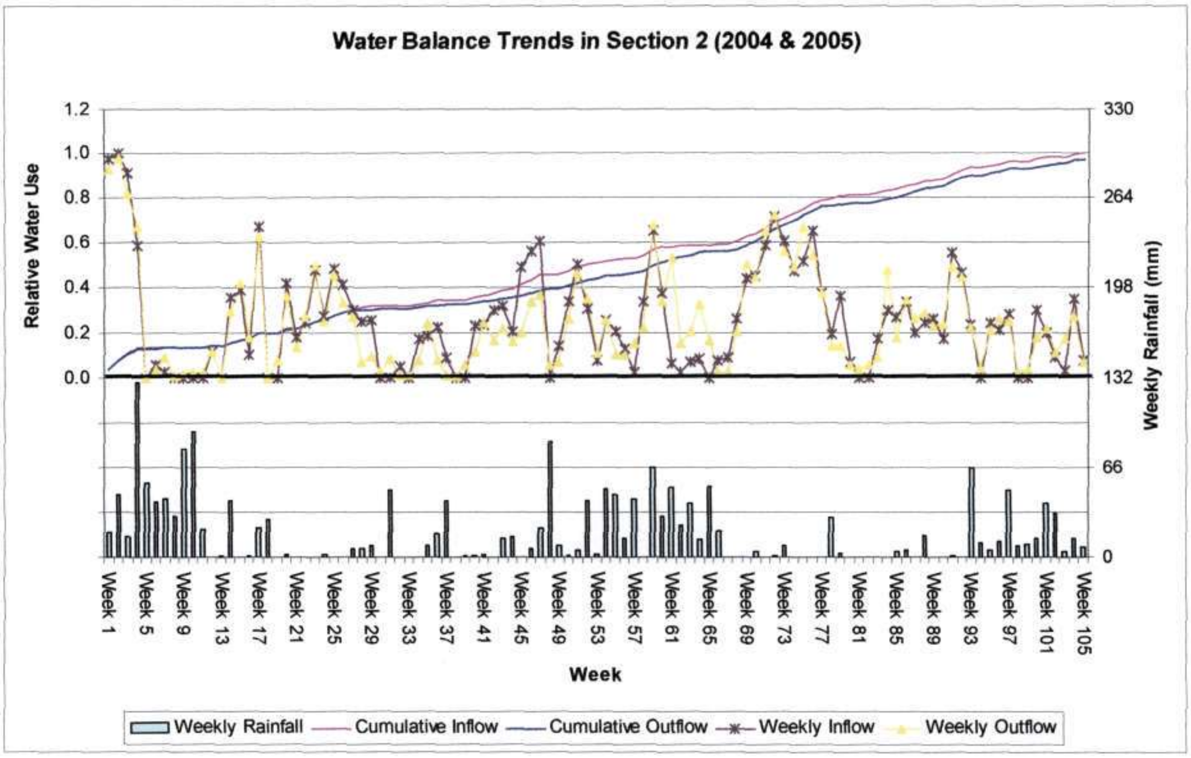

Figure 5.6 Relative weekly water balance trend results (primary y-axis) and weekly rainfall (secondary y-axis) in Section 2 for 2004 and 2005, commencing 1st January 2004.

The results presented in Table 5.4 show that there were substantial differences in the efficiency of water delivery between the two years of investigation. The efficiency increased from between 76.7 and 93.7 % in 2004 to between 96.8 and 114.6 % in 2005. The combined result of the two years yields a delivery efficiency of between 90.8 and 99.6 %. The water use trend graph in Figure 5.4 shows that in 2004, the inflow into the section exceeded outflow from the section just prior to the maintenance shutdown period in weeks 30 and 31. Then during the period from week 45 to 47, inflow once again substantially exceeded the outflow from the section. These two periods in the 2004 year are the main cause of the decreased delivery efficiency during that period. One possible cause of such inconsistencies could have been water meter inaccuracies or errors in data collection. Prior to the initial inconsistency during weeks 28 and 29 in 2004, the cumulative outflow and inflow from the section were very close, which was a favourable situation. Scheme management were unable to recall possible events leading to the period described. The contrasting results for the 2005 year were due to substantially more outflow occurring during the period from weeks 61 to 65. This can be observed in the water balance trends graph in Figure 5.6. Apart from this period in 2005, the weekly inflow and outflow in Section 2 were very similar.

From the results presented for Section 1 and Section 2, it was hypothesized that if the scheme management had access to the type of water balance information presented thus far on an ongoing and continuous basis, inconsistencies could be detected early and investigated. The result would be an increase in scheme delivery efficiency. For example, the incorrect inflow figures observed in Section 1 within 2 weeks of the error and could have been corrected. The use of these management tools would result in water and financial savings for the scheme. Therefore, there is scope to provide such a tool for scheme management to use, and this will be discussed at the end of this chapter

Section 3 of the scheme could not be analysed with the water balance approach that has been described and applied to Sections 1 and 2. This was because there was no water meter on the outflow to Dam I (see Figure 3.1) and therefore the outflow component for that section could not be determined.

5.2.3. Results for section 4

Section 4 of the scheme contained one balancing dam, Dam G, and therefore it was possible to determine the storage efficiency of this dam by utilising the water balance approach. Balancing Dam G received water from Dam F. Dam G was also situated on top of a hill and therefore there was no possibility of runoff entering the dam. There were eight farms supplied with irrigation water from Dam G. A schematic of Section 4 is shown in Figure 5.7. Section 4 was different from Section 1 and 2 because there was no canal or other balancing dams. Therefore any water that was unaccounted for in the water balance was theoretically attributable to storage losses that occurred from the single dam.

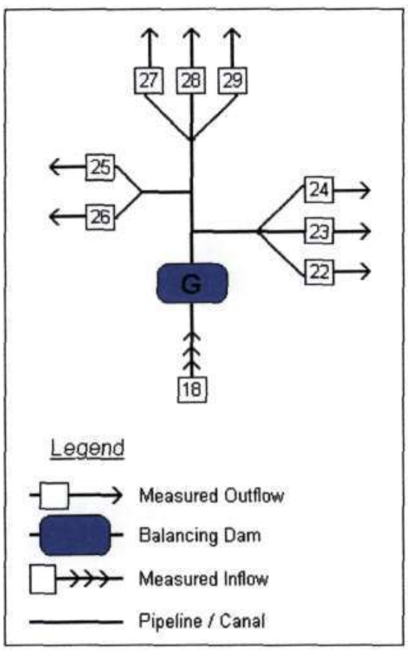

Figure 5.7 Schematic of Section 4 of the study area

The water balance results for Section 4 are contained in Table 5.5. The corresponding water balance trend graph is presented in Figure 5.8.

Table 5.5 Water balance results for Section 4 for 2004 and 2005

	2004 (m^3)	% I (%)	2005 (m^3)	% I (%)	2004+2005 (m^3)	% I (%)	CI (%)	
							Min	Max
Pumped Inflow	2 290 691	99.5	2 301 208	99.6	4 591 899	99.5	-1.0	1.0
Rainfall Volume	12 535	0.5	9 844	0.4	22 379	0.5	-50.0	50.0
TOTAL INFLOW (I)	2 303 226	-	2 311 052	-	4 614 278	-	-1.1	1.1
Pumped Outflow	2 049 590	88.9	2 076 475	89.8	4 126 065	89.4	-1.0	1.0
Losses	253 636	11.1	234 577	10.2	488 213	10.6	-1.1	1.1
LOSSES DETAIL:								
Dam Seepage	8 880	0.4	8 712	0.4	17 592	0.4	-30.0	30.0
Surface Evap	13 145	0.6	12 325	0.5	25 470	0.6	-30.0	30.0
Unaccounted	231 611	10.1	213 540	9.3	445 151	9.6	-5.0	5.0
EFFICIENCY								
Storage	40 000 m^3						CI (%)	
	-100 % ΔS		0 % ΔS		+100 % ΔS		Min	Max
2004	87.2 %		88.9 %		90.6 %		-5.0	5.0
2005	88.1 %		89.8 %		91.5 %		-5.0	5.0
2004 + 2005	88.5 %		89.4 %		90.3 %		-5.0	5.0

The results presented in Table 5.6 show that the storage efficiency for the 2004 and 2005 years were very similar in magnitude. The efficiency was estimated to range between 87.2 and 90.6 % in 2004 and was between 88.1 and 91.5 % in 2005. The combined result of the two years yielded a storage efficiency of between 88.5 and 90.3 %. When the water balance trends were analysed from Figure 5.8, it was evident that there were no obvious causes in either the inflow or outflow records that could have resulted in a loss of water. Rather, it can be seen that the cumulative inflow and outflow trends gradually diverge from one another over the entire period of investigation. This is a different trend when compared to Section 1 and 2. The nature of the gradual divergence could be attributed to seepage that may occur from Dam G, and upon communication with farmers that have fields surrounding Dam G, it seemed that there was a substantial amount of seepage that occured. However, when scheme management were shown the trend, they also discovered a substantial leak on the rising mainline from Dam F to Dam G. The leak in the pipe was the result of a faulty air valve and was a substantial leak that was assumed to have been faulty for a number of years. There was also substantial spillage from the dam that occurred in 2005 when the scheme manager failed to stop pumping water into the dam even though it was full. The dam overflowed for a number of hours and the scour valves for this section had to be opened in an attempt to lower the dam to prevent a possible dam failure. A combination of excessive dam seepage, leaking mainline and the flow from the dam could be the cause of the trend that observed in Figure 5.8. Even though there were losses and water that could not be accounted for, the overall storage efficiency of the section was 89.4 %, and consequently the delivery efficiency of the whole section was well above the recommended norm of 80 % given by van der Stoep *et al.* (2005).

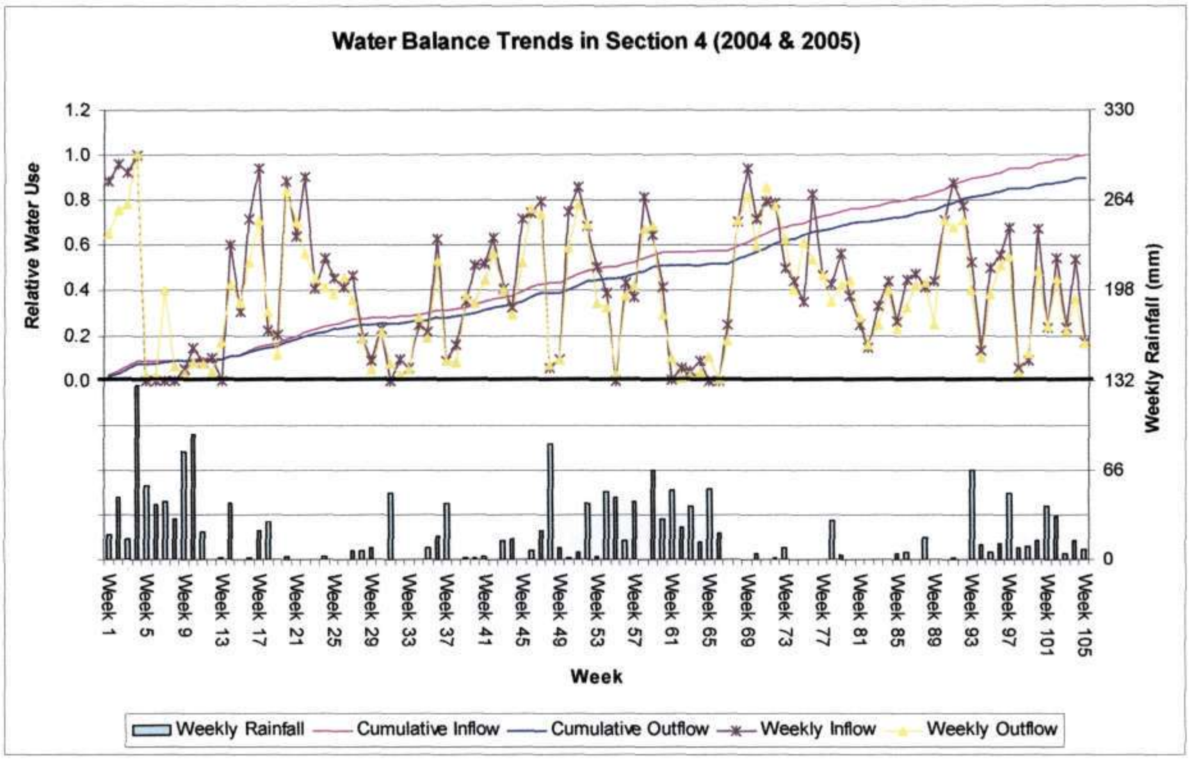

Figure 5.8 Relative weekly water balance trend results (primary y-axis) and weekly rainfall (secondary y-axis) in Section 4 for 2004 and 2005, commencing 1st January 2004.

Figure 5.8 also shows how the eight farms that abstract water for irrigation purposes from Dam G could be seen to make effective use of rainfall, and irrigation water use was decreased after rainfall. These two points are most evident from the changing gradients in the cumulative outflow trend.

Figure 5.8 could also have been used to show the scheme management that there was probably a consistent loss of water occurring in the section. Such information could have been used to induce an inspection of the rising main earlier, which would have resulted in the early detection of the broken air valve. Once again, there is a strong motivation for such a tool to be used by the scheme management to assist in weekly operations at the scheme to help with the early detection of possible inconsistencies in the water balance results.

5.2.4. Results for section 5

Section 5 of the scheme was similar in many respects to Section 4 in that there was only one balancing dam (H) and which was supplied with irrigation water from balancing dam F in Section 1. Dam H was also located on top of a hill and the only inflow into dam H is from direct rainfall and the pumped water from dam F. Eleven farms were supplied with irrigation water in Section 5. The storage efficiency of dam H was calculated using the same water balance methodology applied to all the other sections. A schematic of Section 5 of the scheme is shown below in Figure 5.9

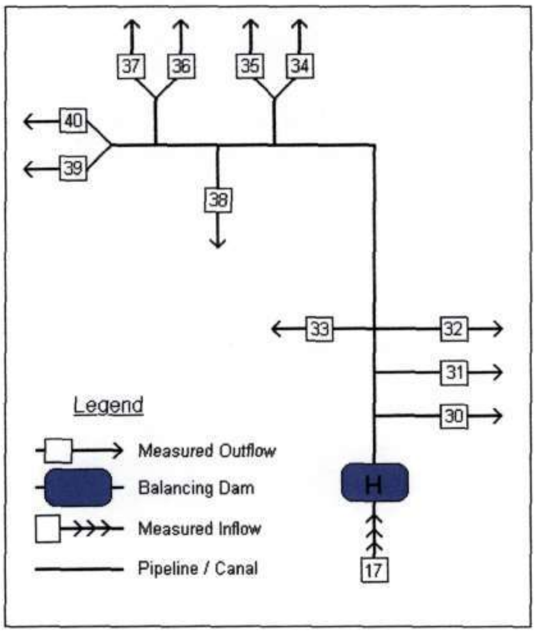

Figure 5.9 Schematic of Section 5.

The results of the water balance computations for Section 5 of the scheme are contained in Table 5.6. The corresponding water balance trends are presented in Figure 5.10.

Table 5.6 Water balance results for Section 5 for 2004 and 2005

	2004 (m^3)	% I (%)	2005 (m^3)	% I (%)	2004+2005 (m^3)	% I (%)	CI (%)	
							Min	Max
Pumped Inflow	3 746 369	99.5	3 487 492	99.6	7 233 861	99.6	-1.0	1.0
Rainfall Volume	18 050	0.5	14 175	0.4	32 225	0.4	-50.0	50.0
TOTAL INFLOW (I)	3 764 419	-	3 501 667	-	7 266 086	-	-1.1	1.1
Pumped Outflow	3 391 742	90.1	3 100 066	88.5	6 491 808	89.3	-1.0	1.0
Losses	372 677	9.9	401 601	11.5	774 278	10.7	-1.1	1.1
LOSSES DETAIL:								
Dam Seepage	13 320	0.4	13 032	0.4	26 352	0.4	-30.0	30.0
Surface Evap	18 928	0.5	17 748	0.5	36 676	0.5	-30.0	30.0
Unaccounted	340 429	9.0	370 821	10.6	711 250	9.8	-5.0	5.0

EFFICIENCY					
Storage	60 000 m^3			CI (%)	
	-100 % ΔS	0 % ΔS	+100 % ΔS	Min	Max
2004	88.5	90.1 %	91.7	-5.0	5.0
2005	86.8	88.5 %	90.2	-5.0	5.0
2004 + 2005	88.5	89.3 %	90.1	-5.0	5.0

The results presented in Table 5.6 show that the storage efficiency of dam H for the 2004 and 2005 years were very similar in magnitude. The efficiency was estimated to range between 88.5 and 91.7 % in 2004 and between 86.8 and 90.2 % in 2005. The combined result of the two years yielded a storage efficiency of between 88.5 and 90.1 %. When the water balance trends graph was analysed (see Figure 5.10) the cumulative inflow and outflows did not reveal any particular singular events that could have resulted in the above mentioned storage efficiencies. The trend depicted in Figure 5.10 was similar to that of Figure 5.8 of Section 4. Therefore, the possible causes could have been excessive dam seepage or a substantial leak in the rising mainline between dam F and dam H. The possibility of the error being related to a water meter was unlikely due to the recalibration of water meters on a two yearly cycle and because farmers pay for water on a volumetric basis. Once again, the perceptions of farmers surrounding dam H confirmed that water seepage was occurring from the dam. This perception was supported by the poor quality of sugarcane growing in the natural drainage lines emerging from the base of the wall of dam H. There was also a substantial leak discovered on another air valve in the rising main between dam F and dam H. The extent of the leak was again emphasized by the poor sugarcane growth surrounding the air valve as a result of the waterlogged conditions around the valve. These two causes of losses could have contributed to the consistent diverging trend between the relative cumulative inflow and outflow in Figure 5.10.

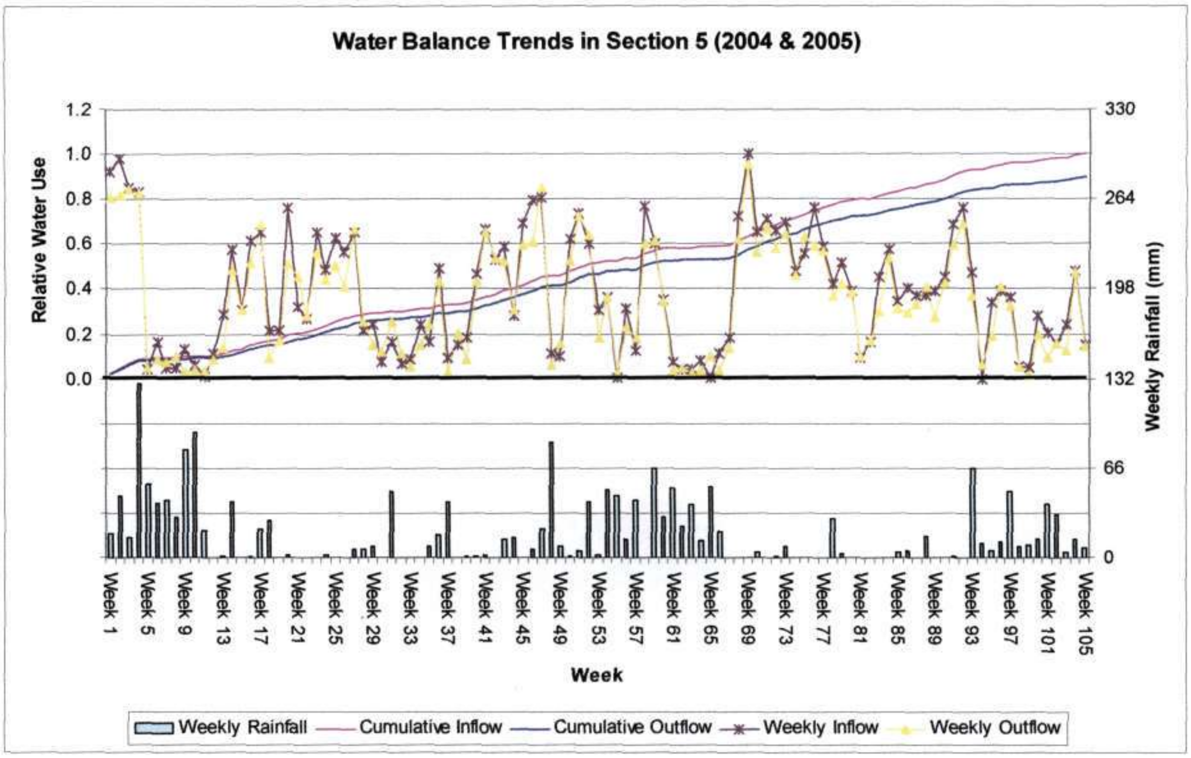

Figure 5.10 Relative weekly water balance trend results (primary y-axis) and weekly rainfall (secondary y-axis) in Section 5 for 2004 and 2005, commencing 1st January 2004.

5.2.5. Results for entire scheme

The scheme delivery efficiency of the entire scheme was also determined with a water balance. The inflow component for the scheme water balance was the water that was pumped into the main canal from the river and any contribution from rainfall. The outflow from the boundaries was water that passed through the water meters at the farm boundaries. The performance of the scheme delivery for the entire scheme was the most important as this used by DWAF to assess the scheme. The water balance results for the entire scheme are presented in Table 5.7.

Table 5.7 Water balance results for Entire Scheme for 2004 and 2005

	2004 (m^3)	% I (%)	2005 (m^3)	% I (%)	2004+2005 (m^3)	% I (%)	CI (%)	
							Min	Max
Pumped Inflow	15 757 900	98.5	15 284 660	98.7	31 042 560	98.6	-1.0	1.0
Rainfall Volume	247 019	1.5	193 984	1.3	441 003	1.4	-50.0	50.0
TOTAL INFLOW (I)	16 004 919	-	15 478 644	-	31 483 563	-	-1.1	1.1
Pumped Outflow	13 504 968	84.4	14 397 132	93.0	27 902 100	88.6	-1.0	1.0
Losses	2 499 951	15.6	1 081 512	7.0	3 581 463	11.4	-1.1	1.1
LOSSES DETAIL:								
Dam Seepage	184 260	1.2	180 276	1.2	364 536	1.2	-30.0	30.0
Surface Evap	259 031	1.6	242 886	1.6	501 917	1.6	-30.0	30.0
Unaccounted	2 056 660	12.8	658 350	4.2	2 715 010	8.6	-5.0	5.0
EFFICIENCY								
Storage	862 549 m^3							
	-100 % ΔS		0 % ΔS		+100 % ΔS			
2004	79.0		84.4		89.8		-5.0	5.0
2005	87.4		93.0		98.6		-5.0	5.0
2004 + 2005	85.9		88.6		91.3		-5.0	5.0

From Table 5.7 it can be seen that the efficiency improved from between 79.0 and 89.8 % in 2004 to between 87.4 and 98.6 % in 2005. When the two years were combined, the scheme delivery efficiency was in a range between 85.9 and 91.3 %. These efficiencies were considered to be acceptable in terms of DWAF standards. However, reasons for losses were identified in the analysis of the results. Table 5.7 shows that in 2004, 12.8 % of the water inflow into the scheme could not be accounted for and the losses decreased to 4.2 % in 2005. However, once again, the values in the water balance table give no indication of why these improvements or differences occurred. In order to understand the efficiencies, the water balance trends presented in Figure 5.11 needed to be analysed.

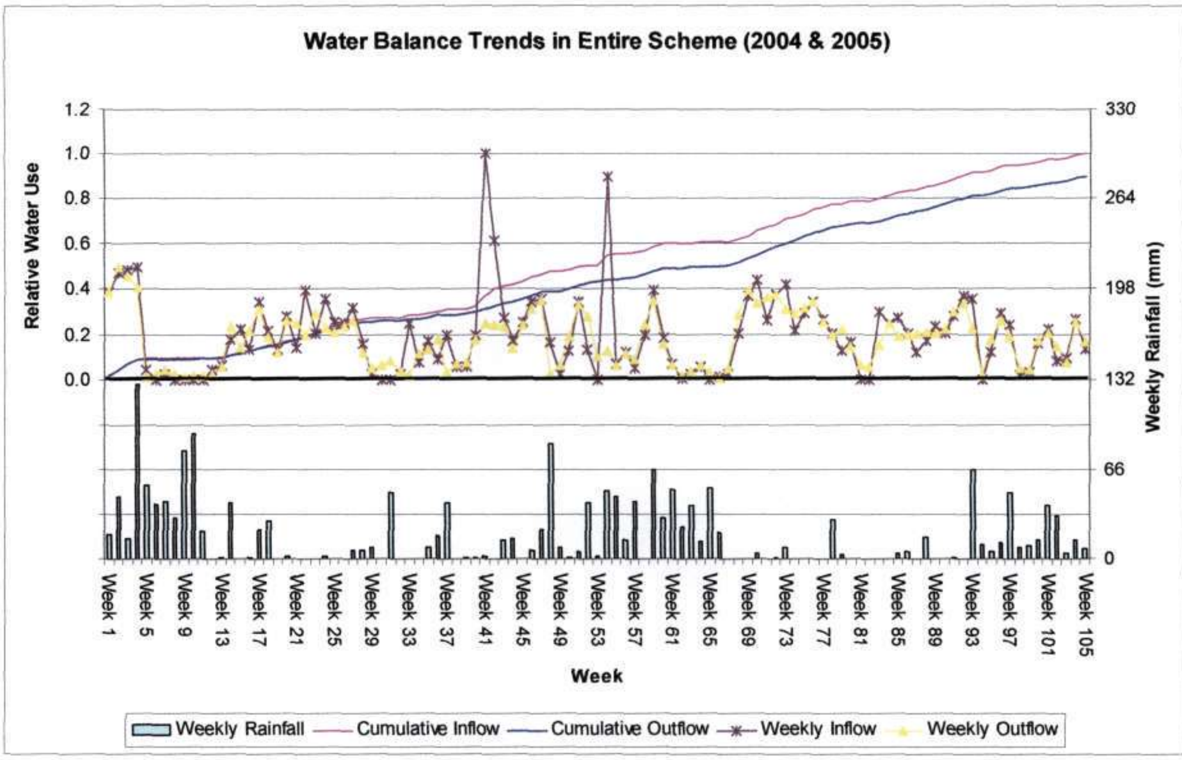

Figure 5.11 Relative weekly water balance trend results (primary y-axis) and weekly rainfall (secondary y-axis) in Entire Scheme for 2004 and 2005, commencing 1st January 2004.

The water balance trend results that are shown in Figure 5.11 reveal that the same three inconsistent water measurements that occurred at the main intakes works during weeks 41, 42 and 54 were the main cause of the 8.6 % of water that could not be accounted for. When these three inconsistent weeks were excluded from the analysis, the values for the 2004 efficiency ranged between 87.8 and 99.8 % which is a substantial improvement compared to the original figures presented in Table 5.7. The corrected 2005 scheme delivery efficiency then ranges between 93.0 and 105.2 %. The scheme delivery efficiency for the two years combined then range between 93.5 and 99.5 %. These scheme delivery efficiencies compare very favourably with the DWAF norm of 80 %.

Figure 5.11 also gives a good indication of how water use trends in the scheme vary between seasons and during and after substantial periods of rainfall. It is the author's view that Figure 5.11 clearly illustrates that the scheme is operating in an efficient manner. This efficiency applies to water supply matching water demand or outflow from the scheme, and how irrigation water use is a function of rainfall. Both these aspects have been previously discussed. Also, where inefficiencies have been observed, scheme managers were able to identify and account for reasons and occurrences when these problems occurred. As such, the scheme managers have a good understanding on the efficient operation of the scheme.

The results in Table 5.7 indicate that the surface water evaporation for the entire scheme in 2004 and 2005 was 1.6 % of the total water inflow for both years. This low level of surface water evaporation is in contradiction to results obtained in Australia by Dalton *et al.* (2001), which investigated evaporation losses from balancing dams. Findings from the Australian project revealed that surface water evaporation for four balancing dams investigated ranged between 13.9 and 38.9 % of inflow into the dams. These values far exceeded the results obtained in this project. The differences between the two sets of results were that the Australian balancing dams had a large surface area relative to the volume of stored water. The balancing dams at the scheme that was studied for this project have a far smaller surface area relative to the volume, and the volume of the dams are small in comparison to the volume of water temporarily stored in each dam.

5.3. Chapter Discussion and Conclusions

Historical water use records for the entire scheme were analysed for the 2004 and 2005 years. Several water balances were computed in order to determine the efficiency with which the scheme was able to deliver irrigation water to the farm boundary. Surface water evaporation, dam seepage, volume contribution from direct rainfall and the pumped inflows and pumped outflows were all used to determine the extent of unaccounted for, or missing water in each section.

It was concluded by the author, in conjunction with scheme management, that it would be beneficial to compute the water balances and update the water balance trend graphs on a weekly basis to assist with the early detection of possible water management problems. The result of this study into the scheme delivery efficiency revealed the benefit of analysing the scheme water use with the water balance trend graphs. When used in conjunction with a water balance, it is possible to identify inconsistencies and problems. The scheme management requested that a Microsoft Excel® Spreadsheet with the water balance results and water balance trends graphs be made available to them so that the scheme water management could be improved. The spreadsheet was made available and at the time of writing, the scheme management were utilising the water balances and trend graphs on a weekly basis to aid with water management in the scheme. The water balance methodology combined with the water balance trend graphs will facilitate the identification of the cause of inefficiencies and the nature of the inefficiencies in the future. An example would be the gross overestimation of water use in Section 1 of the scheme compared with the gradual increase in inefficiency found in Sections 4 and 5.

The recommendations provided by Burt (1999) were used to compute the water balances for the different sections and for the scheme as a whole. The correct three dimensional geographic boundaries and the corresponding temporal time scales of the analyses were correctly defined. Each estimated quantity was given an associated confidence interval and consequently the author was confident that the water balance results were within ± 5 % of the stated values.

The scheme delivery efficiencies for the entire scheme over the temporal boundaries, namely the 2004 and 2005 years, was between 85.9 and 91.3 %. These values were better than the recommended South African norm of 80 %. These efficiency values included the three obvious errors that should have been avoided, but were included in the analysis. If the inconsistent values were replaced with more realistic values, the efficiency would be in the range of 93.5 and 99.5 %. Therefore it can be concluded that the scheme was being managed in an effective manner and that there were no unacceptable losses which occurred between the scheme intake works at the river, and the respective farm boundaries, in any of the sections.

In terms of the stated project objectives, the scheme delivery performance was quantified with the use of a water balance approach. However, the water balance alone was not capable of identifying the cause of inefficiencies and the nature of any losses that occurred. The use of the water balance trend graphs assisted in understanding the losses which occurred in the scheme and how to solve them. The water balance trend graphs also could be used as a testament to water use by the individual farms in the scheme as a collective group. The water balance and the analyses thereof could also be improved by a more accurate estimate of evaporation. The water level of balancing dams and canal could be recorded on a daily basis. However, the magnitude of the evaporation losses, which were found to be less than 2 % of the total water inflow, indicated that the extra effort in improving the evaporation estimate may not be warranted.

The next aspect of the project involved analysing the scheme at an individual farm level. Water use and crop yields were investigated. Chapter 6, which is presented next, focuses on the individual farm water use and performance. This analysis involved investigating both water use and crop yield.

6. ASSESSING INDIVIDUAL FARM PERFORMANCE

In Chapter 4 and Chapter 5 the focus was on assessing the scheme performance with external indicators and water balances respectively. Analysis of the external indicators presented in Chapter 4 indicated that the farmers were not applying sufficient quantities of water during the year to meet evaporative demand at a scheme level. However, the external indicators did not show when during the year this under-irrigation was occurring, and gave little indication of the possible causes. The level of water metering at the scheme meant that it was possible to analyse any trends in the water application patterns for individual farms and compare these trends between farms and to a given standard. Such an analysis was, therefore, the next logical step in assessing irrigation performance.

The focus in this chapter is on assessing irrigation performance from the farm boundary onwards. This involved analysing water use patterns and the performance of the in-field irrigation system infrastructure. The performance of the in-field irrigation systems infrastructure was assessed in order to determine if it had an impact on the total farm water application trends, and consequently the crop yields obtained, i.e. to try and identify if the farms with a poor level of in-field irrigation system performance were also the farms with relatively low annual water applications and low crop yields. The overall objective was to identify possible best management practices and/or problem areas. This information could then be utilised by all of the farmers in the scheme, thereby contributing to an improvement in overall scheme performance.

6.1. Methodology

Only one aspect that influences crop production at a farm scale, *viz* water, was studied in the methodology. A more detailed investigation of total farm production would include all the aspects that influence crop growth, including nutrition, crop husbandry, weed and pest control, labour constraints, financial constraints, soil compaction and soil salinity and sodicity problems. An investigation into all these topics was beyond the scope of this project. Therefore, the author decided to focus on one aspect, namely the impact of poor irrigation systems performance on total annual application depths, and investigate it in more detail. This was based on the assumption that water was the primary factor limiting sugarcane production in the scheme environment.

Figure 6.1 below shows the process that was used to assess irrigation systems performance at the farm level. The interpretation of Figure 6.1 starts with the text box labelled "1" and proceeds in an anticlockwise direction.

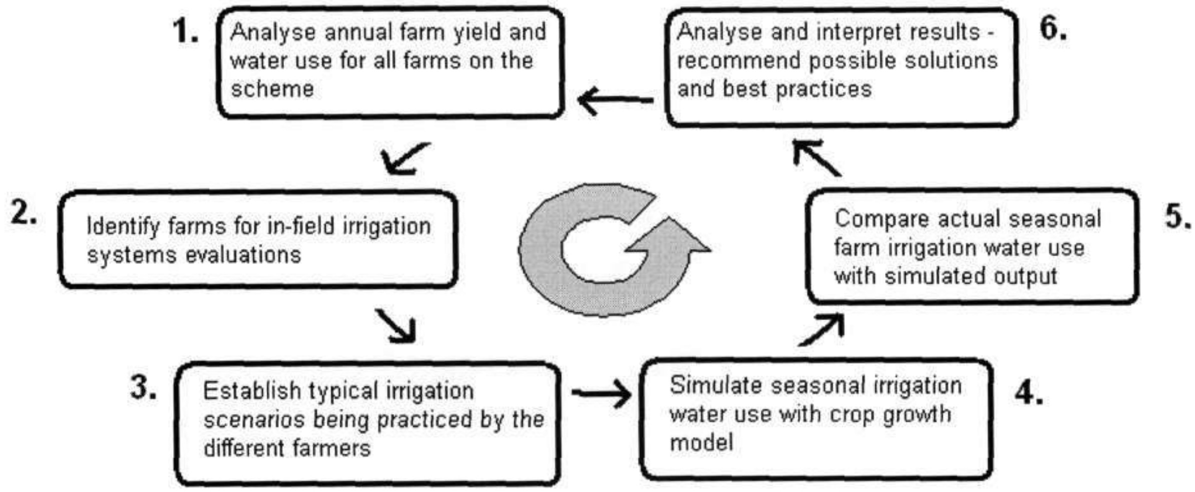

Figure 6.1 Flow diagram of methodology developed to assess individual farm performance.

6.1.1. Ranking farm performance by crop yield and net irrigation water use

Burt and Styles (1998) proposed the external indicator termed "Potential production factor", which could be used to determine if opportunities for improving agricultural production exist in an irrigation scheme (Chapter 2). Burt and Styles (1998) intended it to be used at a scheme scale and then different schemes in the same climatic region could be compared with one another. However, for this study it was decided to reduce the scale and apply the indicator at an individual farm scale. The results from the indicator would be used to create the hierarchy of farm performance in the scheme. The potential production factor indicator that was applied is described by Equation 6.1:

$$\text{Potential production factor} = \frac{\text{Potential production per hectare with irrigation}}{\text{Production per hectare with irrigation}} \qquad (6.1)$$

The potential production per hectare with irrigation was defined as the highest farm production obtained by one of the farms in the scheme. The denominator would represent the farm production under consideration. Equation 6.1 was then calculated for all the farms on the scheme, using the top production farm as the benchmark for the possible potential production that could be obtained. The results obtained for all the farms were then ranked from best potential production factor to worst to determine the range of production that occurred at the scheme. The farm production of each farm was calculated by obtaining the total farm sugarcane production, and dividing it by the actual irrigated area, to determine a production per hectare. The production and the potential production were then combined to calculate Equation 6.1. The use of Equation 6.1 also protected confidential information regarding farm sugarcane yield. The results were relative and therefore no indication of actual individual production could be determined by outside parties.

The use of the potential production factor did have some associated risks. The first of these was that the potential production was based on the highest production achieved by one of the farms in the scheme. There is a strong possibility that even the best producing farm in the scheme would have potential for improvement and this would not be reflected in the use of the potential production factor. However, it was felt that a comparison against the top producing farm would be more accepted by the farmers as opposed to a theoretical climatic potential derived from a simulation model not fully understood by the stakeholders. The second risk associated with using the potential production factor was that the results were dependant on the field area being accurate. There are often gross inaccuracies that are associated with field areas and these could be carried through into the potential production factor results. The area that was used for the calculation of the potential production factors at the scheme were based on data from an aerial photography analysis of the South African sugarcane industry. The different farm areas were therefore consistent with each other and there was no bias introduced into the analysis. If the areas had been calculated based on data supplied by the farmers, the values of farm area may have been more questionable.

Once the hierarchy of farm production had been established, it was necessary to calculate the average total annual net farm water application (NFA) of all the farms in the scheme. The water meter records were utilised, together with assumptions of on farm irrigation water losses, to calculate the NFA for all the farms on the scheme. This facilitated the comparison between the potential production factor and the NFA. The NFA ($mm.ha^{-1}.year^{-1}$), was determined with Equation **6.2.**

$$NFA = c_g \frac{\text{Total annual farm water use}}{\text{Total farm irrigated area} \cdot 10} \qquad (6.2)$$

Where c_g = conversion factor to convert gross farm application to net farm application.

The total farm irrigated area, in hectares, had already been obtained from the farmers and the scheme managers for the calculation of the potential production factor, and the total annual farm water use for each farm was obtained from the individual farm water meter records that were kept by scheme management. As mentioned previously the estimates of area were based on results from an aerial survey conducted by the sugarcane industry. The values for c_g for the drip farms and the overhead farms were 0.9 and 0.8 respectively. These were different to the SABI design norms of 0.95 and 0.7 for drip and overhead farms respectively. For the overhead irrigation farms, a factor of 0.7 was considered too low because net non-beneficial water losses from spray evaporation and canopy intercepted water are reported to be less than 10 % for overhead irrigation (McNaughton, 1981; Tolk *et al.*, 1995 and Thompson *et al.*, 1997). Therefore, the value of 0.8 was used instead.

This conversion factor also included distribution and storage losses that occurred after the water meters on the farms. The value of 0.9 used on the drip farms instead of the SABI value of 0.95 was to account for any distribution and storage losses that occurred on the farm after the water meters. On the farms that had both overhead and drip irrigation systems, the respective areas of both types of systems was obtained from the farmers, and an area weighted average of the c_g factor was calculated.

The results from the potential production factor and the NFA's were used to determine if there was a relationship between farm production and farm water use. It was hypothesised that a higher irrigation water application would result in a higher yield, and this hypothesis needed to be established with the results that were obtained. The next aspect of the methodology cycle depicted in Figure 6.1 required that several farms be selected, based on results from the potential production factor and NFA's, for in-field irrigation systems evaluations. The selection criteria that were used and the motivating reasons for the systems evaluation is covered in the next section.

6.1.2. Selecting farms for in-field irrigation system evaluations

A selection of top performing, average performing and poor performing farms were selected for in-field irrigation system evaluations based on the potential production factors and total net farm applications. The decision on which farm in each performance category would be selected, was based on evaluating the potential farm production factor and the net farm application results in conjunction with one another. If a farm had a high potential production factor but also a low total annual farm water application, that farm would be selected for further investigation. Likewise, if a farm had a poor potential production factor, but a high NFA relative to the other farms, it would also be selected for evaluations. In summary, any farm which had results that differed slightly from the commonly observed trend would be flagged as a potential candidate for an on-farm evaluation.

6.1.3. In-field irrigation system evaluations

The focus of the in-field investigations was to examine if there were any capacity constraints that were evident in any of the systems, or if the distribution uniformities were below recommended standards established by the South African Irrigation Institute (SABI). For the drip irrigation farm evaluations, the main objective was to determine the maximum system capacity, in units equivalent to $mm.day^{-1}$ of cycle. This required management information and system performance information. The management information, such as the cycle length and number of irrigated hours per cycle, were obtained from the farmers. The system performance was determined by performing in field measurements, as recommended by Koegelenberg and Breedt (2003).

For the overhead irrigation farm evaluations, similar procedures to those of the drip irrigation evaluations were followed. Management information, such as cycle length and sprinkler stand times were obtained from the farmers. Field measurements of flow rate and pressure were then obtained to determine the system capacity in units equivalent to mm.day^{-1} of cycle. Once again, the evaluations were performed by following the procedures and guidelines provided by Koegelenberg and Breedt (2003). Unfortunately, due to the time of year when the evaluations were performed (January), the sugarcane was too high to perform the rain gauge evaluations to determine the distribution uniformity of the overhead sprinkler systems.

The results from the systems evaluations, together with management and soils information obtained from discussions with the farmers were then used to simulate a selection of different irrigation scenarios with a crop growth model. The purpose of using actual observed systems performance and management data was to determine what the theoretical irrigation water requirements for different irrigations systems in the scheme were. Once these theoretical farm irrigation water requirements had been established, it was possible to compare the observed farm water use with the simulated demand.

6.1.4. Estimating crop water requirements and net irrigation demands with simulation crop growth models

A credible/reasonable estimate of the crop and net irrigation water requirements of sugarcane was of great importance to achieving the main objectives of the individual farm analysis of all the farms on the scheme. Without a credible irrigation reference, there would be no way of knowing if what occurred on the farms was within standard limits. Therefore, the focus in this section was first on the selection of a suitable model, and then on a description of the data that was required to determine crop and net irrigation water demands using the model. The method used to determine irrigation requirements for a whole farm, with fields cut at different times throughout the harvesting season (March to December) is also described.

6.1.4.1. Model selection

There were two primary reasons to identify and apply irrigation and crop growth simulation models in the analysis of on farm performance in the studied irrigation scheme. The first was to establish the recommended or "standard" crop and irrigation water demand annual time series of sugarcane grown in the study area. The second was to use an appropriate model to investigate how different irrigation system constraints and management schedules impact on water use trends. Seven models were identified and investigated as potential candidates to fulfil these two criteria. It must be noted up front that the objective of the investigations into different models was to identify a tool to assist in establishing best management practices applicable to the study area. The purpose of the analysis was not to compare and rank different models against each another, but rather to investigate the functionality and application potential in relation to the proposed methodology. The seven models that were reviewed are presented below:

- *ZIMsched 2.0 (FAO-56)*, developed by Lecler (2003),
- *ZIMsched 2.0 (ECANE)*, developed by Lecler (2003),
- *SAsched*, developed by Lecler (2004),
- *ACRUcane*, developed by Moult *et al.* (2006),
- SWB, developed by Annandale *et al.* (1999),
- SAPWAT, developed by Crosby and Crosby (1999), and
- CANESIM, developed by Singels *et al.* (1998).

It should also be noted that it was not the intended focus to undertake a detailed and complicated review of the merits and workings of each model. Such a task was beyond the scope of this research and it would not have yielded extra benefit if it had been achieved. Therefore, the review of these seven simulation models was rather completed by investigating the following questions:

- Does the model account for all the components of a daily water budget and how are the components simulated by the model?
- What level of input data/information is needed to run the model and are these readily available?
- What are the outputs of the model and how useful are these outputs?

After having answered these questions, it was also important to check that the results from the model with the required functionality were credible. Therefore, a comparison of the model outputs, relative to an accepted industry standard was undertaken. Proper verification of each model was beyond the scope of this study and had already been reported by the model developers (Singels *et al.*, 1998; Annandale *et al.*, 1999; Crosby and Crosby, 1999; Lecler, 2003; Lecler, 2004; Moult *et al.*, 2006). Each model is introduced and discussed in relation to the questions posed above, in Appendix A.

SAsched (Lecler, 2004) was selected as the model with the required functionality and characteristics. The algorithms used to compute all the aspects of the daily water balance were deemed to be conceptually sound, it had the necessary functionality in terms of representing in-field irrigation systems performance characteristics, such as the distribution uniformity, DU, and the simulated outputs under standard conditions compared favourably with those from the

CANESIM model. The CANESIM model is well accepted in the industry and could be considered as a standard. Therefore, *SAsched* was selected as the appropriate model to use for determining crop and irrigation water requirements for this study.

6.1.4.2. Soils and management inputs

Simulating the net irrigation demand required representative soils and managerial inputs for the *SAsched* model. It was also necessary to simulate the demand for a whole farm, and not for an individual field. This was because the historical water meter readings available from the scheme were at a farm, and not field, scale. Soils data were obtained from stakeholder interaction and data/information reported by Schmidt (2001). Two different Total Available Water (TAW) values were used in the simulations in an attempt to capture the variation in irrigation water requirements as influenced by soil characteristics. These TAW values were determined from Schmidt (2001), and in conjunction with communication from the farmers at the scheme. A poor soil was assumed to have a TAW of 50 mm and a good soil was assumed to have a TAW of 75 mm. These values were not verified at farms within the scheme. However, because they were selected based on values from Schmidt (2000) in conjunction with inputs from the farmers, they were assumed to be representative.

The irrigation management inputs, such as cycle length and application amount were determined from the on farm, in-field irrigation system evaluations that were conducted. The inputs enabled the computation of a range of different irrigation scenarios. The dry off process was also included, as per recommendations provided by SASRI (2005b).

6.1.4.3. Data collection

Data collection was based on meeting the input requirements for the *SAsched* model. The automatic weather station captured the full range of daily data that was required for the South African Sugar Association to calculate the daily Penman-Monteith reference sugarcane evapotranspiration, as developed by McGlinchey and Inman-Bamber (1996). As highlighted in Appendix A, *SAsched* also required daily minimum and maximum temperature, and rainfall, to calculate its daily water budget. The management inputs that were described in the previous section were obtained from discussions held with all the individual farmers and from the on farm systems evaluations that were performed. These evaluations were described in section 6.1.3.

6.1.4.4. Total farm net water applications

The seasonal simulated total net farm water application was calculated for a total farm as such, and not for an individual field. A typical sugarcane farm has sugarcane of different ages, so that a continuous sugarcane supply can be supplied to the mill. The sugarcane mill opens in April/May in autumn, and closes again in December. The crop in a field that was cut/harvested in April would be of a different age to one that was cut in December. A field that was cut in April would consequently also have had a different irrigation water requirement to the December field, because it reached full canopy cover at a different time in the year. These different harvest times and crop ages needed to be simulated and then combined, so that a typical farm water trend could be obtained. The method that was used was to assume that a farm had sugarcane of nine different ages, with the first crop cut in April, and the last cut in December, i.e. one crop cut per month.

Each field was simulated and then a total farm time series of irrigation water requirements was determined. This calculation was further complicated by the temporal boundary of the calculation. For example, to determine the total 2004 water use, the 2003 crops would have to be simulated, and the portion of the irrigation that was carried into 2004 would be included, i.e. if a farmer cut a field in April 2003, there would still be irrigation occurring on that field in January to April in 2004, prior to the crop be cut once more in April 2004. The seasonal time series was determined by adding the irrigation for each of the nine fields during any week to form the farm total time series.

6.1.5. Observed seasonal farm irrigation water application trends

To obtain the seasonal farm irrigation water trends, the individual daily farm water use volumes were combined with the individual farm irrigated areas, to obtain the weekly net farm water application ($mm.ha^{-1}.week^{-1}$). The weekly net farm applications were then accumulated for both the 2004 and 2005 years. The accumulation amounts were plotted and used to determine the different trends of water application for the farms in the scheme. The water application trends included typical farm practices, such as the dry off process, and hence the process of 'drying-off' cane was represented in *SAsched* simulations.

The time series of individual cumulative farm water applications was analysed in order to compare the irrigation application trends of different farms relative to one another. The comparison was both in terms of the total amount applied, and of when each grower applied water. This was done because two different farms may have both applied the same amount of water in the year, but the manner in which it was applied could have been different. The one could have put on a constant amount continuously throughout the year, whilst the other may have applied more during summer than winter. If the yields from these two farm trends were also taken into consideration, it could become evident that a certain application is more advantageous than others. The simulated irrigation requirement as determined with the *SAsched* model also assisted in the interpretation of which application pattern was better relative to a simulated model output. The criterion for this interpretation between observed and simulated applications was based on two factors. The first was an assessment of the total depth of water applied relative to the simulated values, and the second was the temporal distribution with which the total depth was applied relative to the simulated values. An observed application that matched the simulated application in both magnitude and temporal distribution was assumed to be better that an observed application that was the same in annual magnitude but differed in temporal distribution. The same would apply to an application that had a similar temporal distribution to that of the simulated application but differed substantially in the annual application depth.

6.2. Results

The first aspect of the on-farm methodology was to obtain the total farm yields and areas, in order to determine the potential production factor of all the farms in the scheme. The potential production factors were then ranked from best to worst, and compared to the total annual farm water use of each farm. Following this, in-field evaluations were performed on a selection of the farms. The selected farms were chosen from the potential production factor results. After the evaluations were completed, simulations with *SAsched* (using irrigation system and management inputs from the evaluations) produced a theoretical irrigation requirement time series. Finally, a comparison of the observed trends for the 2004 and 2005 seasons were compared to the theoretical irrigation requirement time series. The results presented in this section follow in sequence to the description provided.

6.2.1. Potential production factors and total net farm irrigation water applications

The potential production factor results for each individual farm in 2004 are presented in Figure 6.2 The corresponding 2004 relative net annual farm water application, ranked according to the 2004 potential production factor, is shown directly after in Figure 6.3.

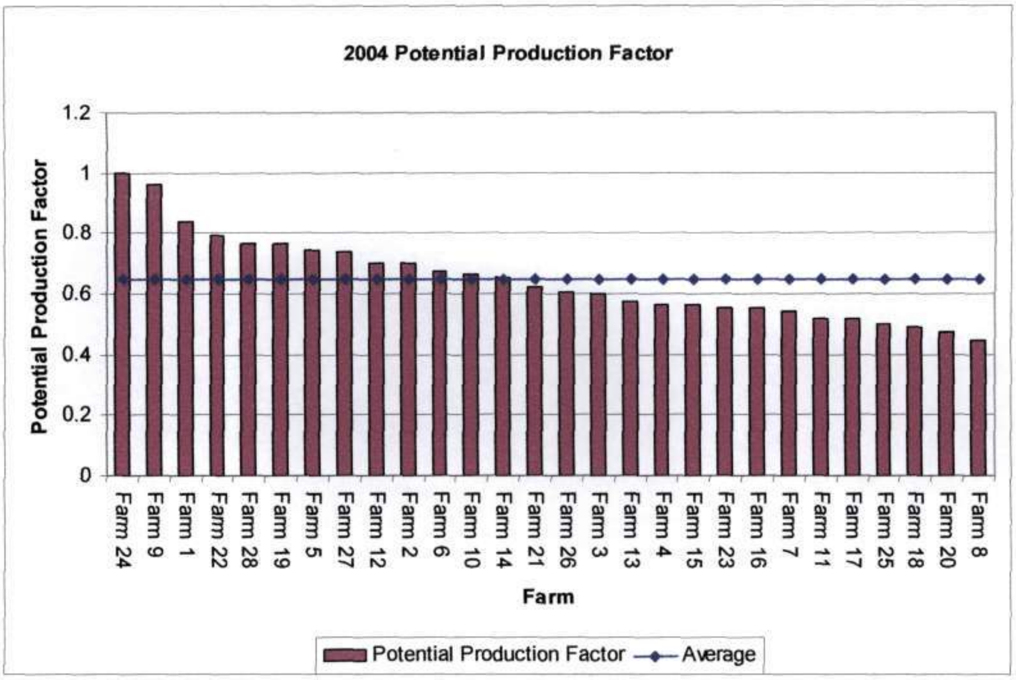

Figure 6.2 Ranked 2004 Farm Potential Production Factor.

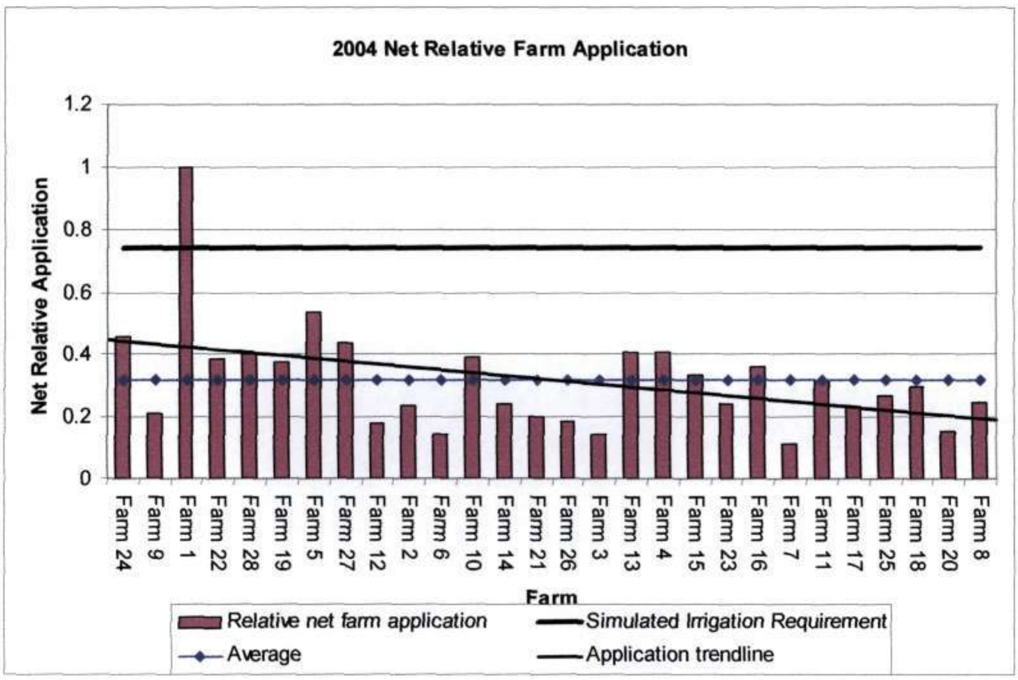

Figure 6.3 2004 Net Relative Farm Applications corresponding to the Potential Production Factors.

The 2005 results are presented in Figures 6.4 and 6.5 below. A discussion of both the 2004 and 2005 results for the potential production factor and the corresponding annual net farm water application are presented after Figures 6.4 and 6.5.

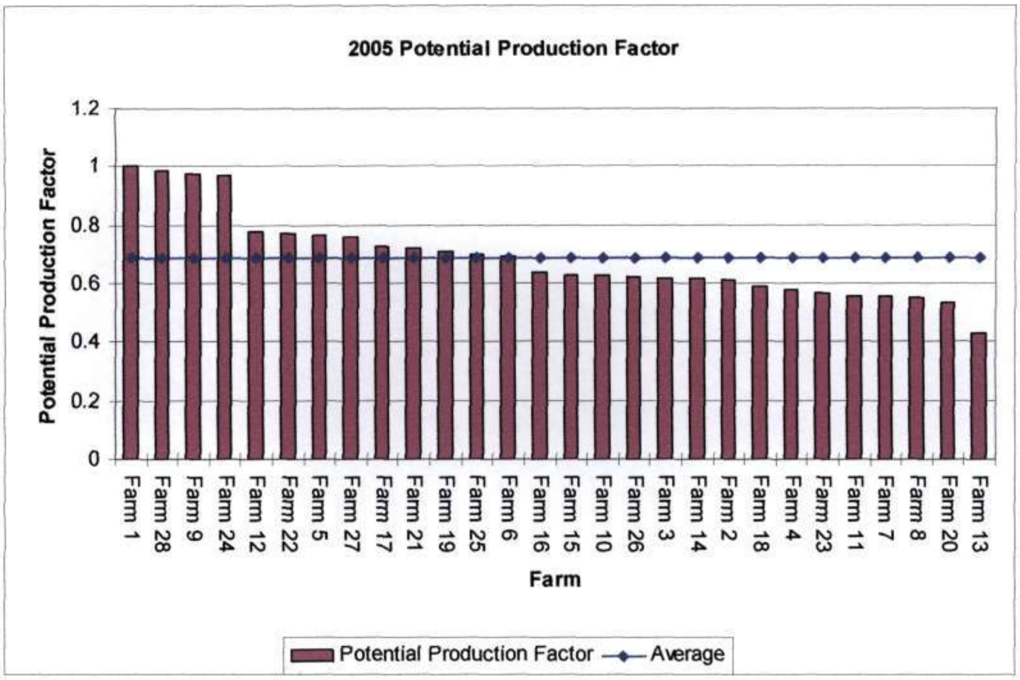

Figure 6.4 Ranked 2005 Farm Potential Production Factor.

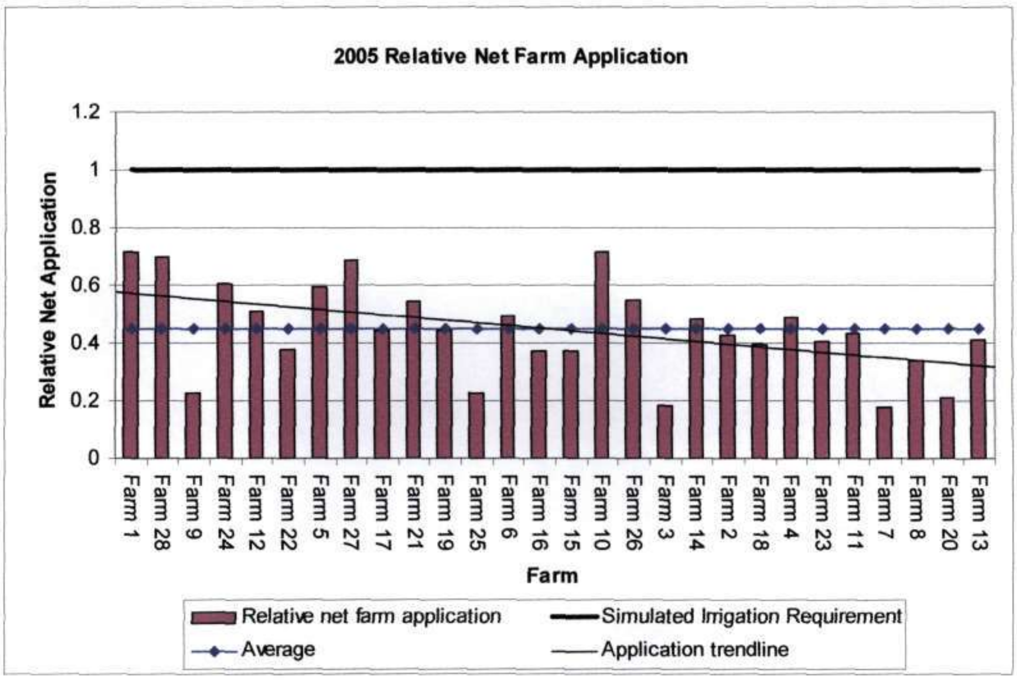

Figure 6.5 Corresponding 2005 Net Relative Farm Applications corresponding to the Potential Production Factors.

A large variation in the potential production factor was observed in both the 2004 and 2005 years. The farm with the greatest potential for improvement had a potential production factor of just over 0.4. Therefore, the potential for improvement relative to other farms in the scheme was large. However, the farm with a potential production factor of 1, which means it was the best production farm in the scheme, also has potential to improve. This was because the potential production factor was based on the highest observed farm yield. But, evidence from model simulations shows that higher yields were still obtainable, even from the better performing farms in the scheme. The simulated crop yields were 30 % higher than the best observed yields and the relative net farm application graphs are low relative to the simulated net irrigation water requirement. Even the top performing farms were applying far less than the theoretical demand as calculated with the *SAsched* model and thus if more water was applied to these farms it is likely that the yields would increase as a consequence.

The water application trend line that is shown in Figures 6.3 and 6.5 reveals that the better performing farms in the scheme generally applied a greater amount of water relative to the poorer performing farms. This is further evidence that a higher water application could produce a better yield and this is explored further in the sections which follow. It must be emphasised, however, that farm production is not totally dependant on water application alone. Soils, management and different farming practices will all have a significant impact on crop production. These different aspects of farm management were not the focus of this research, but they cannot be discounted from having had a significant effect on the crop yields. The possibility of soil influencing farm production was investigated by utilising the soil parent distribution map that was presented in Chapter 3. The conclusion from Chapter 3 did point out that the better soil parent materials (Dolerite and Clarens Sandstone), occurred in the South East border of the scheme. The farms in this area of the scheme were the better performing farms. This is especially noticeable with Farm 9, which was ranked second and third for 2004 and 2005 respectively. Farm 9 is located in the South East of the scheme on the dolerite soils, and has a very low net water application relative to the other farms in the scheme. Yet, Farm 9 was a top performer. Thus the location of the farm, with the good soils, was likely a major contributing factor for the good production. The farmer on Farm 9, also believed that the good dolerite soils on the farm were a large contributing factor for the good production.

Figure 6.6 below is a scatter plot of the 2004 and 2005 potential production factor and net farm water application data. The pattern of data plotted in Figure 6.6 supports earlier observations that higher water applications resulted in higher yields.

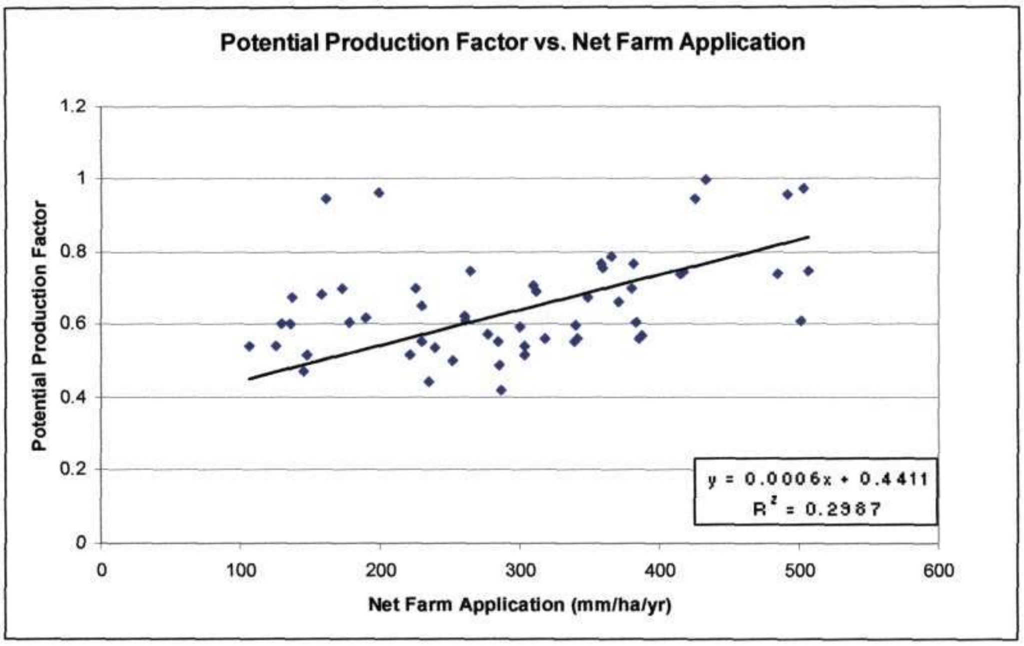

Figure 6.6 Relationship between annual potential production factor and annual net farm irrigation water application.

The two points in the scatter plot that had an excellent potential production factor, with a net farm application that was low relative to the other farms in the scheme were those of Farm 9, that, despite having a low net farm application, performed very well in both 2004 and 2005. The trend shown in Figure 6.6 also corresponds with recommendations of Schmidt (2001), who suggested a higher irrigation water application to increase farm production.

The scheme managers and the farmers in the scheme were not surprised that application depths were too low. However, they were unaware of exactly when the low application rates were the worst, and how the seasonal trends for each farm differed within the year. In order to reveal the nature of the application trends and examine how these trends could have an impact on crop yield, and consequently farm production, the observed results were compared to a theoretical irrigation requirement.

A theoretical irrigation requirement is very dependant on the type of irrigation system, the water application schedule and the characteristics of the predominating soils. The results from the on-farm system evaluations, and a description of which systems capacities, soils and management scenarios were used in the *SAsched* simulations to determine the theoretical irrigation water requirements, follows.

6.2.2. In-field irrigation system evaluations

The infield irrigation systems evaluations were performed on the following farms:

- Farm 9 - drip irrigation,
- Farm 1 - drip irrigation,
- Farm 22 - combination farm, overhead irrigation evaluated,
- Farm 17 - drip irrigation,
- Farm 12 - drip irrigation,
- Farm 24 - overhead irrigation, and
- Farm 20 - overhead irrigation.

These farms were selected based on the potential production factors and annual net farm application results. Farm 9 was of particular interest because the farm had relatively high yields, yet relatively low net water applications. The results of the in-field evaluations of the drip irrigation farms are presented below in Table 6.1

Table 6.1 Pertinent irrigation system evaluation results for evaluated drip irrigation farms

Farm and System Information	DU (%)	SU (%)	CV (%)	Measured gross application per day of cycle ($mm.day^{-1}$)
Farm 9 Dripper: 2.3 $l.hr^{-1}$ Netafim RAM Spacing: 2.6 x 1.0 m Schedule: 6 hrs every day	95.7	96.6	3.44	5.45
Farm 1 Dripper: 1.2 $l.hr^{-1}$ Netafim RAM Spacing: 2.74 x 0.8 m Schedule: 12 hrs every day	90.2	92.4	7.59	6.57
Farm 17 Dripper: 2.3 $l.hr^{-1}$ Netafim RAM Spacing: 3.0 x 1.0 m Schedule: 12 hrs every day	76.9	63.0	37.03	5.25
Farm 12 Dripper: 2.3 $l.hr^{-1}$ Netafim RAM Spacing: 2.68 x 1.0 m Schedule: 6 hrs every 2.5 days	86.1	91.0	8.99	2.47

Note: DU = Distribution Uniformity

SU = Statistical Uniformity

CV = Coefficient of Variation

From the results presented in Table 6.1 it can be seen that the Farm 9 drip irrigation system was capable of applying a gross application of 6.8 $mm.day^{-1}$ of cycle, and the Farm 12 system had a capacity of 2.47 $mm.day^{-1}$ of cycle. These were the best and worst case scenarios for system capacity among the drip irrigation farms that were evaluated. The other two farms had relatively high system capacities of over 5 $mm.day^{-1}$. Although Farm 17 had a relatively high system capacity, the distribution uniformity of 76.9 was below the recommended SABI norm of 90 %. The distribution uniformities of the other systems were acceptable. From Table 6.1, the scenario that was selected to represent a 'good' system was to simulate a system with the capacity to apply a 6mm application every day. The 'poor' system was a system with a capacity to apply a 5mm application every two days. These two scenarios were based on the measurements taken from Farm 9 and Farm 12.

Table 6.2 presents the results that were obtained from the overhead irrigation system evaluations. In total, three systems were evaluated.

Table 6.2 Pertinent irrigation system evaluation results for farms with overhead sprinkler irrigation systems

Farm and System Information	Average Pressure and pressure variation	Nozzle size and wear	Flow variation	Measured gross application per day of cycle ($mm.day^{-1}$)
Farm 24 Cycle: 9 days Stand time: 8 hours Spacing: 18 x 18 m Average delivery: 1.24 $m^3.hr^{-1}$	3.22 bar (30.45 %)	4.8 mm (5.2 %)	13.1 %	3.4
Farm 22 Cycle: 6 days Stand time: 6 hours Spacing: 18 x 18 m Average delivery: 1.73 $m^3.hr^{-1}$	3.20 bar (20.20 %)	4.8 mm (4.9 %)	12.8 %	5.5
Farm 20 Cycle: 6 days Stand time: 8 hours Spacing: 18 x 18 m Average delivery: 1.17 $m^3.hr^{-1}$	2.25 bar (27.18 %)	4.4 mm (6.2 %)	17.6 %	4.8

Table 6.2 shows that the gross application capacities of the irrigation systems ranged from 3.4 $mm.day^{-1}$ to 5.5 $mm.day^{-1}$ of cycle. The schedule with which these amounts were determined are presented in the first column of Table 6.2. Evaluations did not include rain gauge assessments of distribution uniformity because the sugarcane was of too tall. Nevertheless, the remainder of the

evaluations were completed following the recommendations of Koegelenberg and Breedt (2003). The SABI norms state that pressure variation should not exceed 20 % and that flow variation should not exceed 10 %.

A low system capacity of 3 $mm.day^{-1}$ of cycle, and a high capacity of 5.3 $mm.day^{-1}$ were used to represent the worst and best case scenarios for the overhead irrigation simulations. These were used in two different irrigation scenarios described as follows:

- a sprinkler stand time of six hours and a cycle length of six days, i.e. facility to apply 32 (high capacity) or 18.5 mm (low capacity) every 6 days, if required, and
- a sprinkler stand time of ten hours and a cycle length of ten days, i.e. facility to apply 53 mm (high capacity) or 30 mm (low capacity) every 10 days.

Having established representative irrigation system capacities and the water management strategies based on the results of the in-field evaluations, representative soil depth and water holding characteristics needed to be determined for the simulations. Soils in the scheme were generally shallow with low total available moisture. For the purposes of the simulations, it was decided to use two representative total available moisture (TAM) values for the *SAsched* simulations. The poor soil, representing the worst case scenario, would have a TAM of 50 mm. The soil representing a good situation had a TAM of 75 mm. These values were based on surveys reported by Schmidt (2001) and were agreed upon in conjunction with the farmers.

6.2.3. Simulated net irrigation requirements

Table 6.3 shows the simulated net irrigation requirements for overhead irrigation in the study area for 2004 and 2005. The results are shown for the two different soil TAM values, two different cycle lengths and two different system capacity limitations.

Table 6.3 *SAsched* simulated net overhead irrigation water demands. Highest values highlighted in blue, lowest values highlighted in red

Irrigation Schedule	2004 ($mm.ha^{-1}.year^{-1}$)	2005 ($mm.ha^{-1}.year^{-1}$)
Overhead irrigation - Poor Soil (TAM = 50 mm) 10 day cycle, 53 mm application	518.3	585.5
Overhead irrigation - Poor Soil (TAM = 50 mm) 10 day cycle, 30 mm application	518.3	585.5
Overhead irrigation - Poor Soil (TAM = 50 mm) 6 day cycle, 32 mm application	669.3	694.5
Overhead irrigation - Poor Soil (TAM = 50 mm) 6 day cycle, 18.5 mm application	566.2	621.7
Overhead irrigation - Good Soil (TAM = 75 mm) 10 day cycle, 53 mm application	577.9	607.0
Overhead irrigation - Good Soil (TAM = 75 mm) 10 day cycle, 30 mm application	493.3	566.7
Overhead irrigation - Good Soil (TAM = 75 mm) 6 day cycle, 32 mm application	585.7	628.5
Overhead irrigation - Good Soil (TAM = 75 mm) 6 day cycle, 18.5 mm application	469.6	521.0

Note: TAM = Total Available Moisture

Table 6.3 shows the results from the eight different irrigation scenarios that were simulated with the *SAsched* model. The highest and lowest applications for each year are highlighted in blue. The annual values in 2004 ranged from a low of 469.6 $mm.ha^{-1}.year^{-1}$ to a high of 669.3 $mm.ha^{-1}.year^{-1}$. In 2005, the low was 521.0 $mm.ha^{-1}.year^{-1}$ and the high was 694.5 $mm.ha^{-1}.year^{-1}$. Table 6.3 also shows a number of trends that help explain the large variation in annual irrigation demand when different irrigation management practices are used on soils with different TAM values. These trends are revealed and discussed in the list below.

- With the same irrigation schedule, soils with a low TAM will always result in a higher irrigation demand than soils with a high TAM. This was because rainfall was more effective on a deeper soil, and therefore, the number of irrigation water applications required would decrease.
- On the same soils, a system that applies a low irrigation amount frequently resulted in a higher irrigation application than a system that applies a larger irrigation amount less frequently.

- On the same soils, systems with the same cycle time but different capacities will apply different quantities of water. A system with a good capacity will always apply more water than a system with a poor capacity. This applies to soils that have a TAM that is higher than the irrigation system is capable of applying in a typical cycle.

It must be reiterated that the inputs for the simulation results were based on field measurements. Therefore, the observed net farm water applications should have been in between the envelope formed by the lowest simulated irrigation demand and the highest simulated irrigation demand. Table 6.4 shows the simulated net irrigation requirements for drip irrigation in the study area for 2004 and 2005. The results are shown for the two different soil TAM and two different net application capacities.

Table 6.4 *SAsched* simulated net drip irrigation water demands. Highest values highlighted in blue, lowest values highlighted in red

Irrigation Schedule	2004 ($mm.ha^{-1}.year^{-1}$)	2005 ($mm.ha^{-1}.year^{-1}$)
Drip irrigation - Poor Soil (TAM = 50 mm) Capacity to apply 6 mm every day	706.0	735.3
Drip irrigation - Poor Soil (TAM = 50 mm) " 5 mm application every 2 days	511.9	568.3
Drip irrigation - Good Soil (TAM = 75 mm) " 6 mm application every day	650.7	670.7
Drip irrigation - Good Soil (TAM = 75 mm) " 5 mm application every 2 days	482.2	541.4

Note: TAM = Total Available Moisture

The highest net irrigation demand for both 2004 and 2005 occurred when a drip system with good capacity was used on shallow soil, and a poor TAM of 50 mm. These values are highlighted in blue in Table 6.4. The lowest irrigation demand for 2004 and 2005, highlighted in red, occurred when a drip irrigation system with poor capacity was used on a good soil with a TAM of 75 mm. These findings can be explained in the same manner as the overhead irrigation scenarios. For the same irrigation system, a soil with a higher TAM always resulted in a lower irrigation application than a soil with a lower TAM. This was due to the higher effective rainfall simulated for the deeper soil. It is also a logical outcome that a drip irrigation system with a poor capacity will apply less water than a system with a good capacity. These observations were confirmed by the simulations, as shown by the results in presented in Table 6.4.

6.2.4. Seasonal farm irrigation water application trends

The annual net farm water applications of the farms in the scheme were low relative to a simulated irrigation demand. Results obtained by using the historical water meter records to determine seasonal watering patterns or trends are shown here together with patterns obtained for the highest and lowest simulated irrigation water requirements. This facilitates a comparison between what the farmers should be applying, and what they actually were applying, for both high and low system capacity and soil constraints. The graphs for the drip irrigation farms are presented in Figure 6.7 and Figure 6.8 for 2004 and 2005 respectively. The 2004 and 2005 graphs for the overhead irrigation farms are presented in Figure 6.9 and Figure 6.10. Finally, the graphs for the farms with both drip and overhead irrigation systems are shown in Figure 6.11 and Figure 6.12 for 2004 and 2005 respectively. The most important aspect shown by all the seasonal application graphs are the upper and lower limits of the net irrigation water requirements that were determined using the *SAsched* model. Ideally, if all the farms were applying water according to scientifically based recommendations, all the seasonal water application trends should fall in the envelope between these two simulated net irrigation water requirement trends.

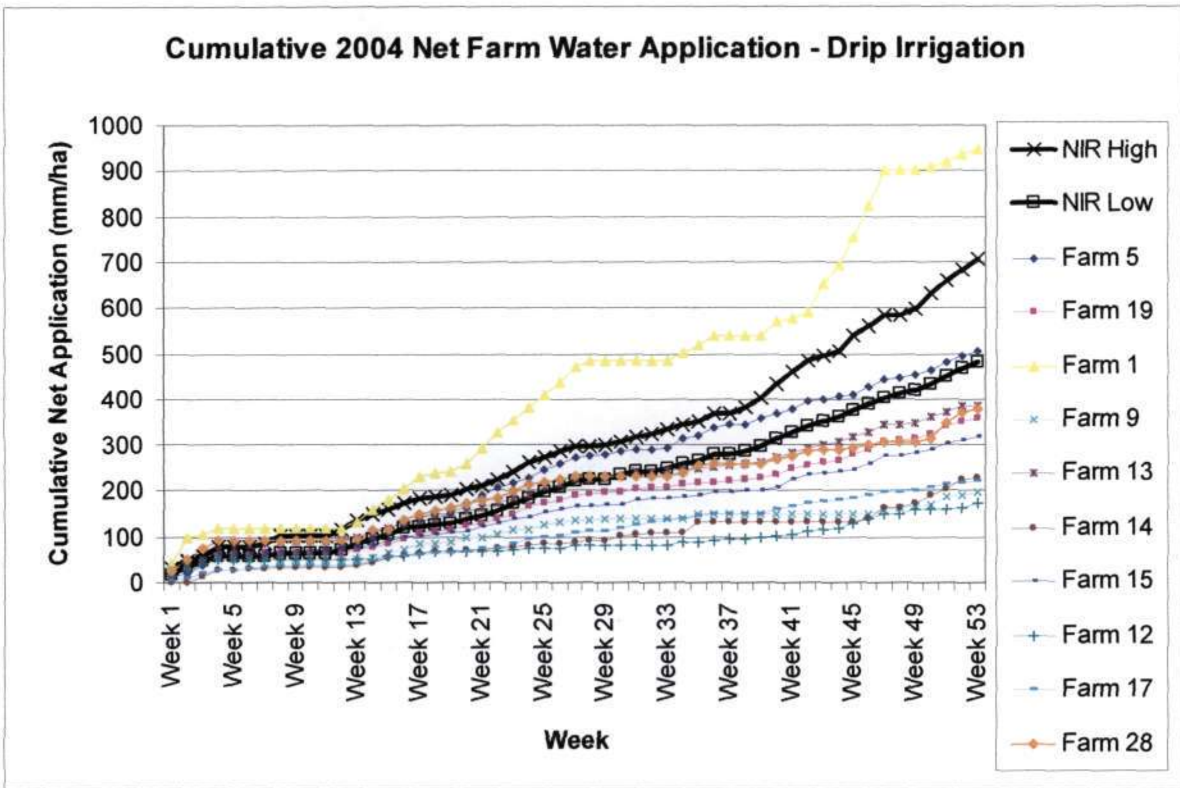

Figure 6.7 Cumulative 2004 net farm water applications for drip irrigation farms.

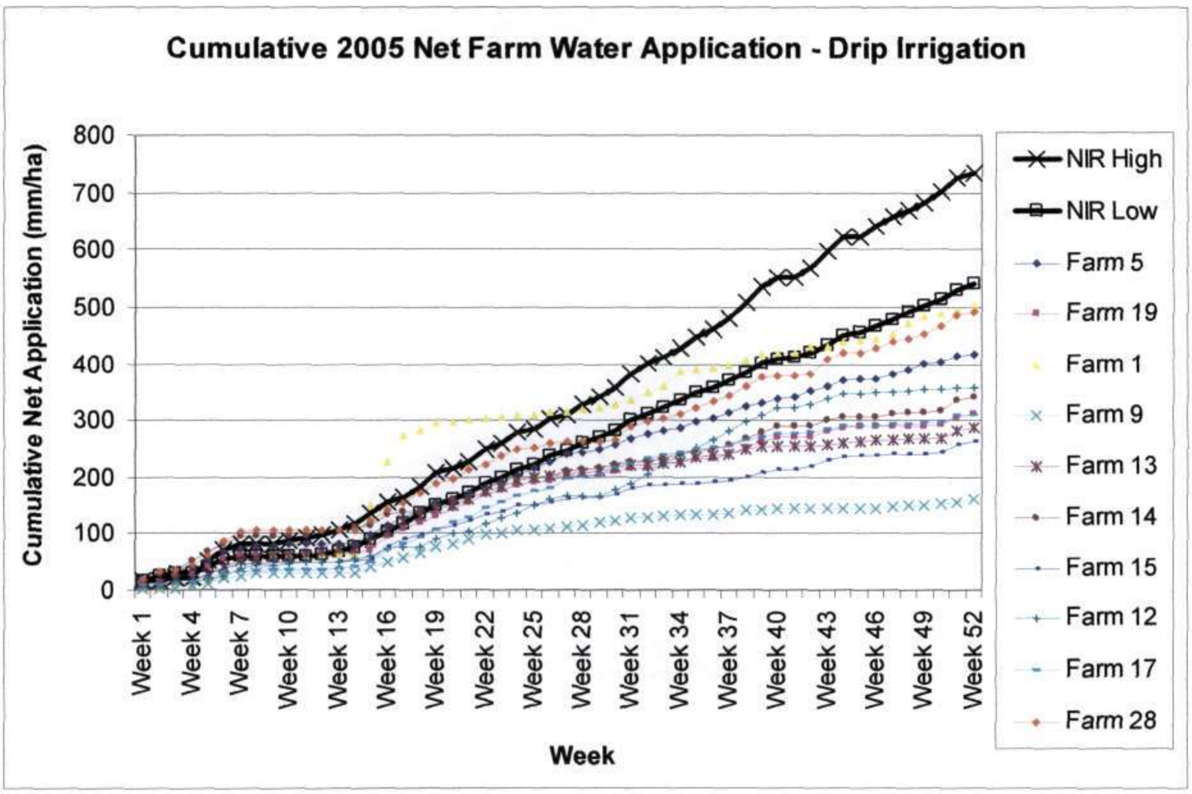

Figure 6.8 Cumulative 2005 net farm water applications for drip irrigation farms.

Figure 6.7 and Figure 6.8 reveal how the majority of the drip irrigation farms in the scheme are applying an insufficient quantity of water relative to the *SAsched* simulated amounts. In 2004, only Farm 1 and Farm 5 applied amounts within the simulated envelope. The figures also show that a number of the farms, such as Farm 9, 12, 14 and 17 apply a very small amount of water relative to the simulated requirements. This is particularly noticeable in the late spring and early summer period when the simulated demand starts to increase, shown by the change in gradient, but the observed results fail to show the same trend.

It must be noted that in simulations with the *SAsched* model no adjustments for forecasted climate events were made. In reality, in a situation where there was a good probability of rainfall in the near future, many farmers would not irrigate, or reduce their irrigation, in the hope of making effective use of the expected rainfall. This lack of prediction in the *SAsched* model would result in the simulated irrigation requirements being higher than the observed water applications because the model did not make these modifications and changes to the simulated irrigation schedules. However, it is believed that this was only a contributing factor as to why the observed results were so much lower than the simulated results and could not be deemed to be the major cause for the large discrepancies between the observed and simulated trends. The use of rainfall forecasts may, however, help explain differences between different farmers. Those farmers who were more optimistic about imminent rainfall would most likely have a lower irrigation water use compared to those who were more risk averse. The risk exists because to reduce irrigation in anticipation of rainfall could lead to severe crop stress later in the cycle if the rain does not materialise and the irrigation systems lack the capacity to 'catch up'.

The 2004 and 2005 net farm application results for all the overhead irrigation farms in the scheme are shown in Figure 6.9 and Figure 6.10.

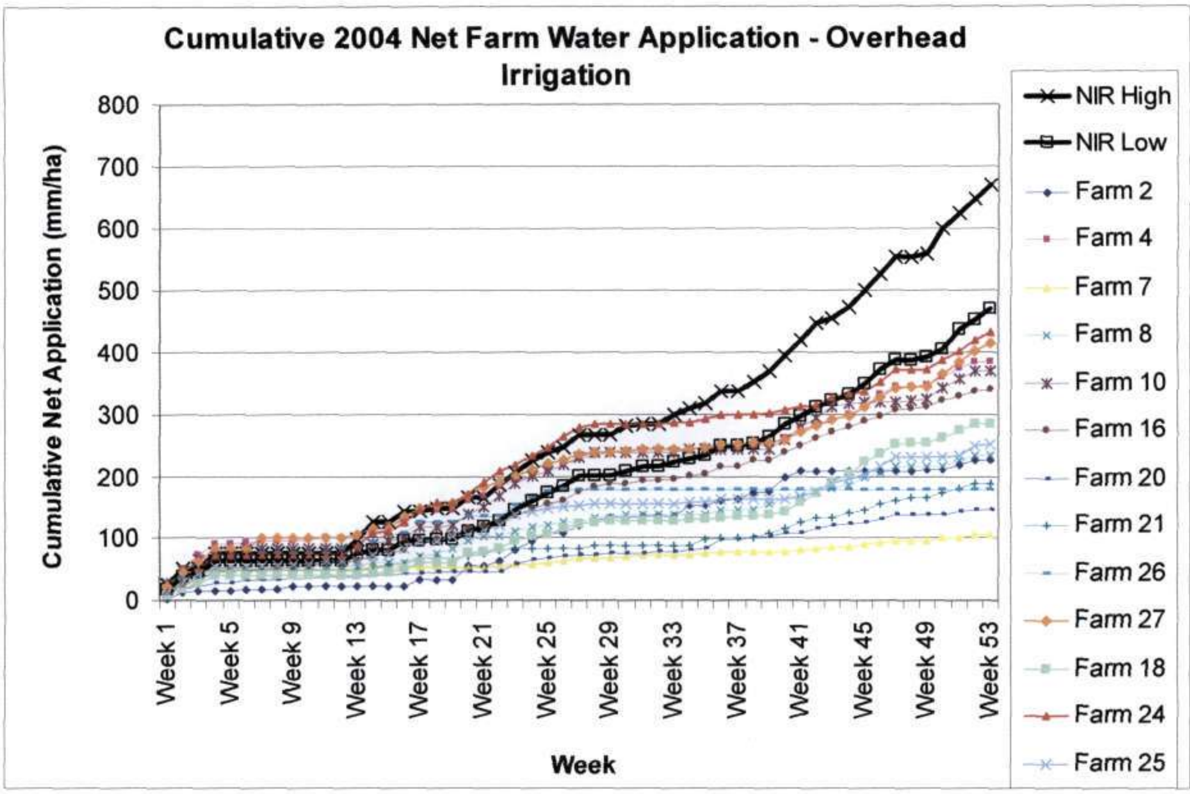

Figure 6.9 Cumulative 2004 net farm water applications for overhead irrigation farms.

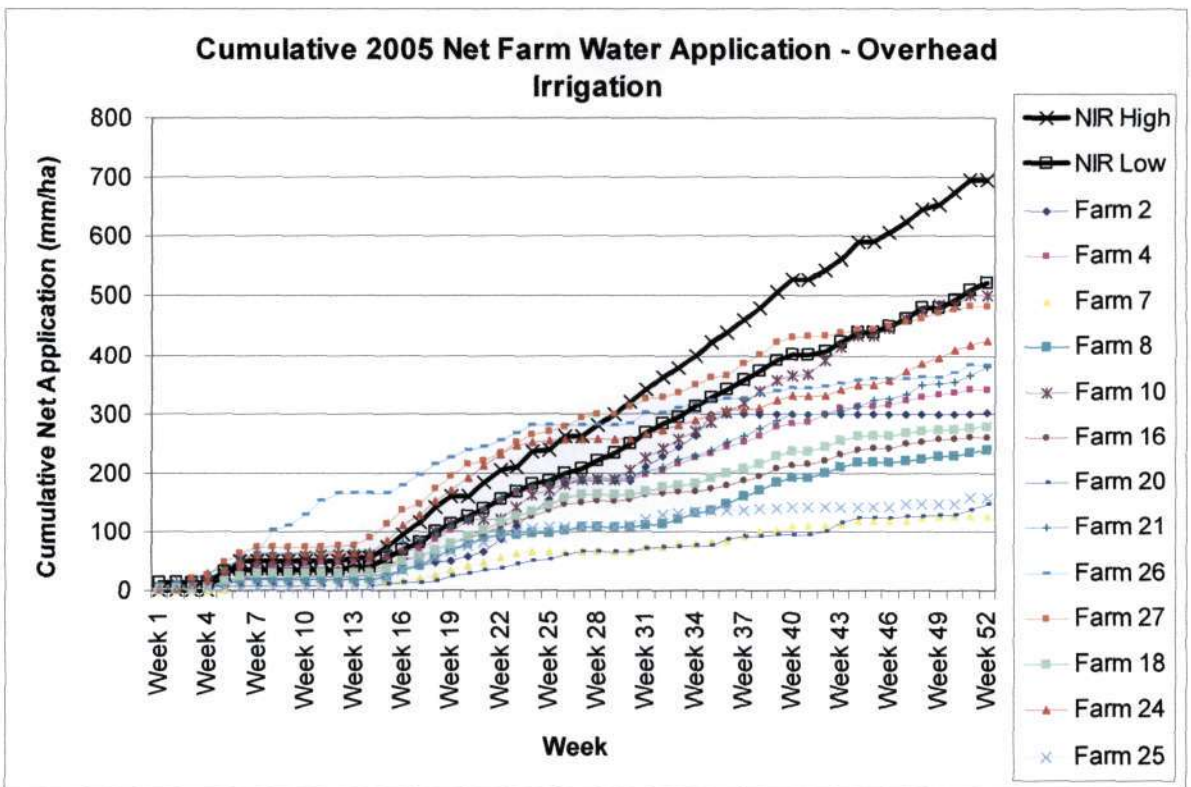

Figure 6.10 Cumulative 2005 net farm water applications for overhead irrigation farms.

The water application trend relative to the simulated demands for the overhead irrigation farms was the same as that observed for the drip irrigation farms. The majority of the farms were under applying relative to the simulated envelopes. However, it can be seen in Figure 6.10 that there were a selection of farms that were applying water in a very similar manner to the lower simulated demand. Once again, there were farms, most notably Farm 7 and Farm 20, which were applying very low amounts of irrigation water over the year. From the potential production factor results, Farm 20 and Farm 7 were poor producing farms with low potential production factors which can be seen in Figure 6.2 and Figure 6.4. It is likely that the very low observed irrigation water application rates were a major contributing factor to the poor production.

An interesting observation is that with the application trends is the trend of Farm 26, shown in Figure 6.9. Farm 26 applied irrigation water in a similar fashion to the majority of the other farms until week 26. After week 26, no irrigation occurred for the remainder of the year. In communications with stakeholders, it was found that there were no water meter errors with the farm during that period, and therefore, it is assumed that there must have been a problem with the infield irrigation systems and the management thereof. The results for the 2005 year in Figure 6.10 show that the same farm had an unusual water application trend compared to all the other farms in the scheme. In the initial stages of the year, Farm 26 continued to apply water when all the other farms, and the simulated irrigation demand, was relatively low. The initial stages of the year had substantial rainfall, and evidently Farm 26 did not cease irrigation during this period. These observations highlight the usefulness of farm water application trend comparisons in a benchmarking environment. The owner of Farm 26 could have observed that his/her irrigation management practices were very different to other farmers in the scheme, and could react accordingly.

The 2004 and 2005 net farm application results for all the overhead and drip (combination) irrigation farms in the scheme are shown in Figure 6.11 and Figure 6.12 respectively. It should be noted that because the different combination farms had different areas of overhead and drip irrigation, it was decided to use the highest drip simulated demand for the upper limit, and the lowest simulated overhead requirement as the lower limit. Therefore the envelope of irrigation water demand encompasses a greater area of possible irrigation demands when compared to just drip or overhead irrigation.

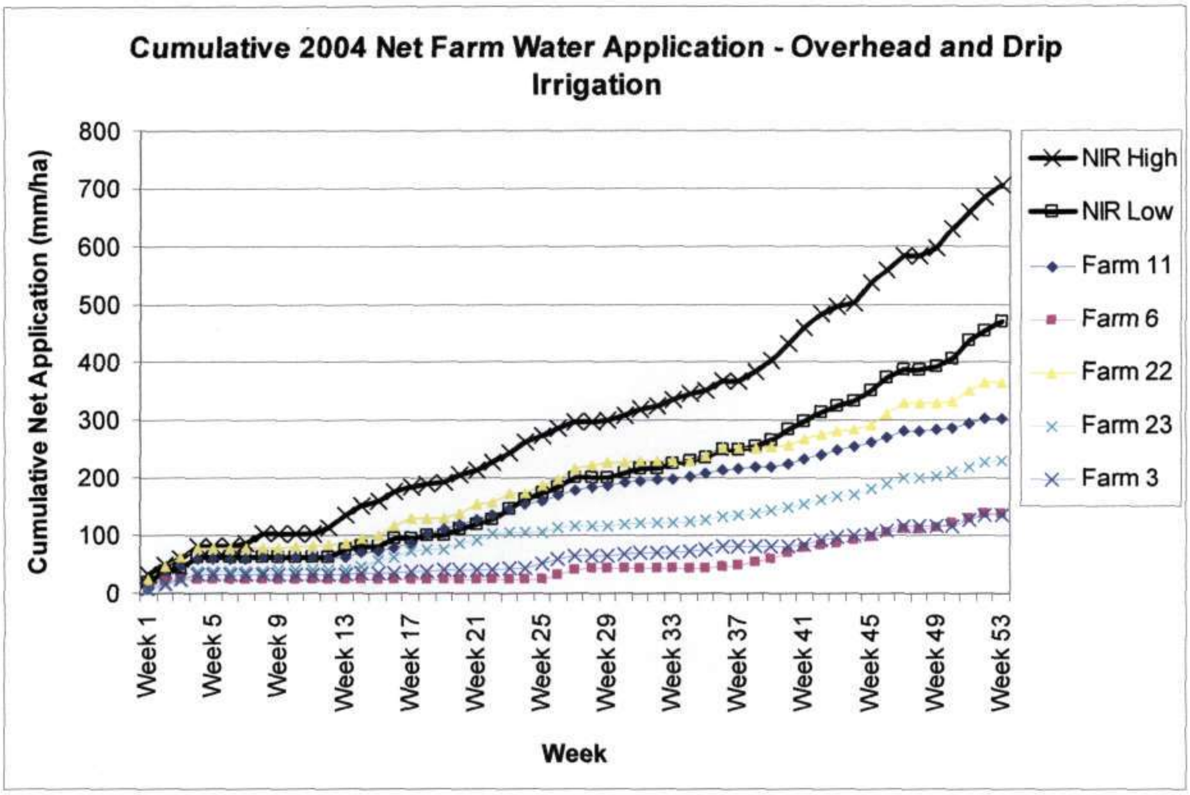

Figure 6.11 Cumulative 2004 net farm water applications for combination overhead and drip irrigation farms.

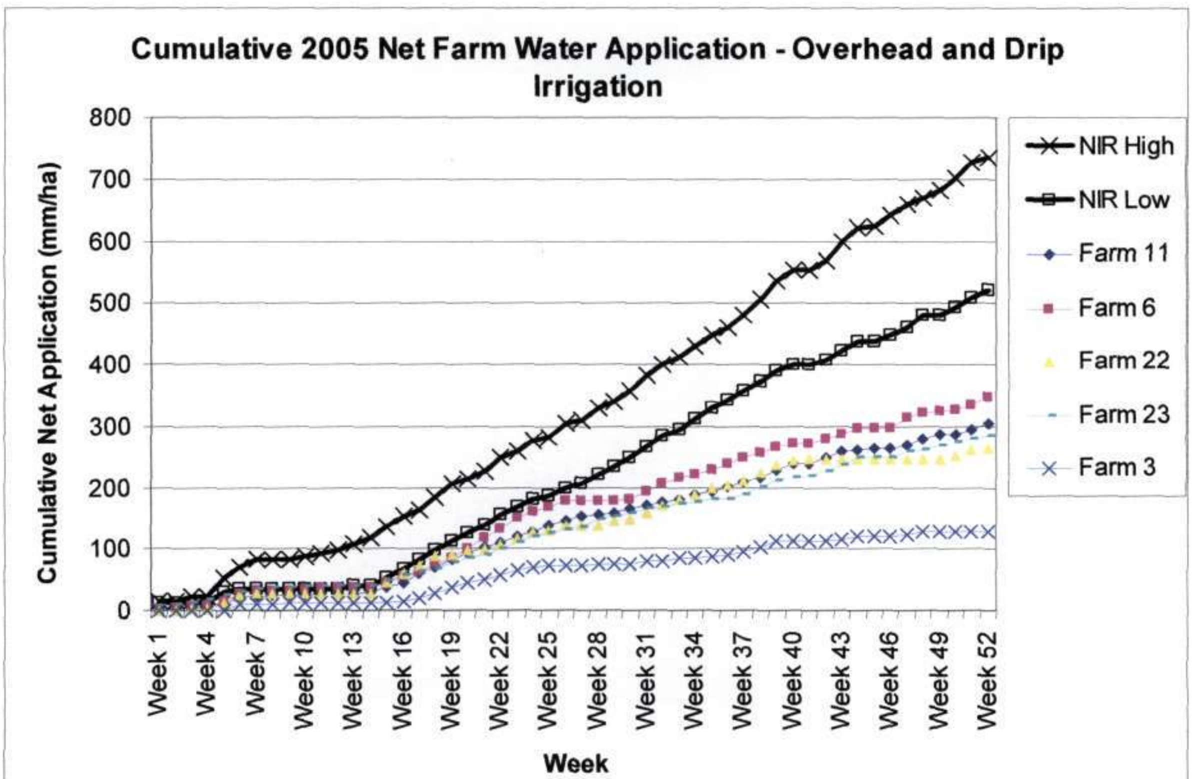

Figure 6.12 Cumulative 2005 net farm water applications for combination overhead and drip irrigation farms.

The 2004 and 2005 results for the combination farms that are presented in Figure 6.11 and Figure 6.12 respectively are similar to all the other results that have been presented thus far. None of the five farms in this category applied what was deemed to be the 'scietnfically-based' requirement on an annual basis. Up until week 38 in 2004, Farm 22 and Farm 11 were applying what the *SAsched* model had simulated for a worst case scenario. However, after week 38, the observed water application trends failed to increase the rate of application. In the lower simulated requirement, it can be seen how the rate of application increases in the late winter or early spring period.

Once again, it must be reiterated that the lower simulated requirement was the worst case scenario, with a poor system operating on a shallow soil with a long cycle time. It is unwise to view the lower requirement as the suitable net irrigation water requirement, and it was included to create an envelope, just to illustrate the fact that the farmers were not applying sufficient quantities of irrigation water. Farm 3 is a good example of how little some of the farmers in the scheme are applying, in 2004 and 2005, Farm 3 applied an annual net irrigation depth of just over 100 $mm.ha^{-1}$. The theoretical requirement should have been in the range of 500 – 700 $mm.ha^{-1}$. There is a good chance that Farm 3 could improve production if a greater depth of irrigation water could be applied. From the potential production factor results that were presented earlier in this chapter, Farm 6 had a potential production factor of 0.65 and 0.7 for 2004 and 2005 respectively. These production factors were in the top half of the results that were presented and were slightly above the scheme farm average. Therefore, if these relatively good results can be obtained with such a low amount of irrigation, an increase in the amount applied would surely result in a substantial improvement in yield.

6.3. General observations and possible best management practices

The on farm evaluations revealed that none of the drip irrigation farms that were investigated practiced fertigation or chemigation. The lack of these practices is surprising due to the excellent distribution uniformities that were encountered. Acid injection to facilitate the cleaning of blocked drippers was also not practiced by any of the evaluated farms. The reason for the lack of these practices is the perception that they decrease the life of the dripper lines, and due to the high cost of the dripper lines the farmers prefer not use the methods (Anon, 2006).

When the water application trends were discussed with the farmers, there was great interest in comparing water application trends relative to other the farmers in the same area. The following hypothetical example describes the reasoning for this. Farmer A would want to see his seasonal application trend together with that of his neighbour, farmer B. Farmer A may have had a uniform application trend throughout the year, with no difference in summer and winter watering pattern, whereas farmer B could have been applying far more water in the summer period relative to the winter period. Farmer A could then assess the possibility that excess irrigation may be occurring on his farm in winter. The stakeholders were then further interested by observing their watering pattern relative to the simulated demand as determined with the *SAsched* model. This was particularly evident because the simulated output was determined with managerial and systems constraints gleaned from the farmers themselves and the in-field evaluations. This point shows the effectiveness of comparisons within the same organisation and promotes the use of benchmarking in the irrigation sector.

6.4. Chapter Discussions and Conclusions

In order to meet the main objectives of the on-farm irrigation systems analysis, on-farm irrigation systems evaluations were conducted. Information obtained during the on farm evaluations was used to determine a range of simulated irrigation water requirements associated with various irrigation system and soil constraints. The observed water application trends were then compared against these simulated requirements, in order to determine how the farms were applying water relative to a scientifically-based reference. To establish a suitable reference, several crop yield and water balance simulation models were investigated. The *SAsched* model was selected as the most appropriate to estimate reference crop and irrigation water requirements for this study.

From the analysis of the individual farm performance of all the farms on the scheme, it was found that there were wide variations in both farm production and farm water use. Furthermore, it was discovered that, in general, the farmers that had a higher net annual water application, also had a higher farm performance. It was also discovered that as a group, the farmers applied too little water relative to the simulated reference irrigation requirement as calculated with the *SAsched* model. This observation was identified as one of the areas that needed to be addressed if production on some of the farms were to improve.

When the systems constraints that were identified during the on-farm system evaluations were used in the SAsched model, the simulated irrigation water requirements did decrease. However, the decrease in the simulated irrigation water requirements was still insufficient to bring them to a level that coincided with the observed net farm applications. Therefore, contrary to a previous hypothesis by Schmidt (2001), system capacity/scheduling constraints were not the main reason why the majority of the farms in the scheme were applying such low amounts of water. However, in reality the system constraints could have been amplified by security, labour and theft issues. Labour and theft constraints may have a greater impact on actual water applications than the type and cycle time of the irrigation system.

7. DISCUSSION, CONCLUSION AND RECOMMENDATIONS

This study aimed to meet three main objectives, which were covered separately in Chapters 4, 5 and 6. The outcomes of this research attempted to assist the larger WRC irrigation efficiency project to achieve its objectives by formulating a methodology and applying it to an irrigation scheme. This chapter contains discussion and draws conclusions from results obtained, and contains recommendations and possible improvements for future research. Before moving further, it is important to review the initial objectives of this study. The main objective of this study was to develop a methodology that could be used to quantify and benchmark irrigation performance in South African irrigation schemes. The following approach was adopted to meet this objective:

1. To review literature on irrigation benchmarking used internationally, specifically the irrigation performance indicator sets and benchmarking methodologies developed by the International Water Management Institute (IWMI), the International Program for Training and Research in Irrigation and Drainage (IPTRID) and those of the Irrigation Training and Research Center (ITRC) in the United States of America.
2. To select a methodology and an appropriate set of performance indicators from the literature reviewed and apply it in a selected irrigation scheme. This methodology would need to focus on three areas, namely:
   i) applying the external indicators to the irrigation scheme as a whole,
   ii) using water balances to quantify the extent of losses and consequently the efficiency scheme water delivery, and
   iii) to quantify the on-farm performance of all the farms on the scheme, and investigate individual water application trends.
3. To identify a suitable South African irrigation scheme to which the proposed methodology could be applied.
4. To apply all three aspects of the methodology and to assess their suitability and usefulness for application in other irrigation schemes identified by the larger WRC project.
5. To recommend possible changes and modifications to the methodology for application to other South African irrigation schemes.

7.1. Discussion and Conclusion

In this study it was established that South Africa is a water poor country with limited and spatially and temporally variable water resources. Water stressed areas in the country were emerging as a result of ever-increasing demands for water. At the time of writing, irrigated agriculture was the largest user of water of South Africa, estimated to utilise 62 % of the country's stored water resources. With the increasing demands for water, and as the largest user, the irrigation sector would have to justify its utilisation of the limited water resources. From the literature reviewed, it was evident that benchmarking irrigation scheme performance with external indicators was a method of quantifying and improving performance. Therefore, four sets of external indicator sets were reviewed and their application potential in a South African context was discussed for this research. The principle of investigating irrigation scheme performance with water balances was also investigated. It was concluded that assessing the water delivery infrastructure of irrigation schemes with water balances would be a suitable method. Traditionally, the external indicators and water balances are used to assess irrigation performance at a scheme scale. However, it was decided that for the purpose of this research, in addition to calculating the external indicators at a scheme scale, the study would also attempt to investigate the performance of all the farms in an irrigation scheme at a farm scale as well. The approach would enable a greater understanding of water use and where potential problems at an irrigation scheme level, and solutions to those problems, could be found.

In order to test the suitability of these methods, it was necessary to select an irrigation scheme where these concepts could be applied. An irrigation scheme in Northern KwaZulu-Natal in South Africa was identified as a suitable study area. The scheme had excellent historical daily water use records that could be used to complete the required water balances and also to investigate farm irrigation water application trends. The scheme also had an automatic weather station that was used to estimate contributions from direct rainfall, and to estimate losses from surface water evaporation. Weather station data was also available and used to provide climatic inputs for the irrigation simulation model *SAsched*. All three of the different aspects of the methodology were applied to the selected scheme. Due to the sensitivity of individual farmers to the results that could arise out of any investigation on irrigation performance and efficiency in the current South African context, the research team was requested by the scheme management and farmers to enter a confidentiality agreement. The agreement stipulated that no information which could potentially reveal the name and location of the scheme should be divulged.

The external indicators that were calculated for the study area were completed according to international guidelines. The results of the analyses were described in detail in Chapter 4. The results from the indicators can be compared to other indicators from other irrigation schemes at an international scale. Certain of the external indicators that were calculated provided valuable information regarding the existing situation in the scheme. The RIS and RWS provided insight into the nature of water application and it was determined that at a scheme level, irrigation demands were not being adequately met. The WDCR was also calculated. The RWS, RIS and WDCR were used in conjunction to conclude that the scheme infrastructure and canal capacities were not the cause of irrigation demands not being satisfied. It was also noted that the RIS and RWS did not give an indication of the time of year that the irrigation demand was not met. Therefore, at an annual scale, the factors could not be used to help identify when problems were occurring, and how they could be solved. The application of the external indicators showed that the greatest benefit would only be realised if more irrigation schemes participated in a benchmarking initiative. The purpose of benchmarking, and the comparison of organisations, requires active participation from several similar organisations. The output per cropped area, output per command area, output per irrigation water supply and output per water consumed, would have been more valuable if there had been other schemes in the analysis with which to compare and benchmark results. The use of these indicators is therefore recommended for the larger WRC efficiency project where a number of schemes could be used to establish guidelines for best irrigation practice. In particular, effort into the calculation of the SGVP is recommended due to the large variety of crops that may be encountered in such an analysis. In irrigation schemes where it may not obvious which crop to select as the base crop for the calculation of SGVP, the base crop could be determined by conducting a sensitivity analysis, considering the entire range of crops grown on any particular scheme together with their respective values. In schemes where the application of SGVP was not possible, as was the case with the study area used in this research, normal non-standardised values of production should be calculated.

The application of the external indicators for the study area reiterated that confidentiality concerns among stakeholders are of great importance to the success of a benchmarking project. The WRC efficiency project should focus on overcoming this issue to motivate successful participation from all the schemes that could participate in their study. This is especially pertinent for irrigation organisations in a water scarce country such as South Africa, where the irrigation sector is perceived as a potentially inefficient user of water. Any results from a benchmarking exercise that could be misinterpreted by external organisations to portray the irrigation sector in a negative light must be guarded against. Chapter 2 described the ANCID benchmarking program in Australia, and particularly how they overcame the stakeholder concerns of sensitive results that originate from a benchmarking exercise. In the Australian study, three different levels of information were made available to three different audiences to prevent any confidential information being misinterpreted. It is recommended that the remainder of research to take place in the WRC irrigation efficiency project take cognisance and place emphasis on these stakeholder concerns, and that the ANCID procedures be followed to secure successful stakeholder participation.

The results from the water balance calculations showed that the scheme was efficient in delivering water to the farm boundary, and the extent of losses that occurred in the 2004 and 2005 years were within the standards set by DWAF. The water balances were further improved by analysing the results in conjunction with the water balance trends graphs, which revealed the nature of losses that occurred in the sections that were examined. The results showed that, depending on the change in storage that occurred, the delivery efficiency for the 2004 year was between 79.0 and 89.8 %. The results for the 2005 year were between the range of 87.4 and 98.6 %. The results of the two years combined were between 85.9 and 91.3 %. However, the water balance trends data indicated that there were three weeks in the time period of investigation where recorded water use was grossly incorrect. It was established that the water meter at the scheme intakes was broken and the scheme management incorrectly estimated the water use for this time period. This error was carried through the water audit system and the scheme and farmers ultimately paid DWAF for water that was not actually used. Prior to the results from this study, the scheme management were unaware of these errors. However, the water balance trends made them obvious. Therefore, the scheme management, upon viewing the water balance trends, requested that use of a spreadsheet that could be made available to them to assess the water balance and trend graphs on a weekly basis to correct problems when they occurred. This spreadsheet was made available to farmers and the scheme management and at the time of writing this dissertation, they were utilising the tool on a weekly basis to assist with water management. It was worth noting that if gross errors were avoided, the scheme delivery efficiency for the two years combined would then have ranged between 93.5 and 99.5 %. As stated in Chapter 5, these results are excellent relative to the DWAF norm of 80 %, and indicated that scheme was very efficient in delivering water to the farm boundary. It is recommended that the WRC efficiency project apply a similar water balance methodology to other schemes, in conjunction with the water balance trend assessment, to investigate the effectiveness of irrigation scheme water delivery.

The focus of the individual farm analysis was to obtain individual farm productions and to relate the farm production values to farm irrigation water use. It was established that the farms that applied more irrigation water generally obtained a higher production. The next step was to assess if what the farmers were applying was sufficient to meet the crop water demand. The *SAsched* model was used to determine irrigation water demands for different irrigation systems in the scheme. The management inputs for the simulated outputs were obtained from performing selected on-farm irrigation systems evaluations, and from discussions with stakeholders at the scheme. A range of different scenarios were simulated, with different soils, different systems, different system capacities and different irrigation schedules. The result of all the different simulations was to determine an upper and lower limit of irrigation water demand for the different systems used at the scheme. This irrigation water demand envelope was then used to compare the observed irrigation water application trends at selected farms. It was found that the majority of farms in the scheme were not applying more than the worst case irrigation simulated demand. These results indicated that irrigation systems with below optimum capacities were not as great a cause for the observed low applications that were observed at the scheme as originally perceived. The view of the stakeholders at the scheme, and which is supported by the author, was that labour, theft and security constraints that prevented irrigation systems being used at night have a greater impact on total water applications in a season than the irrigation system capacity constraints.

It was felt that the mandatory and effective use of water meters in the irrigation sector was necessary before attempting other improvements. The irrigation scheme that was studied in this project made effective use of accurate water meters. The water balance approach that was applied would not have been possible if these meters had not been in operation. The results from the water balance study also assisted the scheme managers in identifying the problem areas in the scheme infrastructure. Through the use of the water balance methodology, and specifically the spreadsheet that was developed for scheme managers, it is anticipated that the technique will continue to be of use in the future. The water meters also facilitated the study into individual farm water use in the scheme. This type of water management, if implemented at all irrigation schemes will assist in identifying problem areas at each scheme, as well as promoting the efficient use of irrigation water. This is necessary given the situation in South Africa where irrigation is the largest water user, and is being highlighted as an inefficient user of water.

The process that was applied for this research has potential for application beyond the scope of the WRC irrigation efficiency project. The proposed structure of water management in South Africa, when implemented, could utilise benchmarking as one method of analysing water use at different levels. Performance indicators, developed in conjunction with stakeholders and the general public, could be used to improve both the efficiency and accountability of water use, and to increase the general awareness of water use efficiency by all water users within the different sectors. These concepts have already been proposed in the water management literature within South Africa, but it is the author's view that that more participation and awareness from stakeholders in the South African context is required if these processes are to be successfully implemented.

It is concluded that the objectives of this project have been successfully met. However, in the course of attaining these objectives, a number of areas for future research and recommendations have been identified. These are described in the following section.

7.2. Recommendations for Future Research

As previously eluded to, a number of aspects for future research were identified during the course of this project. Some of theses aspects involved future research at the scheme that was the focus of this project, whilst others are recommendations for the larger WRC efficiency project.

The following list deals with recommendations for future research at the scheme:

i. The results from the on-farm analyses in Chapter 6 showed wide variations in net farm applications, and under irrigation relative to the *SAsched* simulated output. It is proposed that soil water measurement be implemented on a selection of farms to investigate these findings further. These soil water measurements would have to be done on an individual field scale and with stakeholders at the scheme who are willing to participate.
ii. The *SAsched* model should be used in an economic analysis to assess if systems improvements would realise a sufficient increase in yield to warrant the upgrade expenditure. This analysis should also quantify the negative impact on yield of gross under irrigation relative to simulated values that was observed on some of the farms on the scheme.
iii. The large number of water meters and small balancing dams enables the scheme to be used to determine a range of balancing dam storage efficiencies. Most of these balancing dams would only require the temporary installation of one water meter to accomplish this. The automatic weather station that was used to determine atmospheric evaporative demand could be used for the analysis of surface water evaporation from the balancing dams.
iv. As has been highlighted in the findings from Chapter 5, daily records of balancing dam and canal water levels could be used to improve the water balance calculations that were completed for this research.

In terms of the larger WRC efficiency project, the author would like to make the following recommendations which could result in improved efficiencies if the type of methodology developed through research at this particular scheme was applied to the other irrigation schemes.

i. The procedures adopted by ANCID with different levels of performance reporting, as described in Section 2.7, should be followed to ensure stakeholder confidence and successful participation as a consequence.
ii. Where possible, the application of the water balances, and the water balance trend analysis graphs, should be applied to quantify the extent and nature of any losses occurring within irrigation scheme delivery infrastructures.
iii. In regions and specific cases where the storage capacity of balancing dams is small relative to the volume of water passing through the dams on an annual basis, the accurate determination of surface water evaporation may not be necessary. This is because in such situations, the loss by surface water evaporation may be insignificant relative to the amount of water passing through the dam.

iv. When completing on farm irrigation system evaluations, the results should be combined with simulation models to determine more realistic farm irrigation water requirements and irrigation system capacities. The simulation results could then be compared to observed applications. It is the author's view that stakeholders showed more confidence in simulation estimates that were determined with actual observed irrigation system capacities and not theoretical or design system capacities.

v. The use of weather forecasting could be used to determine more accurate historical irrigation water requirements for comparisons with observed irrigation application results. The forecast methodology that could be used in this type of approach should be developed in conjunction with irrigators who may be using weather forecasts in their decision making process.

8. REFERENCES

Alexander, PJ. 2000. *Benchmarking of Australian Water Providers.* Hydro Environmental, Melbourne, Australia.

Alexander, PJ and Potter, MO. 2004. Benchmarking of Australian Irrigation Water Provider Businesses. *Irrigation and Drainage* 53(2): 165-173.

Allen, RG, Pereira, LS, Raes, D and Smith, M. 1998. *Crop evapotranspiration - Guidelines for computing crop water requirements.* Irrigation and Drainage Paper 56. Food and Agriculture Organisation (FAO), Rome, Italy.

Annandale, J, Benade, N, Jovanovic, NZ, Steyn, JM and Du Sautoy, N. 1999. *Facilitating irrigation scheduling by means of the soil water balance model.* WRC

Report 753/1/99. Water Research Commission, Pretoria, RSA.

ANCID. 2000. *Inflow Outflow Method.* Australian National Committee on Irrigation and Drainage. Victoria, Australia. Available from: www.ancid.org.au/seepage/3_3_11_inflowPrinc.html [Accessed: 8 January 2007]

ANCID. 2004. *Benchmarking Report for 2002/2003.* Australian Water Provider. Australian National Committee on Irrigation and Drainage. Victoria, Australia.

Anonymous. 2006. Personal Communication. 14 January 2006.

Armitage, R. 2006. Personal communication. South African Sugar Research Institute, Mount Edgecomb, South Africa, 25 October 2006.

Ascough, GW. 2001. Procedures for estimating gross irrigation water requirement from crop water requirement. Unpublished MScEng Dissertation, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, RSA.

Ascough, GW, van der Stoep, I, Benadé, N, Koegelenberg, F, du Plessis, F, van Heerden, P, Greaves, KR, Lecler, NL, M'Marete, C, Reinders, F, Steyn, JM and Grove, B. 2004. *Deliverable 2: Interim Report on Standardised Terminology and Essential Variables or Factors.* Project No. K5-1482-4, Water Research Commission, Pretoria, RSA.

Ascough, GW and Lecler, NL. 2005. Accounting for uniformity of applied irrigation water using multiple water balances in *ZIMSCHED 2.0.* Paper presented at the South African National Committee on Irrigation and Drainage Conference. SANCID, RSA.

Bezuidenhout, CN and Singels, A. 2003. How accurate are CANESIM estimates of sugarcane production? In: *Proceedings of the South African Sugar Technologists' Association* 596-600. SASTA, Mount Edgecombe, RSA.

Bos, MG, Murray-Rust, DH, Merry, DJ, Johnson, HG and Snellen, WB. 1994. Methodologies for assessing performance of irrigation and drainage management. *Irrigation and Drainage Systems* 7(2): 231-261.

Burt, CM. 1999. *Irrigation Water Balance Fundamentals.* Benchmarking Irrigation System Performance Using Water Measurement and Water Balances – Proceedings from the 1999 USCID Water Management Conference, San Luis Obispo, California, USA.

Burt, CM. 2001. *Rapid Appraisal Process (RAP) and Benchmarking, Explanation and Tools.* [Internet] Food and Agriculture Organisation of the United Nations, Bangkok, Thailand. Available from: http://www.itrc.org/papers/papersindex.html [Accessed: 11 May 2004].

Burt, CM, Walker, RE and Styles, SW. 1995. *Irrigation System Evaluation Manual – A comprehensive, documented software package for evaluation of agricultural irrigation systems.* ITRC, California Polytechnic State University, USA.

Burt, CM, Clemmens, AJ, Strelkoff, TS, Solomon, KH, Bliesner, RD, Hardy, LA, Howell, TA and Eisenhauer, DE. 1997. Irrigation Performance Measures: Efficiency and Uniformity. *Journal of Irrigation and Drainage Engineering* 123(6): 423-442.

Burt, CM and Styles, SW. 1998. *Modern Water Control and Management Practices in Irrigation: Impact on Performance.* ITRC, California Polytechnic State University, USA.

Clemmens, AJ. 1999. *How accurate are irrigation performance estimates?* Benchmarking Irrigation System Performance Using Water Measurement and Water Balances – Proceedings from the 1999 USCID Water Management Conference, San Luis Obispo, California, USA.

Clemmens, AJ and Burt, CM. 1997. Accuracy of Irrigation Efficiency Estimates. *Journal of Irrigation and Drainage Engineering* 123(6): 443-453.

Crosby, CT and Crosby, CP. 1999. *SAPWAT: a computer program for establishing irrigation requirements and scheduling strategies in South Africa.* WRC Report 624/1/99, Water Research Commission, Pretoria, RSA.

Cross, PR. 2000. Benefits of a Flexible Irrigation Supply. *Journal of Irrigation and Drainage Engineering* 126(5): 275-278.

Dalton, P, Raine, S and Broadfoot, K. 2001. *Best management practices for maximising whole farm irrigation efficiency in the cotton industry.* Final Report for CRDC Project NEC2C. National Centre for Engineering in Agriculture, Publication 179707/2, Toowoomba, Australia.

Degirmenci, H, Buyukcangaz, H and Kuscu, H. 2003. Assessment of Irrigation Schemes with Comparative Indicators in the Southeastern Anatolia Project. *Turkish Journal of Agriculture and Forestry* 27(5): 293-303.

de Jager, JM. 1994. Accuracy of vegetation evaporation ratio formulae for estimating final wheat yield. *Water SA* 20(4): 307-314

Dijkhuis, FJ and Berliner, PR. 1988. *A simple model for the prediction of dryland wheat yield.* Department of Agriculture and Water Supply, Soil and Irrigation Research Institute, Pretoria, RSA

Doorenbos, J and Kassam, AH. 1979. *Yield responses to water.* Irrigation and Drainage Paper 33. Food and Agriculture Organisation (FAO), Rome, Italy.

English, MJ, Solomon, KH and Hoffman, GJ. 2002. A Paradigm Shift in Irrigation Management. *Journal of Irrigation and Drainage Engineering* 128(5): 267-277.

Fairweather, H, Austin, N and Hope, M. 2003. *Irrigation Insights Number Five: Water use efficiency.* [Internet]. Land and Water Australia. Available from: http://www.lwa.gov.au/downloads/publications_pdf/PR030566.pdf. [Accessed: 10 June 2004].

Flowmetrix. 2006. South African Electromagnetic Flow Meters. [Internet]. Available from: http://www.flowmetrix.co.za [Accessed: 10 July 2006].

Ghazalli, MA. 2004. Benchmarking of irrigation projects in Malaysia: initial implementation stages and preliminary results. *Irrigation and Drainage* 53(2): 195-212.

Hughes, AD.1992. Sugarcane yield simulation with the ACRU modelling system. Unpublished MSc dissertation. University of Natal, Pietermaritzburg, Dept of Agricultural Engineering, RSA.

Hydro Environmental. 2002. Irrigation Water Provider Benchmarking Workshop – June. Melbourne, Australia.

Inman-Bamber, NG. 1991. A growth model for sugarcane based on a simple carbon balance and the CERES-Maize water balance. *South African Journal of Plant and Soil* 8(2):93-99.

Inman-Bamber, NG. 2000. History of the CANEGRO model. In: *Proceedings of the International CANEGRO Workshop*, 5-8. SASEX, Mount Edgecombe, Durban, RSA.

Inman-Bamber, NG. 2005. Personal Communication. 20 December 2005.

IPTRID Secretariat. 2000. *Benchmarking irrigation and drainage service provision*. IPTRID, the World Bank, IWMI, FAO and ICID. [Internet]. www.hrwallingford.co.uk/projects/IPTRID/grid/pdf-files/grid17articles/G17pg8.pdf. [Accessed 14 July 2004].

Jensen, ME, Burman, RD and Allen, RG. 1989. *Evapotranspiration and irrigation water requirements*. American Society of Civil Engineers, New York, USA.

Kloezen, WH and Garces-Restrepo, C. 1998. *Assessing Irrigation Performance with Comparative Indicators: The case of the Alta Rio Lerma Irrigation District, Mexico*. Research Report 22. IWMI, Colombo, Sri Lanka.

Koegelenberg, FH and Breedt, HT. 2003. *Manual for the Evaluation of Irrigation Systems*. Agricultural Research Council - Institute for Agricultural Engineering, Pretoria, RSA.

Lecler, NL. 2000. "ZIMsched": An Irrigation Management and Yield Forecasting tool. In: *Proceedings of the South African Sugar Technologists' Association*. 124-130. SASTA, Mount Edgecombe, Durban, RSA.

Lecler, NL. 2003. A model for the evaluation of irrigation and water management systems in the Lowveld of Zimbabwe: Model development and verification. In: *Proceedings of the South African Sugar Technologists' Association*, 322-333. SASTA, Mount Edgecombe, Durban, RSA.

Lecler, NL. 2004. *"SAsched": A water conservation and demand management tool for irrigated agriculture*. Paper presented at SANCID 2004 symposium, Port Elizabeth, RSA.

Lecler, NL. 2005. Personal communication. South African Sugar Research Institute, Mount Edgecomb, RSA, 7 December 2005.

Lecler, NL. 2006 Personal communication. South African Sugar Research Institute, Mount Edgecomb, RSA, 16 October 2006.

Levine, G. 1982. *Relative water supply: an explanatory variable for irrigation systems*. Technical Report No. 6. Cornell University, Ithaca, New York, USA.

Lorite, IJ, Mateos, L and Fereres, E. 2004. Evaluating irrigation performance in a Mediterranean environment - Model and general assessment of an irrigation scheme. *Irrigation Science* 23(2): 77-84.

Malano, H. 2000. *Benchmarking Irrigation and Drainage Performance - A case Study in Australia.* [Internet]. Report on Benchmarking Workshop. FAO, Rome, Italy. Available from: http://www.wca-infonet.org/servlet/BinaryDownloaderServlet?filename=1017320530078_Malano.pdf&refID=18600. [Accessed: 5 October 2004].

Malano, H and Burton, M. 2001. *Guidelines for Benchmarking Performance in the Irrigation and Drainage Sector.* IPTRID and FAO, Rome, Italy.

McGlinchey, MG and Inman-Bamber, NG. 1996. Predicting sugarcane water use with the Penman-Monteith equation. *Proc. Evapotrans. Irrig. Sched.* Am. Soc. Agric. Eng.. San Antonio, USA. 592-597

McGlinchey, MG and Inman-Bamber, NG. 2002. Robust evaporation estimates of evapotranspiration for sugarcane. In: *Proceedings of the South African Sugar Technologists Association* 245-249 SASTA, Mount Edgecombe, Durban, RSA.

McGlinchey, MG. 2005. Personal Communication. 18 December 2005.

McNaughton, KG. 1981. Net interception losses during sprinkler irrigation. *Agricultural Meteorology*, 24: 11-17.

Molden, DJ, Sakthivadivel, R, Perry, CJ and de Fraiture, C. 1998. *Indicators for Comparing Performance of Irrigated Agricultural Systems.* Research Report 20. IWMI, Colombo, Sri Lanka.

Moult, N. 2005. A catchment scale irrigations systems model for sugarcane. Unpublished MScEng Dissertation, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, RSA.

Moult, N, Lecler, NL and Smithers, JC. 2006. Application of a catchment scale irrigation systems model. In: *Proceedings of the South African Sugar Technologists' Association*, 148 - 152. SASTA, Mount Edgecombe, Durban, RSA.

Murray-Rust, DH and Snellen, BW. 1993. *Irrigation System Performance Assessment and Diagnosis*. International Irrigation Management Institute, Colombo, Sri Lanka.

National Water Act. 1998. *RSA Government Gazette No. 36 of 1998: 26 August 1998, No. 19182.* Cape Town, RSA.

NWRS. 2004. National Water Resource Strategy – First Edition, September 2004. Department of Water Affairs and Forestry, Pretoria, RSA.

Perry, CJ. 1996. *Quantification and measurement of a minimum set of indicators of the performance of irrigation systems*. International Irrigation Management Institute, Colombo, Sri Lanka.

SAGIS. 2006. The South African Grain Information Service - Historical Price Database. African Grain Information Service, Pretoria, RSA. Available from: www.sagis.org.za [Accessed: 5 January 2007].

SASRI. 2005a. GIS - Soil Parent Material data. Agricultural mapping office. South African Sugar Research Institute, Mount Edgecomb, RSA.

SASRI. 2005b. Drying off advice. South African Sugar Research Institute, Mount Edgecomb, RSA. Available from: www.sugar.org.za/sasri/about/agronomy/amatikulu80.htm [Accessed: 15 December 2005].

Schmidt, EJ. 2001. Annexure a-i, Chapter 4 – Irrigated Agriculture Sector. In: *Mhlathuze River Catchment Water Conservation and Demand Strategy Study.* Report No. WC W122-00-2401, Department of Water Affairs and Forestry, Pretoria, RSA.

Schmidt, EJ and Asburner, B. 2001. Chapter 4 – Irrigated Agriculture Sector. In: *Mhlathuze River Catchment Water Conservation and Demand Strategy Study.* Report No. WC W122-00-2401, Department of Water Affairs and Forestry, Pretoria, RSA.

Schulze, RE. 1995. *Hydrology and Agrohydrology: A text to accompany the ACRU 3.00 Agrohydrology Modelling System.* WRC Report TT69/95. Water Research Commission, Pretoria, RSA.

Schulze, RE. 1995a. Soil Water budgeting and Total Evaporation. In: Schulze, RE. 1995. *Hydrology and Agrohydrology: A text to accompany the ACRU 3.00 Agrohydrology Modelling System.* WRC Report TT69/95. Water Research Commission, Pretoria, RSA

Schulze, RE. and Kunz, RP. 1995. Reference Potential Evaporation. In: Schulze, RE. 1995. *Hydrology and Agrohydrology: A text to accompany the ACRU 3.00 Agrohydrology Modelling System.* WRC Report TT69/95. Water Research Commission, Pretoria, RSA.

Schulze, RE and Smithers, JC. 1995. Procedures to improve and verify streamflow simulations. In: Smithers, J.C. and Schulze, R.E. *Hydrology and Agrohydrology: User manual version 3.00.* Water Research Commission, Pretoria, RSA.

Schulze, RE, Smithers, JC, Lecler, NL, Tarboton, KC and Schmidt, EJ. 1995. Resrvoir Yield Analysis. In: Schulze, RE. 1995. *Hydrology and Agrohydrology: A text to accompany the ACRU 3.00 Agrohydrology Modelling System.* WRC Report TT69/95. Water Research Commission, Pretoria, RSA.

Singels, A, Kennedy, AJ and Bezuidenhout, CN. 1998. Irricane: A simple computerised irrigation scheduling method for sugarcane. In: *Proceedings of the South African Sugar Technologists' Association*, 117-122. SASTA, Mount Edgecombe, Durban, RSA.

Singels, A. and Donaldson, RA. 2000. A simple model of unstressed sugarcane canopy development. In: *Proceedings of the South African Sugar Technologists' Association* 151-154. SASTA, Mount Edgecombe, Durban, RSA.

Singels, A. and Bezuidenhout, CN. 2002. A new method of simulating dry matter partitioning in the Canegro sugarcane model. *Field Crops Research* 78:151-164.

Slabbers, PJ., 1980. Practical prediction of actual evapotranspiration. *Irrigation Science* 1: 186-196.

Small, LE and Svendsen, M. 1992. *A Framework for Assessing Irrigation Performance.* Working Papers on Irrigation Performance 1. International Food Policy Research Institute, Washington, USA.

Smith, M. 1992. CROPWAT - *A Computer Program for Irrigation Planning and Management.* FAO Irrigation and Drainage Paper No. 46. FAO, Rome, Italy.

Smith, M, Allen, RG and Pereira, LS. 1996. Revised FAO methodology for crop water requirements. *Proceedings of the International Conference on Evapotranspiration and Irrigation Scheduling.* San Antonio, Texas, USA.

Smithers, JC and Schulze, RE. 1995. *Hydrology and Agrohydrology: User manual version 3.00.* Water Research Commission, Pretoria, RSA.

Smithers, JC, Schulze, RE, Lecler, NL, Kienzle, SW, Lorentz, SA and Kunz, RP. 1995. User guidelines for setting up information. *In*: Smithers, JC and Schulze, RE. *ACRU Agrohydrological Modelling System : User Manual Version 3.00.* Water Research Commisiion, Pretoria, Report TT70/95. pp AM6.12 -42

Thompson, GD.1976. Water use by sugarcane. *South African Sugar Journal* 60: 598-600

Thompson, AL, Martin, JM, Norman, JA, Tolk, TA, Howell, JR, Gilley, JR and Schneider, AD. 1997. Testing of a water loss distribution model for moving sprinkler systems. *Trans. ASAE* 40(1): 81-88.

Tolk, JA, Howell, TA, Steiner, JL, Krieg, DR and Schneider, AD. 1995. Role of transpiration suppression by evaporation of intercepted water in improving irrigation efficiency. *Irrigation Science* 16: 89-95.

USDA, 1985. National Engineering Handbook, Section 4, Hydrology. United States Department of Agriculture (USDA), Soil Conservation Service, Washington DC, USA

Van der Stoep, I, Benade, N, Smal, HS and Reinders, FB. 2005. *Guidelines for Irrigation Water Measurement in Practice.* WRC Report No TT248/05, Water Research Commission, Pretoria, RSA.

Willmott, CJ. 1981. On the validation of models. *Physical Geography* 2:184-194.

WRC. 1999. *Technical Report 1998- Water Research Commission*. Water Research Commission, Pretoria, RSA.

APPENDIX A - A REVIEW OF SIMULATION MODELS TO ASSESS THE PERFORMANCE OF SUGARCANE IRRIGATION PRACTICES

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1. Introduction

There were two primary reasons to identify and apply irrigation and crop growth simulation models. The first was to establish the recommended or "standard" crop and irrigation water demand of sugarcane grown in the study area. The second was to use an appropriate model to investigate how different irrigation system management scenarios impact on crop yields, water use and associated irrigation performance indicators including those relating to profitability. Seven models were identified and investigated as potential candidates to fulfil these two criteria. They were:

- *ZIMsched 2.0 (FAO-56)*, developed by Lecler (2003),
- *ZIMsched 2.0 (ECANE)*, developed by Lecler (2003),
- *SAsched*, developed by Lecler (2004),
- *ACRUcane*, developed by Moult *et al.* (2006),
- SWB, developed by Annandale *et al.* (1999),
- SAPWAT, developed by Crosby and Crosby (1999), and
- CANESIM, developed by Singels *et al.* (1998).

The objective of these investigations into different models was to identify a tool to establish best management practices applicable to the study area. The purpose of the analysis was not to compare and rank different models against each another, but rather to investigate the functionality and application potential in relation to the proposed methodology in order to answer questions such as:

- Does the model account for all the components of a daily water budget and how are the components simulated by the model?
- What level of input data/information is needed to run the model and are these readily available?
- What are the outputs of the model and how useful are these outputs?

However, having answered these questions, it is important that the results from the model with the required functionality are not compromised by poor simulations. Therefore, a comparison, relative to a defined "standard", of the simulated results from each of the models was performed to investigate the performance of the models.

In this appendix, each model is introduced and the concepts used in their development are discussed. With the results that are presented, cognisance must be taken of the fact that it was not the purpose of the chapter to validate or verify each of the models. The validation and verification of each model has already been achieved by the model developers (Singels *et al.*, 1998; Annandale *et al.*, 1999; Crosby and Crosby, 1999; Lecler, 2003; Lecler, 2004; Moult *et al.*, 2006). Therefore, outputs will not be compared against actual measured data, but rather against a defined "standard", which will be identified as one of the model outputs.

2. *ZIMsched 2.0*

ZIMsched 2.0 is a deterministic crop and irrigation systems simulation model (Lecler, 2003). The model is a refinement of the original spreadsheet-based irrigation scheduling and crop yield simulation model (*ZIMsched*) which was developed by Lecler (2000).

2.1 Model description

The refinements that were made to *ZIMsched* to produce *ZIMsched 2.0* were done to investigate how water management, different irrigation systems and in-field measures of irrigation system performance, such as the distribution uniformity, DU, impact on crop yields, irrigation water requirements and water use efficiency. Lecler (2003) emphasised that *ZIMsched 2.0* is unique in this regard in that it is capable of investigating how different levels of in-field irrigation system performance, for example, the DU, impact on the water budget of the irrigated field and consequently on simulated yields of sugarcane. In *ZIMsched 2.0*, this is achieved by quantifying all the components in a daily water balance in a spatially representative manner. This section introduces and discusses the processes used to quantify the different components of this water balance.

The first components of the water balance are crop transpiration and evaporation from the soil surface. According to Lecler (2003), evaporation from the cropped surface (evapotranspiration) is a function of the climatic conditions, soil water status, crop canopy and rooting characteristics. In *ZIMsched 2.0* evaporation from the soil and crop are determined separately by using the algorithms developed by Allen *et al.* (1998) in FAO Irrigation and Drainage Paper No. 56. Lecler (2003) emphasises that separating these two processes is important because prior to the development of significant canopy cover, water is predominately lost by evaporation from the soil surface. As much as 100% of evapotranspiration comes from evaporation from the soil surface when the crop canopy is not well developed. However, once a full crop canopy has developed, more than 90% of evapotranspiration is due to crop transpiration (Allen *et al.*, 1998). Evaporation from the soil surface is also dependant on the type and management of irrigation system being used. In addition

to variations due to different management approaches, different types of irrigation systems have different typical wetting frequencies and wet different fractions of the soil surface.
The *ZIMsched 2.0* method of determining crop transpiration differs from the Allen *et al.* (1998) methodology in that crop development and hence transpiration is a function of accumulated thermal time and is not based on calendar days. Lecler (2003) motivated this change because the rate of canopy development in sugarcane is dependant on temperature. Therefore, to facilitate this change, Lecler (2003) determines an average crop coefficient and then relates the basal crop coefficient to the average crop coefficient. The relationship between an average crop coefficient for sugarcane and thermal time, for the period from germination to full canopy, is determined using a relationship developed by Hughes (1992). The relationship was derived from lysimeter data and included one plant and four ratoon crops. The relationships between the basal crop coefficient and the different values of average crop coefficient were then determined by Lecler (2003). These relationships were validated by Lecler (2003) using data recorded at the Zimbabwe Sugar Association Experiment Station. Crop transpiration is then determined by multiplying the basal crop coefficient with the atmospheric evaporative demand (AED). In *ZIMsched 2.0*, AED was initially represented by USWB Class A-pan measurements. However, Lecler (2005) made refinements to *ZIMsched 2.0* such that AED can also be represented by Penman-Monteith short grass reference evapotranspiration, as defined by Allen *et al.* (1998), or by a modified version of the Penman-Monteith equation reference evapotranspiration developed specifically for sugarcane by McGlinchey and Inman-Bamber (1996). For the purpose of this review, the A-pan version of *ZIMsched 2.0* was excluded due to a lack of reliable data in the study area and the two different Penman-Monteith references were utilised. The version that uses Penman-Monteith short grass as a reference for evapotranspiration is referred to as *ZIMsched 2.0 (FAO-56)* and the sugarcane reference evapotranspiration version is referred to as *ZIMsched 2.0 (ECANE)*. For descriptive purposes, when the term *ZIMsched 2.0* is used, reference is being made to both versions.

ZIMsched 2.0 calculates evaporation from the soil surface by the product of a soil evaporation coefficient and AED. Evaporation from the soil surface takes place in two stages. The first stage involves evaporation when the soil surface is wet following a rainfall or irrigation event. The second stage of evaporation occurs when a certain amount of water has evaporated from the surface. The rate at which soil evaporation occurs is consequently much higher during the first stage. The methodology used by *ZIMsched 2.0* is adopted from Allen *et al.* (1998). Lecler (2003) made two changes to the Allen *et al.* (1998) methodology, namely to allow transpiration to occur from soil moisture stored in the upper soil layer and to account for runoff. Allen *et al.* (1998) reserved the upper soil layer for evaporation from the soil surface only. Lecler (2003) refined this, reasoning that substantial sugarcane root activity occurs in this upper soil layer.

Stormflow, or surface runoff, is also accounted for in *ZIMsched 2.0*. According to Lecler (2003), surface runoff needs to be simulated in order for rainfall effectiveness to be estimated. In *ZIMsched 2.0*, surface runoff is defined as the water that is generated on or near the surface from a rainfall and/or irrigation event (Lecler, 2003). In *ZIMsched 2.0* the surface runoff is estimated using the Soil Conservation Service (SCS) (USDA, 1985) stormflow equation as modified by Schulze (1995a). A major difference between Equation used by Lecler (2003) 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 (1995a). 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

ZIMsched 2.0 does calculate drainage through the soil profile. Lecler (2003) explains that drainage is only initiated if the soil water content is higher than the drained upper limit for the soil. 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. 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, e.g. as used in SAPWAT, 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. Lecler (2005) reports that he has frequently observed such discrepancies with the over-simplified, hand-calculated water budgets typically used on the sugar estates in the Lowveld of Zimbabwe. 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 and the 'time-to-drain' underestimated.

An estimation of crop yield is important to establish the performance of a predetermined irrigation system and the level of management. The algorithm used in *ZIMsched 2.0* to estimate yields of estimated recoverable crystal (ERC) 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 irrigation 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 versus ET relationship. The reference potential sucrose estimate in *ZIMsched 2.0* is adjusted according to the timing and magnitude of any water stress that may have occurred during the growing season using procedures based on research by de Jager (1994) and Doorenbos and Kassam (1979).

ZIMsched 2.0 incorporates irrigation system performance parameters, i.e. either the statistical uniformity, SU, coefficient of uniformity, CU, or low quarter distribution uniformity, DU_{lq}, index, in order to estimate the impact of irrigation system performance on crop yield (Lecler, 2003). This is achieved by simulating three different water budgets on three equally sized portions of the irrigated field. Each area receives a different depth of irrigation dependant on the specified performance of the simulated irrigation system. One third of the irrigated field receives the mean application, one third receive the mean application less a certain deviation percentage ($D_{\%}$) and the remainder of the field receives the mean application plus a certain deviation percentage ($D_{\%}$). Lecler (2003) assumed the distribution of applied irrigation water was normally distributed in a field.

ZIMsched 2.0 is therefore capable of being used to differentiate between different types of irrigation systems. In addition to having a comprehensive and representative water budget, differences in soil water evaporation between different types of irrigation system are represented and the actual performance of those irrigation systems in terms of application uniformity is also represented by utilising the multiple water balance approach.

2.2 Model inputs

Lecler (2003) stated that soil, management and climate data are required to perform simulations with the *ZIMsched 2.0* model. These data are given below.

Management data:

- starting date of simulation,
- planting/harvest date,
- irrigation schedule,
- irrigation system, and
- in-field irrigation systems parameters (distribution uniformity).

Soil data:

- soil depth,
- drainage characteristics (slow, average or fast), and
- soil texture.

Climate data:

- maximum and minimum temperature,
- rainfall, and
- AED, represented as:
  - Penman-Monteith short grass reference evapotranspiration for *ZIMsched 2.0 (FAO)*, or
  - McGlinchey and Inman-Bamber (1996) sugarcane reference evapotranspiration for *ZIMsched 2.0 (ECANE), or*
  - USWB Class A-pan data for the version of *ZIMsched 2.0* developed using A-pan data.

2.3 *ZIMsched 2.0* summary

In summary, Lecler (2003) utilised the incorporation of the FAO 56 methodologies described by Allen *et al.* (1998) because they are currently widely accepted as a world standard in estimating crop water requirements. The addition of a canopy development process that is related to accumulated thermal time was found to be very reasonable when compared against measured LAI data (Lecler, 2003). The runoff and drainage algorithms were based on well tested methodologies used in the *ACRU* agrohydrological model developed by Schulze (1995a).

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 observation 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.

In terms of the capability of *ZIMsched 2.0* to simulate and account for in-field irrigation systems performance, a study by Ascough and Lecler (2004) showed that *ZIMsched 2.0* with the multiple water budget approach was sensitive to both under- and over- irrigation. Therefore, *ZIMsched 2.0* was unique in its capabilities to successfully account for such processes and is therefore a suitable tool for comparing one management system with another in relative terms (Lecler, 2003).

In terms of inputs, *ZIMsched 2.0* is not data demanding and many of the required inputs have default values. The water holding capacities of soils are defaulted according to texture. Therefore, climate data are the only inputs that need to be obtained. Fortunately, SASRI has reliable weather data for all the sugarcane growing areas within South Africa, and therefore obtaining climate data is not an arduous task.

ZIMsched 2.0 is a sugarcane specific model. However, it would be possible to include other crops in the model. To achieve this, the different growth stages would have to be based on calendar days and not thermal time. This is due to the large amount of research required to obtain thermal time relationships for all different crops. The result of such an exercise would be a model based on FAO-56 crop factors and crop growth stage lengths, but with the advantage of a comprehensive water budget that can account for deep percolation, runoff and the affects of too little or too much water. Crop yield could also be included by using Allen *et al.* (1998) recommended yield algorithms from FAO-56.

Lecler (2003) summarized the capabilities of *ZIMsched 2.0* with the following statement: "*ZIMsched 2.0* has potential to be used to plan, design and evaluate, *inter alia*, irrigation strategies, taking into account the effects of different water application targets, scheduling practices, irrigation systems and irrigation systems performance measures on crop production, using commonly available data/information". Therefore, it is concluded that *ZIMsched 2.0* is a model that could be used in this study.

The next model to be described is the *SAsched* simulation model. It was developed by Lecler (2004) and has had subsequent modifications made to it by the author for the purpose of this project.

3. *SAsched*

The original *SAsched* model was a spreadsheet-based water management and yield forecasting tool. It was developed to be a user friendly tool that could be applied near-real time to assist sugarcane irrigation farmers in managing their irrigation systems (Lecler, 2004). The author made modifications to *SAsched* that resulted in *SAsched* being turned into a multiple water balance, yield forecasting tool that is capable of accounting for different levels of in-field irrigations systems performance, such as distribution uniformity. The following subsections describe and refer to the new modified version of the *SAsched* model.

3.1 Model description

As is the case with *ZIMsched 2.0*, the new *SAsched* quantifies all the components of a daily water budget. This water budget is based on algorithms and methodologies developed by Allen *et al.* (1998) and Schulze (1995a). It must be noted here that the processes in the new *SAsched* model that account for surface runoff, deep percolation, soil evaporation and crop rooting characteristics are the same as those used in *ZIMsched 2.0*. Therefore, the description of these processes will not be discussed in this section, and can be found in Section 2.1. The processes for calculating yield, both total above ground biomass and ERC yield, are also the same as those found in *ZIMsched 2.0*. The difference between the new *SAsched* model and *ZIMsched 2.0* is the use of a different reference evapotranspiration to account for AED, and a different method of estimating the basal crop coefficient. This new method of estimating the basal crop coefficient is described in the following paragraph.

Unlike *ZIMsched 2.0*, which relates the basal crop coefficient to an accumulated thermal time derived total crop coefficient, *SAsched* relates the basal crop coefficient to a calculated crop canopy cover. The crop canopy cover is estimated using the relationship derived by Singels and Donaldson (2000), which relates crop canopy cover to a thermal time index for different sugarcane row spacings. An average crop coefficient is then estimated from this calculated canopy cover. Following that, the basal crop coefficient is derived from the average crop coefficient. Therefore, the method of calculating the basal crop coefficient in the new *SAsched* model is in principle essentially the same as that used in *ZIMsched 2.0*, the only difference being the way in which the crop canopy cover is estimated.

As already eluded to, *SAsched* uses a different reference evapotranspiration than *ZIMsched 2.0* to represent AED. *SAsched* uses the Penman-Monteith reference sugarcane evapotranspiration developed by McGlinchey and Inman-Bamber (1996).

The modification made to *SAsched* by the author also included the ability to simulate multiple separate water balances in order to represent the effect of in-field irrigation systems performance, such as distribution uniformity, on crop yield. This was achieved by including the Lecler (2003) methodology developed for *ZIMsched 2.0*, as described in Section 1.2.1.

3.2 Model inputs

The new *SAsched* model also requires management, soil and climate data to perform simulations. These data requirements, which are inherently very similar to *ZIMsched 2.0*, are listed below.

Management data:

- starting date of simulation,
- planting/harvest date,
- row spacing,
- plant or ratoon crop,
- irrigation schedule,
- irrigation system, and
- in-field irrigation systems parameters (distribution uniformity).

Soil data:

- soil depth,
- drainage characteristics (slow, average or fast), and
- soil texture.

Climate data:

- maximum and minimum temperature,
- rainfall, and
- AED, represented as the Penman-Monteith reference sugarcane evapotranspiration developed by McGlinchey and Inman-Bamber (1996).

The inputs described above are not exhaustive and are easily obtainable for the different sugarcane growing regions in South Africa. The climate data, which includes the Penman-Monteith reference sugarcane evapotranspiration, is available on the South African Sugarcane Research Institute website (http://sasex.sasa.org.za/irricane/tables, accessed 12/10/2005) for twenty-three locations in South Africa.

3.3 *SAsched* summary

The new modified version of the *SAsched* model now has the same functionality as *ZIMsched 2.0*. It requires the same level of input data, which is not exhaustive, and therefore is an appropriate tool to investigate different irrigation strategies and scenarios with different types and levels of in field irrigation systems performance impact on crop yield. The Singels and Donaldson (2000) method of estimating crop canopy cover that is used to determine crop coefficients are based on accumulated thermal time. This means that climatic effects on crop water use are accounted for, as was the case with *ZIMsched 2.0*. An added advantage of using the Singels and Donaldson (2000) canopy cover to estimate crop coefficients is that the different row spacing, often encountered because of system or management constraints, can be simulated and thus accounted for.

Therefore, in conclusion, *SAsched* is a model capable of fulfilling the requirements that are needed in the methodology described in the previous chapter.

4. *ACRUcane*

The *ACRUcane* model is an irrigated sugarcane sub-model which is linked to water supply in the ACRU model. The *ACRU* model is a catchment scale agrohydrological model which can be used to simulate many different water supply or availability scenarios, of which irrigation water supply is included. Moult *et al.*, (2006) state that the *ACRU* model is capable of testing and assessing different operating, water allocation, water management and water resources development strategies at a catchment scale. However, the *ACRUcane* model can also be run independently from the *ACRU* model, which enables *ACRUcane* to be used to assess different in-field irrigation strategies and the impact of different strategies on crop yield. This section covers the development of the *ACRUcane* model and the methodologies used to estimate the different parameters in the daily water balance. These water balance parameters are sugarcane transpiration, evaporation from the soil surface, deep percolation, rainfall, irrigation and surface runoff. *ACRUcane* also provides an estimate of sugarcane, ERC and sucrose yield and this is also discussed.

4.1 Model description

Moult *et al.* (2006) state that soil evaporation and crop transpiration are simulated separately in *ACRUcane*. This is achieved by using the dual crop coefficient method described by Allen *et al.* (1998). The dual crop coefficient method in *ACRUcane* uses the Penman-Monteith short grass reference evapotranspiration to estimate AED. As was the case with *ZIMsched 2.0* and *SAsched*, *ACRUcane* calculates an accumulated thermal time that is used to determine the basal crop coefficient in the dual crop coefficient approach. Therefore, *ACRUcane* is able to account for climatic effects on crop growth, which is often incorrectly assumed to be negligible with time based crop factor models. Also, like *SAsched*, *ACRUcane* uses the canopy cover algorithms developed by Singels and Donaldson (2000) to determine the basal crop coefficient which is used to estimate crop transpiration (Moult *et al*., 2006). The benefits and needs of a model with the capabilities of distinguishing between crop transpiration and soil evaporation have been discussed in Section 2.1.

Drainage from the soil profile is determined by dividing the soil into two layers. The first layer is the depth of soil occupied by roots and the second is the depth of soil not currently occupied by roots and which decreases as the roots grow. Drainage occurs from one layer into the next, and then finally out from the bottom of the soil profile. The rate at which water percolates out of the soil is a function of soil texture (Moult *et al*., 2006). Runoff is estimated using the Soil Conservation Service (SCS) (USDA, 1985) stormflow equation as modified by Schulze (1995a) and used in *SAsched* and *ZIMsched 2.0*.

In terms of sugarcane crop yield, *ACRUcane* can estimate crop yield using any one of four different methodologies. The first yield estimate is ERC, made using the same methodology as used by Lecler (2003) and Lecler (2004) in *ZIMsched 2.0* and *SAsched* respectively. The second method for determining yield is a radiation based, accumulated biomass estimate which was developed by Singels and Bezuidenhout (2002) for use in the CANEGRO model. The third method that can be used to estimate yield in *ACRUcane* is the Thompson (1976) methodology which simulates sugarcane yield as a function of crop evapotranspiration using an empirical relationship. Finally, *ACRUcane* is also able to estimate yield with the method described by Singels *et al*. (1998). The yield, in tons per hectare, is a function of the accumulated transpiration and is the same method used in CANESIM, which will be introduced in a following section.

The manner in which *ACRUcane* accounts for in-field irrigation system performance is similar to that described by Lecler (2003), as discussed in the *ZIMsched 2.0* section, but the field may be divided into more than 3 sections, each of which receives a different application amount. Advantages of the *ACRUcane* model compared to *ZIMsched 2.0* and *SAsched* models are the inclusion of a 2 layer soil profile, which is very important in a catchment context for the estimation of return flows and the integration with water supply constraints.

4.2 Model inputs

ACRUcane requires management, soils and climate data. The *ACRUcane* model is also run within the larger ACRU model, which has its own data requirements. The *ACRUcane* model does utilise some of the existing ACRU irrigation input data, such as the different irrigation schedules, in its algorithms. The reader is referred to Smithers and Schulze (1995) for a detailed description of the ACRU data requirements to apply *ACRUcane* within the ACRU model for a catchment level assessment. However, for the purposes of this research, the *ACRUcane* model was run independently of the ACRU model and as such did not require a full ACRU model configuration. The list of sugarcane specific data that was required to run the model is presented below.

Management data:

- starting date of simulation,
- planting/harvest date,
- row spacing,
- plant or ratoon crop,
- irrigation schedule,
- irrigation system, and
- in-field irrigation systems parameters (distribution uniformity).

Soil data:

- soil depth, and
- soil texture.

Climate data:

ACRUcane was based on FAO guidelines and as such required Penman-Monteith reference short grass evapotranspiration to represent AED. Moult (2005) incorporated the routines described by Allen *et al.* (1998) to calculate the Penman-Monteith reference short grass evapotranspiration. Therefore the model can be run in situations with limited data, or can be applied where the full range of measured climate data is available. As a minimum, the model requires minimum and maximum daily temperature, and daily rainfall.

4.3 *ACRUcane* summary

ACRUcane is a sugarcane and irrigation crop growth model. *ACRUcane* does account for all the different components in a daily water balance and therefore would be suitable for use in this study. *ACRUcane* also accounts for different irrigation systems and the level of in-field performance of those systems. Therefore, as was the case for *ZIMsched 2.0* and *SAsched*, *ACRUcane* could be used to investigate the impact of in-field irrigation system performance on yield. *ACRUcane*, even though it is a daily time step model, does not require exhaustive inputs and many of the inputs, such as Drained Upper Limit, DUL, and Permanent Wilting Point, PWP, for the soil can be calculated by using one of the default soil textures. In terms of climatic inputs to estimate the Penman Monteith reference grass evapotranspiration, *ACRUcane* uses the FAO 56 (Allen *et al.*, 1998) recommended methodologies to estimate evapotranspiration with limited climatic data.

In terms of accurately predicting crop yield, *ACRUcane* is well suited with four different methods of estimating sugarcane yield, which have been verified by Moult (2005) using data from La Mercy and Zimbabwe.

ACRUcane, together with the larger *ACRU* model, is a very good tool to investigate water supply and demand interactions with irrigation at a catchment scale. Although these catchment water supply interactions were not identified as an important factor in the study area, they could be important in other case studies or research projects. None of the other models that were reviewed in this chapter are capable of linking catchment water supply to irrigation demand and simulating the interactions between them. Therefore the *ACRUcane* and *ACRU* models are superior in this regard. Moult *et al.* (2006) concluded along the same lines by saying that *ACRUcane* could be used to determine impacts of a given area of irrigated sugarcane on water availability for a wide range of irrigation systems and water management scenarios. However, at present, the superior model characteristics present in *ACRUcane* are only available to account for sugarcane, therefore other crops need to be added to the *ACRUcane* model so that it can be utilised on any irrigation scheme.

While *ACRUcane*, *ZIMsched 2.0* and *SAsched* are all sugarcane specific models, the Soil Water Balance (SWB) model is a generic crop growth model capable of simulating a wide range of South African crops. SWB is reviewed in the next section.

5. SWB

The SWB model is a mechanistic, real time, generic crop, soil water balance, irrigation scheduling model (Annandale *et al.*, 1999). This section introduces and discusses the processes used in SWB to simulate the soil-plant-atmosphere continuum and the data requirements needed to run simulations with the model.

5.1 Model description

The SWB model can simulate plant processes with one of two sub-models. The first is the crop growth model, which calculates crop growth and soil water balance parameters mechanistically. The second one is a FAO-type crop factor model which calculates the soil water balance without simulating dry matter production mechanistically. Annandale *et al.* (1999) motivated the inclusion of the FAO crop parameters to include more crops in the SWB database. The FAO database that is used in SWB includes the basal crop coefficients, growth periods, root depths, crop heights, stress factors and potential yields for a wide range of crops. Annandale *et al.* (1999) state the crop growth model in SWB makes use of three separate units, namely the weather, soil and crop unit.

Weather unit

The weather unit calculates the Penman-Monteith grass reference daily evapotranspiration, which SWB uses to estimate AED. The procedures which are used in the weather unit are those recommended by the FAO and are dependant on the level of input data available (Smith *et al.*, 1996; Smith, 1992; cited by Annandale *et al.*, 1999).

Soil unit

The SWB model uses a multi-layer soil, and the movement of water from one layer to the next is simulated by a cascading soil water balance (Annandale *et al.*, 1999). SWB uses the Penman-Monteith grass reference evapotranspiration to estimate potential evapotranspiration which is divided into potential evaporation from the soil surface and potential plant transpiration. The soil unit simulates whether the supply of water from the soil to the surface or the plant is limiting the soil and plant evaporation processes. The root density weighted average soil water potential is also determined in the soil unit and is used to describe the water supply capabilities of the soil-root system (Annandale *et al.*, 1999). If the soil is unable to supply water at the potential rate, the potential transpiration is reduced to actual transpiration, which is indicative of plant stress, and crop development is reduced accordingly. The corresponding leaf area index during these periods is also reduced. Therefore, if favourable growing conditions occur after a period of severe stress, crop transpiration will not resume at the same rate as before the severe stress period because of the corresponding reduction in leaf area index. Annandale *et al.* (1999) emphasise that this facility in SWB makes the crop growth model suitable for predicting crop water requirements when deficit irrigation strategies are applied, especially where the deficits are severe enough to impact on the crop canopy development and recovery.

Crop unit

The crop unit in SWB calculates the accumulated crop dry matter and then partitions it into the roots, stem, leaves and grain or fruits. The dry matter accumulation is directly proportional to the crop transpiration (Annandale *et al.*, 1999).

The SWB method calculates evaporation from the soil surface and crop transpiration separately (Annandale *et al.*, 1999). The evaporation processes are driven by evapotranspiration potential in the atmosphere, determined in the weather unit, and the fractional radiation intercepted by the crop, which is calculated in the crop unit (Annandale *et al.*, 1999). The actual evaporation from the soil surface and crop transpiration are then calculated in the soil unit as the actual transpiration values depend on the prevailing soil water status and resistances to water transport within the plant. This effectively means that as the crop grows and intercepts more incoming radiation, the potential evaporation from the soil surface will be reduced and the potential crop transpiration increases. However, the actual values of evaporation and transpiration are ultimately determined in the soil unit.

In the SWB crop growth model, crop transpiration is a function of the soil matrix potential, which is essentially the combination of prevailing soil water status and climate conditions. If the soil matrix potential is low, potential transpiration is reduced. The loss of soil moisture due to transpiration is also a function of the plant water xylem potential and the root fraction in the soil, which is a function of the rooting depth relative to the soil layer depth. A detailed description of the procedures used in SWB to estimate transpiration is provided by Annandale *et al.* (1999).

Evaporation of water from the soil surface in SWB is calculated for the uppermost soil layer only. Evaporation from the soil surface also decreases with increasing canopy cover as a result of the corresponding increase in the interception of radiation. Evaporation from the soil surface continues at a maximum rate until the permanent wilting point of top soil layer is reached (Annandale *et al.*, 1999). It must be noted that no transpiration occurs from water stored in the uppermost soil layer, and therefore the soil water in this layer is reserved exclusively for soil water evaporation. This concept can lead to errors as most of sugarcane root activity occurs in the upper soil layer. Therefore, should this layer be too deep, crop transpiration and therefore crop evapotranspiration results may be misleading. The soil water evaporation procedures in SWB differentiate between different irrigation systems with different wetted fractions. Therefore, the effect of different irrigation systems on total water use can be simulated.

In SWB, runoff is calculated on days when either rainfall or irrigation occur, either individually or simultaneously. Runoff is calculated with a semi-empirical formula and is assumed to occur when precipitation or irrigation is greater or equal to the infiltration and surface storage capacities of the soil (Annandale *et al.*, 1999). If the sum of precipitation and irrigation is less than 20% of the surface storage capacity of the soil, runoff is assumed to be zero. If the sum of precipitation and irrigation is greater than 20% of the surface soil storage capacity of the soil, surface runoff is calculated. The storage capacity of the soil surface is a function of a runoff curve number of the soil, which is an input parameter in the model. Once runoff has been initiated, i.e. the soil surface storage capabilities were not capable of absorbing the precipitation or irrigation event, runoff increases with increasing precipitation or irrigation (Annandale *et al.*, 1999).

In SWB, a cascading soil water balance is utilised in the multi-layer soil component of the model, thereby ensuring a realistic simulation of infiltration, redistribution and drainage processes (Annandale *et al.*, 1999). These processes are simulated on days when irrigation or precipitation occurs. On days when rainfall or precipitation does not occur, water is extracted from each layer according to the root density in that layer. The soil water deficit for each layer in the multi-layer soil is calculated by relating the current soil water status to the volumetric soil water content in a specific layer. When SWB calculates drainage, it is assumed to occur in a cascading fashion from the top soil layer to the bottom soil layer and eventually out the bottom of the soil profile. If the amount of water penetrating a specific layer is larger than the difference between field capacity and saturation, the drainage into the next soil layer is reduced by the difference between the actual soil water content and saturation. If the amount of water penetrating a specific layer is less than the soil water holding capacity of that layer, the drainage into the next soil layer set to zero. The water content at saturation is a function of the soil bulk density, and is therefore different for different types of soil.

The maximum drainage rate per day can vary from a value of zero, which could be the case when an impermeable layer prevents drainage from the soil, to several hundred millimeters per day for very sandy soils. With the drainage factor and the maximum drainage rate per day, SWB is capable of simulating a shallow water table caused by soils with very slow drainage rates. If large amounts of precipitation or irrigation are encountered on a soil with a slow drainage rate, the level of the water table rises in the soil. If the water table reaches the surface, excess water then becomes runoff (Annandale *et al.*, 1999).

5.2 Model inputs

Annandale *et al.* (1999) mention that in order to simulate crop water use with SWB, management, weather and soil inputs are required as inputs into the model. The essential data requirements in each of these categories are given in the list below.

Management data:

- starting date of simulation,
- planting date,
- irrigation schedule,
- irrigation system, and
- field area.

Soil data:

- runoff curve number,
- drainage fraction and maximum drainage rate,
- soil layer:
  - thickness
  - volumetric soil water content at field capacity and permanent wilting point,
  - initial volumetric water content, and
  - bulk density.

Weather data:

- latitude,
- maximum and minimum daily temperatures, and
- precipitation.

The data requirements given above represent the minimum required to perform a simulation. The soil data, which are typically regarded as the hardest inputs to acquire, can be simplified by generating a multilayered soil in which each layer has the same properties. This effectively creates a uniform soil in the model. Should more detailed weather data, i.e. solar radiation, wind speed, relative humidity and vapour pressure, be available to assist in computing the reference grass evapotranspiration for AED, these can be entered and used. The author acknowledges that SWB was not a complicated model to run. All the data requirements to perform a satisfactory simulation were readily available.

5.3 SWB summary

The SWB model accounts for all the components in the daily water budget. It also relies on an accumulated thermal time to grow the crop mechanistically. Therefore it is able to account for variations in climate during the growing season. The fact that SWB can reduce the Leaf Area Index under conditions of severe stress makes it unique in its capabilities to simulate crop water use under severe water deficits. This is facilitated by of the reduction in leaf area index and the changing rates of transpiration during and after these periods of severe stress.

SWB also does not require exhaustive inputs to run a simulation. This was highlighted in the previous section. The minimum data requirements needed for simulations are easily obtainable. Should more detailed input data be available, the quality of the simulation would be increased. Climate data are needed to generate the Penman-Monteith short grass reference which is used to estimate AED, and soils and crop information are needed to grow the crop.

Therefore, as a generic crop growth model, SWB is very well suited to investigate crop and irrigation water requirements in South Africa. However, with specific reference to sugarcane, SWB is presently only capable of simulating a plant crop, which is not ideal. Furthermore the parameters used in SWB to simulate the growth and development of sugarcane need to be refined and verified (Annandale *et al.* 1999). Another disadvantage is that SWB does not account for infield irrigation systems performance like the *ZIMsched 2.0, SAsched* and *ACRUcane* models do.

6. SAPWAT

This section deals with the SAPWAT computer program developed by Crosby and Crosby (1999). The acronym stands for "South African Procedure for determining crop WATer requirements".

6.1 Model description

SAPWAT utilizes the four stage FAO crop factor approach to determine crop factors (Crosby and Crosby, 1999). This approach is based on different crop growth stages with different lengths, represented by calendar days. The AED in SAPWAT is represented by monthly average Penman-Monteith grass reference evapotranspiration values. The reference evapotranspiration values are then multiplied by a crop factor to yield the actual crop evapotranspiration.

SAPWAT accounts for variations in soil water evaporation which occur as a result of different wetting frequencies. The procedures to achieve this are similar to those described in the "single crop coefficient" approach by Allen *et al.* (1998) where the value of the initial crop coefficient is varied depending on the wetting frequency However, in the 'management' section of SAPWAT, this averaged initial crop coefficient is fixed despite the user, possibly exploring further variations in watering strategies/frequencies. This means that when using the 'management' section of SAPWAT, variations in soil water evaporation associated with different watering strategies are not well represented.

SAPWAT does not determine surface runoff and drainage separately. Rather, a value for the amount of irrigation water and rainfall that is "lost" is calculated. SAPWAT calculates both a rainfall loss and an *irrigation* water loss. The amount of rainfall loss is the difference between total rainfall and effective rainfall, and is described in SAPWAT as the "Total Rain Loss". The quantity of irrigation water that is lost to runoff and drainage is referred to in SAPWAT as the "Total Irrigation Loss". The total irrigation loss is the difference between the total irrigation water applied and the actual irrigation water requirement. The actual irrigation water requirement is calculated by subtracting the effective rainfall from the actual crop water use. Therefore, it can be noted that the determination of both the actual irrigation water requirement and the consequently the losses in SAPWAT ultimately depends on the correct estimation of effective rainfall.

Crosby and Crosby (1999) state that in SAPWAT, effective rainfall is calculated for each month using the well established Soil Conservation Service routine quoted by Jensen *et al.* (1989). The routine estimates the mean monthly effective rainfall stored in the soil as a function of mean monthly rainfall, the average monthly evapotranspiration of the crop and the normal depth of soil depletion prior to the irrigation event (Jensen *et al.*, 1989). Whilst the calculation of a gross rainfall and irrigation loss is useful for interpreting different irrigation strategies, the inability of SAPWAT to differentiate between surface runoff and deep percolation makes it unsuitable to scientifically examine different irrigation management practices. However, Crosby and Crosby (1999) acknowledge that SAPWAT is not a crop growth model. Therefore the need to differentiate between runoff and deep percolation did not form part of SAPWAT's "designing for management" objectives. The way that monthly rainfall is divided into user specified events could also lead to problems when using SAPWAT to assess various water management strategies.

SAPWAT does have procedures to account for irrigation system performance in the determining irrigation water requirements. Two efficiency values are used to describe the overall performance of the irrigation system. The first is the efficiency of the water conveyance and storage system in an irrigation system. The second term is to describe the distribution uniformity of the in-field irrigation systems. A combination of the two efficiency factors is used to convert the net irrigation requirements into a gross value based on procedures described by Ascough (2001). These procedures are based on the assumption that an irrigation event would be terminated when the target irrigation water application depth or soil water depletion would just be met by the average of the values in the low quarter of the irrigation infiltration distribution.

The two efficiency factors can be used to investigate how different system efficiencies could potentially impact on overall water use, provided that there is an awareness that it is based on the simplifying 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 an assumption may not be optimal and needs to be tested/evaluated for different circumstances, for example, deficit irrigation or when considered in combination with different irrigation scheduling strategies. The conversion from net to gross irrigation requirements in SAPWAT also implies certain fixed assumptions regarding the timing and magnitude of irrigation events. SAPWAT is, therefore, not ideal for a representative and integrated assessment of how efficiency, uniformity and water management impact on crop yield and the water budget.

6.2 Model inputs

When it comes to inputs, SAPWAT is the least demanding of the models reviewed thus far. Like all of the models, SAPWAT requires management, soils and climate information to perform crop water use simulations. However, the provision of a "built-in" climate database, though limited in coverage, can make it easy for a user to obtain simulation results. However, representative climate data is not always available in the database. The inclusion of a climate database means that, ideally, a user need only select a climate data set that is most representative for their particular simulation scenario. Once achieved, monthly means for ten years of historical data is provided. Therefore, only management and soil information really need to be specified. In these areas as well, SAPWAT has been geared to be a very user friendly model. The following list is what needs to be entered by a user in terms of management and soil data.

Management data:

- planting date of crop,
- type of irrigation system,
- efficiency of water conveyance and application,
- irrigation application depth, and
- schedule by which water is applied.

Soil data:

- soil depth,
- soil type (one of five default soil textures), or,
- customised soil, for which the following are required:
  - total available moisture,
  - rain infiltration rate,
  - initial available soil moisture, and
  - rooting depth (if different from soil depth).

6.3 SAPWAT summary

SAPWAT was an important model to include in the investigation. It has been identified in a schedule to Section 56 (1) of the National Water Act (1998) as the tool to be used to estimate crop and irrigation water requirements in South Africa. Therefore, it has become a *de facto* standard for estimating these quantities. To put this in perspective with this investigation, it is important that the accepted "standard" decided on in this chapter must be close in value to SAPWAT or must be values calculated with SAPWAT. This is because of the fact that it has already been accepted as a standard for determining crop water requirements even though users can obtain very different estimates for the same crop and area dependent on SAPWAT input parameters.

However, in terms of this study, SAPWAT is not suitable to determine "standard" irrigation and crop water requirements. The reasons for this are that it relies on long term monthly means to calculate a modified daily water budget. Over the short term, or when comparing particular seasons, this could lead to substantial inaccuracies because of infrequent climatic events that may be included in the monthly means. For example, should the mean average rainfall used in the model not be a true reflection of the precipitation in a particular study area, actual irrigation requirements may be underestimated. Given the status of SAPWAT and with regard to its widespread use, such an inaccuracy could have serious repercussions in terms of return on investment. SAPWAT also does not include an accumulated thermal time into its calculations to account for seasonal effects on crop growth. These are important characteristics that are needed in the chosen model to determine the "standard" requirements. These points are not meant to detract from the strengths of SAPWAT and the developers, Crosby and Crosby (1999), state that it was not designed as a crop growth model and thus this functionality was not included in the development.

SAPWAT is also not capable of determining the impact of in-field irrigation system performance on crop yield.

7. CANESIM

This section introduces and discusses the CANESIM simulation model, as initially developed by Singels *et al.* (1998) and with subsequent additions and improvements.

7.1 Model description

CANESIM was developed as a simple, computerised, weather based irrigation scheduling procedure for use in the South African sugarcane industry (Singels *et al.*, 1998). The CANESIM daily water balance is calculated for a single soil layer. The components of the water balance that are accounted for include effective irrigation or rain reaching the soil surface (which is dependant on crop interception), drainage, runoff, crop transpiration and soil evaporation. CANESIM is also not a data intensive model, and consequently the inputs needed to run simulation are not excessive. Work completed by Singels *et al.* (1998) found that CANESIM was an appropriate tool to support irrigation planning and management. Planning and evaluation strategy comparisons are facilitated by inputs which are not exhaustive and users need only supply variables such as irrigation cycle, total available moisture and allowable depletion and refill levels. Therefore, CANESIM meets the requirement of this study and is included in this review.

The fact that CANESIM is not a data intensive and a complicated model to run has made it well received within the South African sugarcane industry. The model requires climate, soil, irrigation and management inputs. The climate data needed to run a simulation is acquired when the user selects a representative weather station closest to their field of interest. The irrigation inputs are dependant on the scheduling of irrigation applications and the irrigation system used.

CANESIM does calculate evaporation from the soil surface and plant transpiration separately. Plant transpiration is a function of the fractional interception of light by the crop canopy and a relative water stress index (F_v). The crop canopy cover, which is needed to determine the fractional interception of light, is calculated using the Singels and Donaldson (2000) methodology. The water stress index is a function of soil moisture. When soil moisture is above 50% of total available moisture, $F_v = 1$. Below a soil moisture of 50% total available water, F_v decreases linearly with decreasing available soil water content to a value of zero at permanent wilting point (Singels *et al.*, 1998). The McGlinchey and Inman-Bamber (1996) sugarcane reference evapotranspiration is used to represent AED for the CANESIM model. Thus both crop transpiration and evaporation from the soil surface are driven by that reference.

Evaporation from the soil surface is dependant on a relative soil surface wetness index Singels *et al.* (1998) state that this soil index is weighted by the unit area wetted during a wetting event and is calculated as a function of days elapsed since the last wetting event. This process of determining F_s is also dependant on whether the wetting event is a result of rain or irrigation and also a function of the type of irrigation system. CANESIM calculates soil water evaporation by introducing an evaporation pool which is maintained by additions from irrigation and rainfall and subtracting soil evaporation. Once the water in this evaporation pool is depleted, there will be no further soil evaporation until further addition of water (Singels *et al.*, 1998).

Singels *et al.* (1998) state that CANSIM does estimate runoff and drainage that may result from excess rain or irrigation water in the soil profile. Drainage occurs at a rate of 40% per day of the surplus water above total available moisture in the soil. Therefore drainage is not a function of the type of soil and is a function of antecedent soil moisture conditions only. Runoff is calculated as the amount of excess water above the saturated available water content. Singels *et al.* (1998) assumed the saturated water content to be 200% of total available moisture. Although runoff and drainage are calculated in the model in a relatively simplistic fashion, they are not generated as outputs and therefore cannot be investigated.

Sugarcane yield in CANESIM is estimated with a procedure described by Singels *et al.* (1998). The yield, in tons per hectare, is a function of the accumulated transpiration, which is determined with the CANESIM daily water budget. The yield relationship was developed by fitting a second order polynomial to Canegro simulated stalk dry matter and simulated cumulative transpiration for numerous widely varying situations (Singels *et al.*, 1999).

7.2 Model inputs

The CANESIM model requires management, soil and climate inputs to run a simulation. The climate data needed to run a simulation is acquired when the user selects a representative weather station closest to their field of interest. The irrigation inputs are dependant on the scheduling of irrigation applications and the irrigation system used. The required management and soil inputs are highlighted in the list below.

Management data:

- crop start date,
- crop harvest date,
- irrigation schedule, and
- irrigation system.

Soil data:

- total available soil moisture.

7.3 CANESIM summary

CANESIM operates on a daily time step and accounts for all the components of a daily water balance, namely crop transpiration, evaporation from the soil surface, crop interception, rainfall, irrigation, surface runoff and deep percolation. It is also a crop growth model in that it uses and accumulated thermal time index to grow the crop with the Singels and Donaldson (2000) canopy cover. CANESIM can differentiate between four different types of irrigation systems and has several irrigation scheduling options. CANESIM does not require exhaustive inputs and is a simple tool that can be used by farmers and scientists alike via the internet. This simplicity and easy internet access has made CANESIM well accepted within the South African sugarcane industry. It is already regarded as the tool to determine "standard" crop and irrigation water requirements with the industry. It also estimates a sugarcane yield for a given irrigation schedule and management approach. These facts make CANESIM a suitable model to determine "standard" crop and irrigation water requirements in the study area.

The following section presents results of simulations done with each of the models that have been described in the preceding sections. It is necessary to emphasise once again that the purpose of the analysis is not to compare and rank different models against one another, but rather to investigate the functionality and ease of application of the models in relation to the proposed methodology, while at the same time ensuring that the simulated output are reasonable.

8. Results

To compare the outputs of the different models, weather data from SASRI was utilised. Seven years of data, 1997 to 2004, from the Pongola automatic weather station situated in Northern KwaZulu-Natal (27° 24' S; 31° 35' E; 308 m ASL) was downloaded from the SASRI website (http://sasex.sasa.org.za/irricane/tables, accessed 12/10/2005). These weather data were then combined with soils and irrigation scheduling information to simulate total sugarcane evapotranspiration. In order to account for differences in sugarcane evapotranspiration during the year, four typical harvest dates were simulated for each of the seven years of weather data. These four simulated harvest dates were 1st May (autumn), 1st July (winter), 1st October (spring) and 1st December (summer). The growth period of each simulation was 12 months from harvest date to harvest date.

8.1 Soils and irrigation scheduling information

To ensure that the results would be comparable, each of the inputs used to run simulations needed to be identical. These soil and irrigation inputs are shown in Table 8.1. It is noted that each of the models have different input requirements. For example, *ZIMsched 2.0*, *SAsched*, *ACRUcane* and SWB are more data demanding than both CANESIM and SAPWAT. However, each of the models was used as recommended by the model developers, *viz* Lecler (2003), Lecler (2004), Moult (2005), Annandale *et al.* (1999), Singels *et al.* (1998) and Crosby and Crosby (1999) respectively. Therefore, the results of the simulations are assumed to be realistic and comparable. The initial soil moisture content for each simulation was set at zero, which meant that the soil moisture was at the drained upper limit for the soil.

Table 8.1 Soils and irrigation scheduling information used to simulate sugarcane evapotranspiration with the seven different simulation models (after Smithers *et al.*, 1995)

Simulation Model	Soil Input Parameters					Irrigation Scheduling Parameters	
	Soil Texture	DUL ($mm.m^{-1}$)	PWP ($mm.m^{-1}$)	TAM ($mm.m^{-1}$)	Soil Depth (m)	Allowable depletion (% TAM)	Refill point
ZIMsched 2.0 (FAO-56)	SaCl	323.0	228.0	95.0	1.0	35.0	DUL
ZIMsched 2.0 (ECANE)	SaCl	323.0	228.0	95.0	1.0	35.0	DUL
SAsched	SaCl	323.0	228.0	95.0	1.0	35.0	DUL
ACRUcane	SaCl	323.0	228.0	95.0	1.0	35.0	DUL
SWB	SaCl	323.0	228.0	95.0	1.0	35.0	DUL
CANESIM	N/A	N/A	N/A	95.0	1.0	35.0	DUL
SAPWAT	N/A	N/A	N/A	95.0	1.0	35.0	DUL

It was assumed that by initiating irrigation at a soil water at a depletion of 35% TAM the crop would not have undergone any stress and that growing conditions were ideal. This would ensure that all the models were simulating a crop being grown under ideal conditions at optimum growth rates. A dry-off period, which is a deliberate cause of crop stress through water stress to increases sucrose yield, was not included in the simulations. The following sections present results obtained for each of the four different harvest dates.

8.2 Results for an autumn harvest ratoon crop

Total simulated sugarcane evapotranspiration for an autumn harvest crop for each of the seven years are shown in Figure 8.1. As can be seen in the Figure 8.1, the trends in changing total evapotranspiration from year to year are captured by all six of the daily time step simulation models. From Figure 8.1 it can also be seen that the models that utilise the FAO-56 short grass reference evapotranspiration, namely *ACRUcane,* SWB and *ZIMsched 2.0 (FAO-56)*, yield higher values for sugarcane evapotranspiration than the models that utilise the sugarcane reference for AED. Possible causes for this occurrence are discussed in Section 8.6.

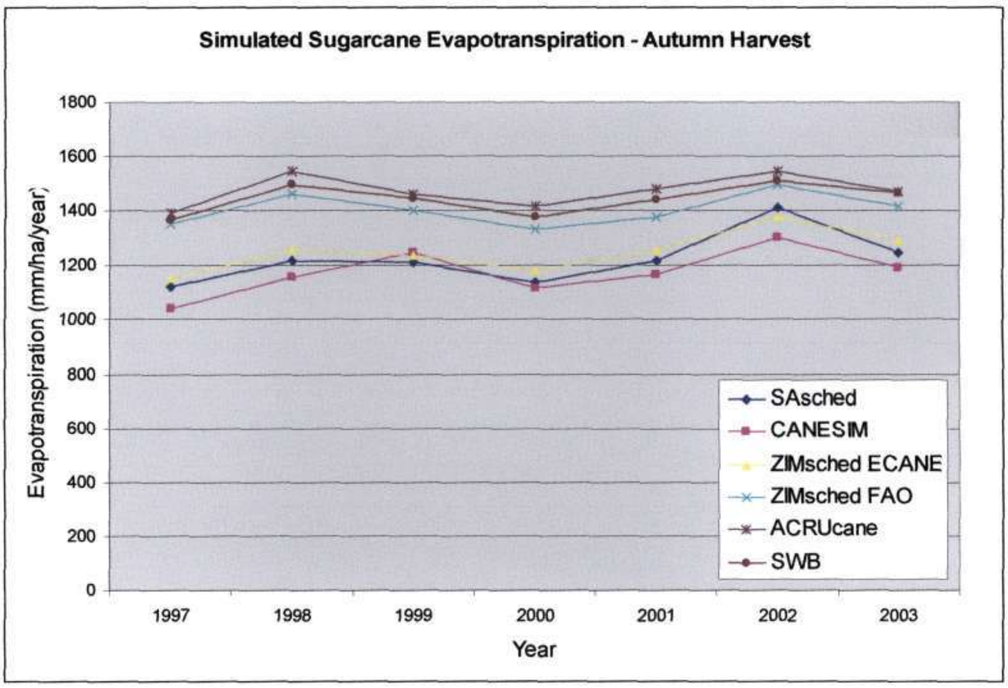

Figure 8.1 Simulated sugarcane evapotranspiration for seven seasons using six different simulation models for an autumn harvest ratoon crop.

8.3 Results for a winter harvest ratoon crop

Total simulated sugarcane evapotranspiration for a winter harvest crop for each of the seven years are shown in Figure 8.2. As was the case with the autumn harvest results, the trends in changing total evapotranspiration from year to year are captured by all six of the daily time step simulation models. Once again it can be noted that the models which utilise the FAO-56 short grass reference evapotranspiration yield higher values for sugarcane evapotranspiration than the models that utilise the sugarcane reference for AED. From the autumn and winter harvest graphs, it can be seen that the *ZIMsched 2.0 (ECANE)*, *SAsched* and CANESIM estimates for total evapotranspiration are all very similar. These similarities are investigated in more detail in Section 8.6.

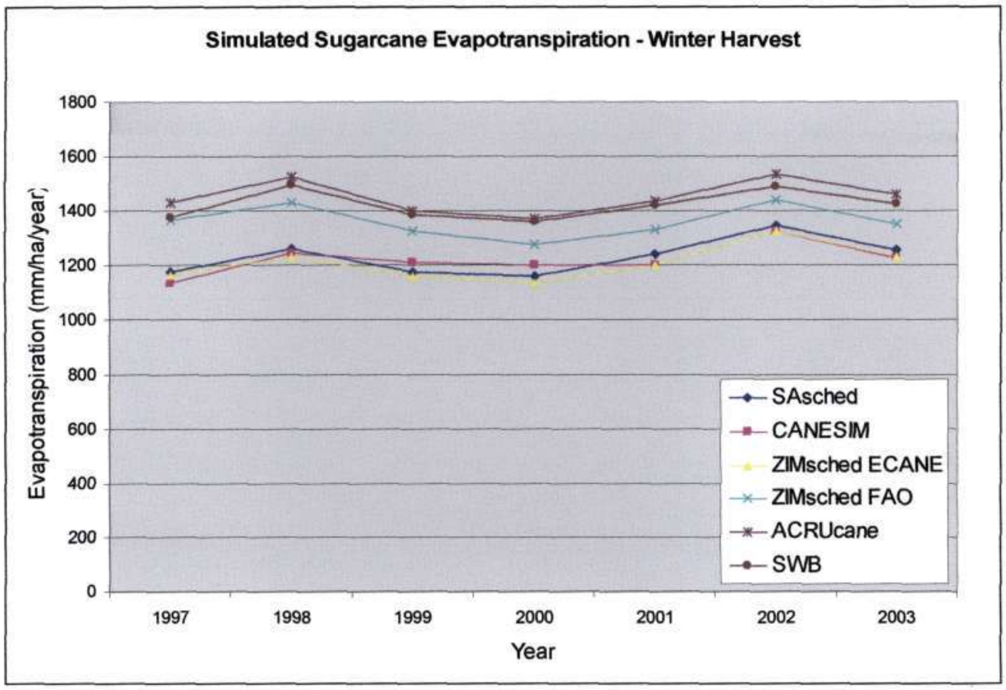

Figure 8.2 Simulated sugarcane evapotranspiration for seven seasons using six different simulation models for a winter harvest ratoon crop.

8.4 Results for a spring harvest ratoon crop

Total simulated sugarcane evapotranspiration for a spring harvest crop for each of the seven years are shown in Figure 8.3. The trend of the FAO-56 reference driven models having higher evapotranspiration than the McGlinchey and Inman-Bamber (1996) sugarcane reference models was also noted in the spring harvest results. The CANESIM results for the different years were once again closely matched by the results obtained with *SAsched*.

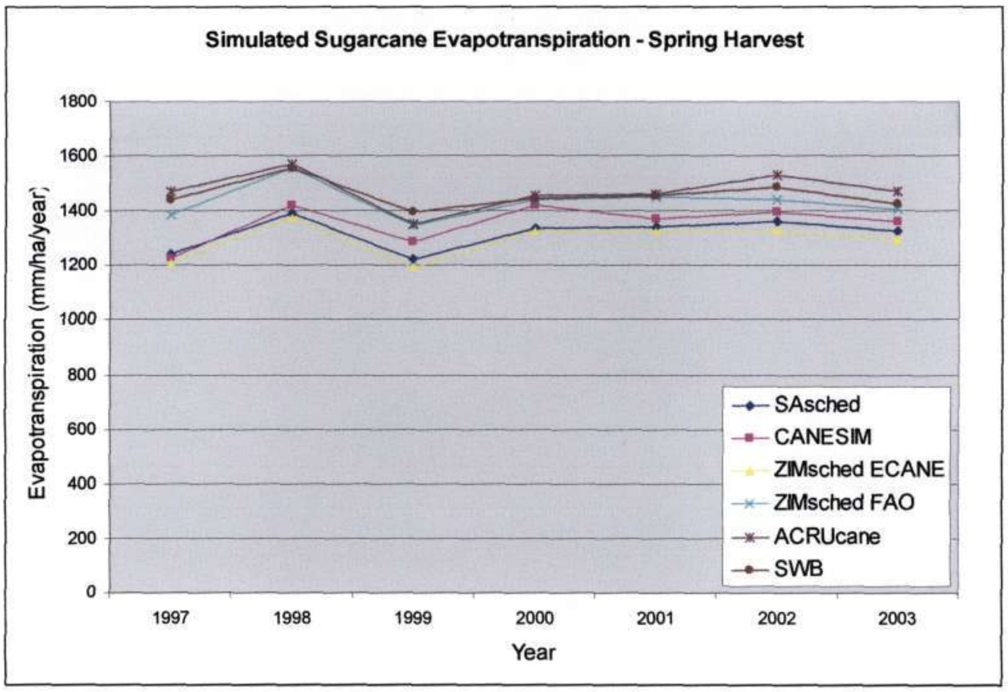

Figure 8.3 Simulated sugarcane evapotranspiration for seven seasons using six different simulation models for a spring harvest ratoon crop.

8.5 Results for a summer harvest ratoon crop

Total simulated sugarcane evapotranspiration for a summer harvest crop for each of the seven years are shown in Figure 8.4 below. Once again, each of the models followed the trends that were set by the CANESIM model. The models utilising the FAO-56 reference were still overestimating sugarcane evapotranspiration relative to the CANESIM "standard".

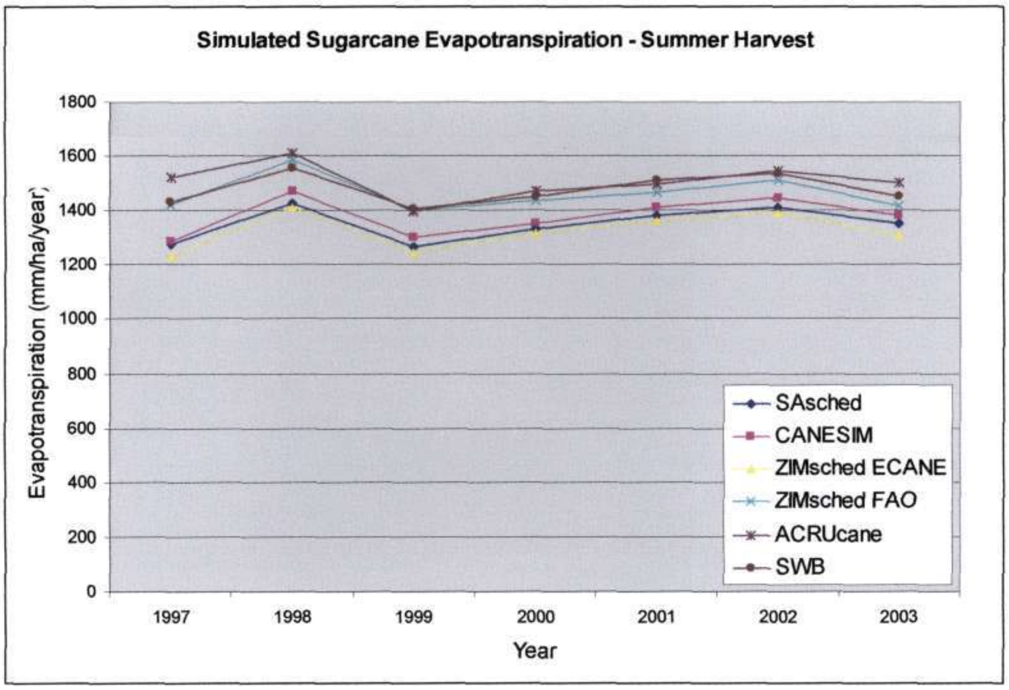

Figure 8.4 Simulated sugarcane evapotranspiration for seven seasons calculated using six different simulation models for a summer harvest ratoon crop.

8.6 Discussion of simulation results

To reiterate the purpose of comparing the results of the model outputs, the methodology required that a value be assigned to irrigation and crop water requirements of sugarcane in the study area. As stated in the CANESIM summary (Section 7.3), the CANESIM model is regarded as the standard for determining irrigation and crop water demands in the South African sugarcane industry. Therefore, using CANESIM to determine "standard" values for these quantities was a logical conclusion. However, in terms of investigating how different water management strategies and levels of infield irrigation systems performance, such as distribution uniformity, impact on yield, CANESIM was found to be inadequate. However, CANESIM is still capable of investigating how different irrigation systems and scheduling scenarios impact on crop yield and total irrigation water use. But, as highlighted in the introduction, the impact of in-field irrigation system performance on crop yield, such as distribution uniformity, needed to be investigated. Therefore, given the inability of CANESIM to achieve this, other models that had this functionality needed to be identified. Unlike CANESIM, the *SAsched, ZIMsched 2.0 (FAO-56), ZIMsched 2.0 (ECANE)* and *ACRUcane* models have the functionality and were thus included in the investigation.

Figures 8.1, 8.2, 8.3 and 8.4, as presented in earlier sections, provided a good indication of which model output was most similar to CANESIM. By analysing Figures 8.1, 8.2, 8.3 and 8.4, it was noted that the models which utilise the FAO-56 short grass reference evapotranspiration yielded high values for sugarcane evapotranspiration. The models which utilised the McGlinchey and Inman-Bamber (1996) sugarcane reference evapotranspiration yielded lower values for simulated sugarcane evapotranspiration. The McGlinchey and Inman-Bamber (1996) method uses a modified version of the Penman-Monteith equation to specifically estimate sugarcane crop water use. McGlinchey and Inman-Bamber (1996) reported excellent measures of model performance relative to measured data that were obtained when a linear regression analysis was performed.

The observation between the difference in sugarcane evapotranspiration with models that use different references was made obvious when comparing the outputs from *ZIMsched 2.0 (FAO-56)* and *ZIMsched 2.0 (ECANE)*. Apart from using different references, these two models are exactly the same. Therefore, provided that the ratio of sugarcane evapotranspiration relative to the reference is correct, the output should have been identical. However, as shown by Figures 8.1, 8.2, 8.3 and 8.4, they were not. Therefore, the different references and the ratios between them were investigated. The results are shown in Table 8.2.

Table 8.2 Table showing the mean values of sugarcane reference and FOA-56 reference short grass evapotranspiration for four different harvesting periods. The actual and recommended ratios of the two references are shown

Harvest Period	Penman-Monteith sugarcane reference ($mm.ha^{-1}.year^{-1}$)	FAO-56 short grass reference ($mm.ha^{-1}.year^{-1}$)	Actual ratio of sugarcane reference to FAO-56	Recommended ratio of sugarcane reference to FAO-56*	% difference between actual ratio and recommended ratio
Autumn	1486.83	1313.39	1.132	1.250	9.44
Winter	1487.50	1313.28	1.133	1.250	9.39
Spring	1500.59	1319.99	1.137	1.250	9.05
Summer	1513.24	1326.70	1.141	1.250	8.75
Mean	1497.04	1318.34	1.136	1.250	9.16

* $K_{c\ mid}$ values not adjusted for relative humidity, wind speed and crop height (Lecler, 2006).

Allen *et al.* (1998) recommend a crop factor of 1.25 in the middle stage of sugarcane crop development. This crop factor was for a reference short grass evapotranspiration. Table 8.2 shows that on average, the ratio of sugarcane reference to FAO-56 short grass reference, for the same climatic data used for the 28 simulations, was equal to 1.136. This corresponds to a 9.16% difference from the Allen *et al.* (1998) ratio of 1.25. This discrepancy would cause, and evidence shows that it did cause, a substantial difference in sugarcane evapotranspiration obtained with the two different versions of *ZIMsched 2.0*. The reason is that for the models that use sugarcane reference, a maximum crop factor of 1.0 is assumed. Whilst those models which use the FAO-56 short grass reference, the recommended maximum crop factor is 1.25 (Allen *et al.*, 1998). If the ratio of 1.25 was not reflected in the different reference evapotranspiration, a discrepancy in the initial model assumptions would have arisen. However, the value of 1.25 was recommended for climates where the relative humidity and average wind speed were in the region of 45 % and 2 $m.s^{-1}$ respectively. For specific adjustments to crop factor values ($K_{c\ mid}$), where the relative humidity and average wind speed values differ from the previously stated values, Allen *et al.* (1998) stated that Equation 8.1 should be utilised. It should be noted that Equation 8.6 was not calculated for the results displayed in Table 8.2.

$$K_{c\,mid} = K_{c\,mid\,(Tab)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)] \cdot \left(\frac{h}{3}\right)^{0.3} \quad (8.1)$$

Where: $K_{c\,mid\,(Tab)}$ = value for $K_{c\,mid}$ taken from Table 12 (Allen *et al.*, 1998),

u_2 = mean value for daily wind speed at 2 m height over grass during the mid season growth stage ($m.s^{-1}$), for $1\ m.s^{-1} \leq u_2 \leq 6\ m.s^{-1}$,

RH_{min} = mean value for daily minimum relative humidity during the mid-season growth stage (%), for $20\ \% \leq RH_{min} \leq 80\ \%$, and

h = mean plant height during the mid-season stage (m) for $0.1\ m < h < 10\ m$.

In addition to the direct discrepancies caused by the significant difference in reference evapotranspiration when the crop factor is not adjusted, the models utilising the Penman-Monteith reference short grass evapotranspiration would have had higher levels of evaporation from the soil surface prior to the attainment of full canopy. This would have been caused by increased number of irrigation applications resulting from the higher reference evapotranspiration. This would have in turn have resulted in the soil surface being wetter for longer periods in the initial stages of the crop growth cycle when compared to the models using the lower reference evapotranspiration. These observations made it necessary to investigate the discrepancies in reference evapotranspiration in more detail.

The developers of the modified Penman-Monteith sugarcane reference evapotranspiration, McGlinchey and Inman-Bamber (2002) decided to check the value of 1.25 described by Allen *et al.* (1998). This was achieved and documented by McGlinchey and Inman-Bamber (2002) when they compared Bowen Ratio Energy Balance (BREB) values for sugarcane evapotranspiration from two locations to calculate values of a sugarcane crop coefficient to use with the FAO-56 short grass reference evapotranspiration. The ratio for the BREB sugarcane evapotranspiration to the FAO-56 value was 1.24 in the middle stage of sugarcane growth. This supports the value of 1.25 given by Allen *et al.* (1998).

McGlinchey (2005) and Inman-Bamber (2005) stated that Crop factors are notoriously difficult to compare and that plants are living things and have complex feedback controls. The value stated by Allen *et al.* (1998) is an average and a search of the literature on sugarcane crop factors will reveal full canopy values between 1.1 and 1.4 (McGlinchey, 2005). Therefore the calculation of, and comparison between, crop factors is very case specific and dependant on local prevailing conditions.

Table 8.3 shows the statistical results from the 28 different simulations that were completed with each of the 7 models.

Table 8.3 Statistical results of comparisons made between CANESIM versus *ACRUcane*, *SAsched*, SWB, *ZIMsched 2.0 (FAO-56)* and *ZIMsched 2.0 (ECANE)* for total sugarcane evapotranspiration (Willmott, 1981)

	CANESIMET ($mm.ha^{-1}$)	Standard deviation ($mm.ha^{-1}$)	Mean Model ET ($mm.ha^{-1}$)	Standard deviation ($mm.ha^{-1}$)	A ($mm.ha^{-1}$)	B ($mm.ha^{-1}$)	RMSE ($mm.ha^{-1}$)	**Agreement Index** (d) ($mm.ha^{-1}$)
SAsched	1282.0	110.6	1280.3	87.6	350.9	0.725	45.8	0.943
ACRUcane	1282.0	110.6	1475.5	63.4	1077.8	0.310	214.0	0.490
ZIMsched 2.0 (FAO)	1282.0	110.6	1415.1	70.0	834.6	0.453	153.4	0.611
ZIMsched 2.0 (ECANE)	1282.0	110.6	1268.8	78.2	511.6	0.591	62.7	0.878
SWB	1282.0	110.6	1450.0	55.5	1012.3	0.341	182.6	0.532
SAPWAT	1282.0	110.6	1198.9	-	-	-	-	-

From Table 8.3 it can be seen that of the five models regressed against CANESIM, the *SAsched* output was most similar with an index of agreement of 0.943 and a RMSE of 45.8 mm. The *a* and *b* regression coefficients were also the best with *SAsched*, with values of 350.9 and 0.725 respectively. The *b* coefficient of 0.712 was indeed far from the perfect value of 1; however, it was much higher than the other models. *ZIMsched 2.0 (ECANE)* was the next best with a *b* coefficient equal to 0.591 and an *a* coefficient of 511.6mm. The results for simulated sugarcane yield are presented in Table 8.4.

Table 8.4 Statistical results of comparisons made between CANESIM versus *ACRUcane*, *SAsched*, *ZIMsched 2.0 (FAO-56)* and *ZIMsched 2.0 (ECANE)* for total sugarcane yield (Willmott, 1981)

Model	CANESIM Yield ($t.ha^{-1}$)	Standard deviation ($t.ha^{-1}$)	Mean Model Yield ($t.ha^{-1}$)	Standard deviation ($t.ha^{-1}$)	A ($t.ha^{-1}$)	B (-)	RMSE ($t.ha^{-1}$)	Agreement Index (d) (-)
SAsched	136.2	10.0	132.7	8.6	22.1	0.812	4.9	0.931
ACRUcane	136.2	10.0	146.4	7.6	-110.9	0.944	11.3	0.707
ZIMsched 2.0 (FAO)	136.2	10.0	142.9	4.9	101.3	0.306	10.3	0.616
ZIMsched 2.0 (ECANE)	136.2	10.0	130.2	6.4	64.8	0.483	8.7	0.742

The simulated sugarcane yield from four of the models, namely *SAsched*, *ACRUcane*, *ZIMsched 2.0 (FAO-56)* and *ZIMsched 2.0 (ECANE)*, were regressed against the simulated sugarcane yield obtained with CANESIM. From the results presented in Table 4.4, it can be seen that *SAsched* was the most similar to CANESIM with an index of agreement of 0.931 and a RMSE of 4.9 $t.ha^{-1}$. The a and b linear regression coefficients were 22.1 $t.ha^{-1}$ and 0.812 respectively, indicating a good relationship between CANESIM and *SAsched*. It can be noted that the methodology used to obtain the yield was described in Section 2.1, and that the seasonal yield is a function of sugarcane evapotranspiration. Therefore, the models that simulated a high evapotranspiration relative to CANESIM, would have also over estimated the yield. This is confirmed in Table 8.3 and 8.4.

9. Conclusion

Seven different simulation models were used to investigate total seasonal sugarcane evapotranspiration and yield. Five of the models, namely CANESIM, *SAsched*, *ZIMsched 2.0 (FAO-56)*, *ZIMsched 2.0 (ECANE)* and *ACRUcane* were sugarcane specific with a daily time step models. The SWB model was a generic crop, daily time step simulation model that was also included because it has been well supported by the Water Research Commission (WRC) for computing crop and irrigation water requirements. The SAPWAT model was also used in a comparison of mean results because it was currently being used as the standard for computing crop and irrigation requirements in South Africa (National Water Act, 1998). Seven years of daily weather data from the SASRI Pongola automatic weather station and standardised soil inputs were used to run 28 different harvest periods with each of the models.

It was decided that CANESIM should be used to determine "standard" values for crop and irrigation water demand and sugarcane yield. This was because CANESIM is already well accepted in the South African sugarcane industry and because it is scientifically sound and has been validated for use on sugarcane. From the statistical results, it was found that *SAsched* generated outputs of evapotranspiration and yield that were most similar to those of CANESIM. Therefore, it was decided that *SAsched* would be utilised to reach the specific objectives described for this analysis, namely to identify a model that can be used to investigate the impact of infield irrigation system performance on crop yield.

In terms of the other simulation models, SAPWAT was excluded as a possibility to determine "standard" requirements because it does not include seasonal climatic effects in its calculations of crop water use, it is based on monthly means and not daily data and because it cannot estimate sugarcane yield. SWB was eliminated because it cannot account for in-field irrigation system performance and it cannot simulate a ratoon sugarcane crop and the sugarcane crop growth parameters in SWB have not been well verified. SWB was also found to overestimate crop water use relative to the "standard" values provided by CANESIM. *ZIMsched 2.0 (FAO-56)*, *ZIMsched 2.0 (ECANE)* and *ACRUcane* have the required functionality that were identified, but their estimates of crop water use were much higher than the estimates obtained using the CANESIM "standard". The reasons for the different crop water use estimates were related to the different reference potential evapotranspiration estimates and because the crop factors were not adjusted for relative humidity and wind speed. These differences are the subject of further research and investigation. It was also found that crop factors are difficult to compare due to case specific conditions.