THE DEVELOPMENT OF A CATCHMENT SCALE IRRIGATION SYSTEMS MODEL FOR SUGARCANE

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ABSTRACT

The implementation of the National Water Act (1998) requires significant changes in the institutional arrangements for water management and, to cater for human and environmental needs, as well as addressing historical inequities, water allocations to irrigated agriculture are likely to be affected. As a result, farmers are facing increasing pressure to use water more effectively, to justify existing water requirements and to budget and plan with growing uncertainty regarding water availability. Therefore, a tool to manage and assess catchment water supply and demand interactions and the associated impacts on the profitability of irrigated sugarcane would be of great value. Although there have been several independent model developments in the fields of water management and sugarcane growth, none provide the required management information in an integrated manner. However, these models provide the foundation for the development of the required modelling tool.

An irrigation model for sugarcane, *ACRUCane*, was developed and incorporated into the *ACRU2000* modelling system. The water budget simulated by *ACRUCane* is linked to a surrounding catchment, the hydrology of which is simulated by the *ACRU* model. In doing so, a tool has been developed that has the capacity to:

- model the soil water balance at a field scale for irrigated areas and at a catchment scale for non-irrigated areas,
- link an accurate estimation of crop water requirement for an irrigated area with the availability of water at a catchment scale,
- explicitly account for the impact of the performance of different irrigation systems on the hydrology and, ultimately, on the sugarcane yield of an irrigated area,
- assess the impact of different supply constraints on sugarcane yield, and
- estimate both sugarcane and sucrose yield.

Extensive verification of the model has been undertaken using data from an irrigation trial at La Mercy, South Africa and two separate trials conducted in the Lowveld of Zimbabwe, with the primary objective of the verification studies being to assess the model's ability to account for different scheduling strategies on sugarcane and sucrose yield. The results obtained show that the model accurately captured the relative differences in yield associated with different irrigation treatments and can thus be used evaluate the impact of different scheduling strategies.

A case study was conducted where the feasibility of several hypothetical irrigation scenarios were compared. Different scenarios were created by varying application uniformity, scheduling strategies and system type. This case study illustrated how *ACRUCane* can be used to provide reliable decision support information to irrigators.

PREFACE

The work described in this dissertation was carried out in the School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, from January 2003 to December 2005, under the supervision of Professor J.C. Smithers.

These studies represent original work by the author and have not otherwise been submitted in any form for any degree or diploma to any university. Where use has been made of the work of others it is duly acknowledged in the text.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABREVIATIONS

Δ

Δ	=	Ripening gradient ($ha.t^{-1}$)
ΔFNS	=	Daily fibre plus non-sucrose increment ($t.ha^{-1}.d^{-1}$)
ΔL	=	Change in root length from day i-1 to day i (m)
Δ_{max}	=	Cultivar specific maximum ripening gradient
	=	0.7 $ha.t^{-1}$
ΔSK	=	Daily stalk mass increment ($t.ha^{-1}.d^{-1}$)
ΔSUC	=	Daily sucrose increment ($t.ha^{-1}.d^{-1}$)

θ

θ_{FC}	=	Soil water content at field capacity ($mm.mm^{-1}$)
θ_r	=	Soil water content in the root zone
$\theta_{r,i}$	=	Soil water in the root zone on day i ($mm.mm^{-1}$)
$\theta_{r,i-1}$	=	Soil water in the root zone on day i-1 ($mm.mm^{-1}$)
θ_s	=	Soil water content in the remainder of the potential root zone
$\theta_{s,i-1}$	=	Soil water in the sub-root zone on day i-1 ($mm.mm^{-1}$)
θ_{WP}	=	Soil water content at wilting point ($mm.mm^{-1}$)

Σ

ΣET	=	accumulated evapotranspiration (mm)
ΣI	=	accumulated irrigation over the course of the season (mm)
ΣT	=	accumulated transpiration over the course of the season (mm)
ΣT_1	=	accumulated transpiration for growth stage 1 (mm)
ΣT_2	=	accumulated transpiration for growth stage 2 (mm)
ΣT_p	=	accumulated potential transpiration (mm)
ΣT_{p1}	=	accumulated potential transpiration for growth stage 1 (mm)
ΣT_{p2}	=	accumulated potential transpiration for growth stage 2 (mm)
ΣR	=	accumulated rainfall over the course of the season (mm)

ψ

ψ_{cl}	=	Critical leaf water potential
	=	-1200 kPa for sugarcane

A

a	=	Intercept of least of squares regression between simulated and observed values
ADM	=	Aerial dry mass ($t.ha^{-1}.d^{-1}$)
ADMPF	=	Aerial dry matter partitioning fraction ($t.t^{-1}$)
$ADMPF_{max}$	=	Maximum *ADMPF*
	=	0.88 $t.t^{-1}$
AED	=	Atmospheric evaporative demand
AWS	=	Automatic weather station

B

b	=	Partitioning coefficient
	=	0.6
b	=	Slope of least of squares regression between simulated and observed values
BPC	=	Base production cost ($R.ha^{-1}$)

C

c	=	Coefficient of initial abstraction
CapC	=	Capital cost ($R.ha^{-1}$)
CC	=	Canopy cover
CD	=	Canopy development
CV	=	Coefficient of variation
CU	=	Coefficient of uniformity

D

d	=	Index of agreement
$D_{e,\,i-1}$	=	Cumulative depth of evaporation (depletion) from the soil surface layer at the end of day i – 1 (mm)

$D_{e,i}$	=	Cumulative depth of evaporation following complete wetting from the exposed and wetted fraction of the topsoil at the end of day i (mm)
$DP_{e,i}$	=	Deep percolation from the topsoil layer on day i (mm)
DU	=	Distribution uniformity
dW/dT	=	Daily biomass increment ($t.ha^{-1}.d^{-1}$)

E

EC	=	Electricity cost ($R.ha^{-1}$)
E_i	=	Evaporation from the soil surface on day i (mm)
ERC	=	Estimated recoverable crystals
E_s	=	Evaporation from the soil
ET	=	Actual evapotranspiration (mm)
ET_0	=	Reference grass evaporation (mm)
ET_{ave}	=	Average evapotranspiration rate for the previous seven days
ET_m	=	Maximum evapotranspiration (mm)

F

f_c	=	Fraction of soil covered by vegetation
FC	=	Field capacity
$FCAP$	=	Potential structural growth of the plant for current day ($t.ha^{-1}$)
f_{ew}	=	Fraction of exposed and wetted soil
Fid	=	Estimated number of days to the next irrigation
FNS_{eq}	=	Theoretical mass of fibre plus non-sucrose ($t.ha^{-1}$)
FNS_i	=	Fibre plus non-sucrose at the beginning of the day ($t.ha^{-1}$)
$f_{r,i}$	=	Irrigation reallocation fraction for sub-area 'i'
f_s	=	Fraction of TAM at which stress sets in
$f_{s\ mod}$	=	f_s, modified for soil texture
FT	=	Temperature control factor
F_T	=	Fraction of actual transpiration extracted from the soil evaporation layer (mm)
$FTCON$	=	Temperature response coefficient
	=	0.32
f_{text}	=	Soil textural dependent percentage increase or decrease in the fraction of TAM at which stress starts (%)

f_w	=	Fraction of soil wetted by irrigation
FW	=	Water stress control factor
$FWCON$	=	Soil water deficit sensitivity parameter
	=	0.5

G

Grd_{ini}	=	Initial ground cover

H

h	=	Mean maximum plant height during the period of calculation
	=	3 m
HC	=	Haulage cost ($R.ha^{-1}$)
HRU	=	Hydrological response unit

I

i	=	Integer corresponding to sub-area 'i'
I_i	=	Infiltrated irrigation depth on day i (mm)
int	=	Current interest rate
	=	10.5 %
IWC	=	Irrigation water cost ($R.ha^{-1}$)

K

k	=	Empirical shape constant
	=	2.453
K_{cb}	=	Basal crop coefficient
K_{cmax}	=	Maximum crop coefficient
K_e	=	Coefficient controlling evaporation from the soil
K_k	=	Total capital costs ($R.ha^{-1}$)
K_{yi}	=	Yield response factor for the i-th growth period

L

LAI	=	Leaf area index
LC	=	Labour cost ($R.ha^{-1}$)
L_i	=	Light interception

L_r	=	Depth of root soil layer
$L_{r,\, i-1}$	=	Root length on day i-1 (m)
L_s	=	Depth of sub-root layer
Ltl	=	Lower level of *SWC* range

M

MC	=	Maintenance cost (R.ha^{-1})

N

n	=	Term of repayment, taken as the life of the system (years)
N	=	Number of data points
NRH	=	Net return per hectare (t.ha^{-1})

O

O_{mean}	=	Observed mean

P

PAR	=	Photosynthetically-active radiation (MJ.m^{-2}.d^{-1})
PARCE	=	Photosynthetically-active radiation conversion efficiency
	=	5.68 g.MJ^{-1}
P_g	=	Gross daily photosynthate (t.ha^{-1})
P_i	=	Precipitation on day i (mm)
PI	=	Daily wetting amount (mm), i.e. rainfall and/or irrigation
PO	=	Porosity

Q

Q	=	Surface runoff depth (mm)
Q_i	=	Runoff from the soil surface on day i (mm)

R

r	=	Response in *TThalf* to unit change in row spacing (°C.d.m^{-1})
r	=	Pearson's r
R	=	Revenue (R.ha^{-1})
r^2	=	Coefficient of determination, Pearson's r squared

R_{fac}	=	Current proportion of maximum effective rooting depth in soil profile
R_{gr}	=	Growth respiration
	=	0.242 $g.g^{-1}$
RH_{min}	=	Minimum relative humidity (%)
R_m	=	Maintenance respiration
	=	0.004 $g.g^{-1}$
RMSD	=	Root mean squared deviation
RMSE	=	Root mean square error
RS	=	Row spacing (m)

S

S	=	Potential maximum water retention of the top 0.3 m of soil (mm)
SC	=	Sucrose content ($t.t^{-1}$)
SC_{ave}	=	Average sucrose content ($t.t^{-1}$)
SC_{max}	=	Uniform maximum *SC* ($t.t^{-1}$)
S_{dep}	=	Maximum potential effective rooting depth for a fully grown crop (m)
sk	=	Cumulative stalk mass measured from the base of the crop ($t.ha^{-1}$)
SK_f	=	Stalk mass at the end of the current day ($t.ha^{-1}$)
SKPF	=	Stalk partitioning fraction ($t.t^{-1}$)
SIE	=	Seasonal irrigationtion efficiency
S_{mean}	=	Simulated mean
SSR	=	Sink activity
	=	0.99
SU	=	Statistical uniformity
SUC_{eq}	=	Theoretical sucrose mass ($t.ha^{-1}$)
SWC	=	Soil water content
SWDF1	=	Soil water deficit factor 1
SWDF2	=	Soil water deficit factor 2

T

T	=	Payment per annum (R)
T50	=	Temperature where well-watered ripening gradient is half of Δ_{max}

	=	25°C
TAM	=	Total available moisture
TAM_{10}	=	Total available moisture in the top 0.1 m of soil
T_{base}	=	Base temperature (°C)
TT_{emerge}	=	Thermal time until emergence
	=	403 °C.d for a plant crop
	=	203 °C.d for a ratoon crop
TEW	=	Total Evaporable Water
$T_{ew, i}$	=	Depth of transpiration from the exposed and wetted soil surface on day i (mm)
T_{max}	=	Daily maximum temperature (°C)
T_{mean}	=	Mean daily temperature (°C)
T_{min}	=	Daily minimum temperature (°C)
T_p	=	Potential transpiration (mm)
TT	=	Daily thermal time (°C.d)
TT_a	=	Accumulated thermal time since the beginning of the season (°C.d)
TT_{ae}	=	Accumulated thermal time since emergence (°C.d)
$TThalf$	=	TT_{ae} required to half canopy development (°C.d)
$TThalf_{1.4}$	=	Half canopy thermal time at row spacing of 1.4 m
	=	250°C.d
TTI	=	Thermal time index

U

u_2	=	Wind speed ($m.s^{-1}$)
UML	=	Unified Modelling Language
Utl	=	Upper level of SWC range

W

W	=	Total accumulated biomass ($t.ha^{-1}$)
wb	=	Total number of sub-areas
WP	=	Wilting point

Y

Y_a	=	Actual yield ($t.ha^{-1}$)

Y_c	=	Tons of cane per hectare with AC-CANESIM ($t.ha^{-1}$)
Y_p	=	potential *ERC* yield ($t.ha^{-1}$)
Y_T	=	Tons of cane per hectare with AC-THOMPSON ($t.ha^{-1}$)

Z

Z_e	=	depth of soil evaporation layer
	=	0.1 m

1. INTRODUCTION

The implementation of the National Water Act (1998) requires significant changes in the institutional arrangements for water management in South Africa. To cater for human and environmental needs, as well as addressing historical inequities, water allocations to irrigated agriculture, which is estimated to use 53% of the country's total available surface water (WRC, 1999), are likely to be affected, particularly in catchments where the demand currently exceeds the supply of water. Thus, it is anticipated that the irrigation industry in South Africa will need to promote and implement more conservative and efficient use of irrigated water. Sugarcane is a major crop grown in the KwaZulu-Natal and Mpumalanga provinces in South Africa and competes with other crops as well as domestic and industrial users for water resources (Schmidt, 2001). As a result, growers are facing increasing pressure to use water more effectively and to justify existing water use amounts. The implications for irrigators of sugarcane of the increased demand for water will be a more involved managerial approach to water use. Consequently, there is a need for reliable advice with respect to management and operating strategies which takes cognisance of irrigation from both the water resource managers' and irrigators' perspectives. The development of a tool to asses the performance and profitability of different irrigation systems, management approaches and supply constraints at both a catchment and a local/on-farm scale would thus be of substantial value to the irrigated sector of the sugar industry. By simulating different systems and management strategies, such a tool would be able to provide irrigators with information on best management practices and, in effect, promote the more efficient use of water.

An ideal tool for this purpose would be a simulation model that facilitates more efficient use of water by modelling the important aspects of irrigation and water management. These aspects include: different irrigation systems operating at different performance levels, estimating crop water requirements, estimating cane yield, soil water budgeting, supply and demand interactions, water management, economics and impacts on the environment.

There have been many independent sugarcane model developments for a variety of different purposes. However, none of these provide all the necessary support information for the required decision support tool as outlined above. The *ACRU* model (Schulze, 1995) is a catchment scale model capable of simulating water supply and demand interactions. It accounts for different management strategies via a water budget and estimates sugarcane yield using the Thompson (1976) equation. CANEGRO (Inman-Bamber, 1991) is a determinstic crop model that simulates several physiological process of the sugarcane crop and ultimately provides, amongst other outputs, an estimate of sucrose yield. APSIM (McCown *et al.*, 1996) is also a deterministic crop growth model, but uses different algorithms to CANEGRO to predict sucrose yield. CANESIM (Singels *et al.*, 1998) is a semi-deterministic model that estimates sugarcane yield and provides scheduling advice through a simple water budget. *ZIMsched 2.0* (Lecler, 2003) is a deterministic physical-conceptual model that facilitates multiple water budgets and accounts for different system hardware and different levels of system performance and the associated impact on estimated recoverable crystal (*ERC*). The Soil Water Balance (SWB) model (Campbell and Diaz, 1988) is a deterministic crop growth and irrigation scheduling model that can be used for a variety of different crops, provided input data are available. IrriEcon (Singels *et al.*, 1999a) is an economic model for comparing two irrigation strategies or irrigation versus rainfed conditions.

The concepts and algorithms required to develop an integrated "ideal" model have been developed. Thus, the primary focus of this project was to utilize the available concepts and algorithms in the creation of a catchment scale irrigation simulation model for sugarcane. The main objectives of the project were as follows:

(a) To develop, validate and verify an integrated modelling tool capable of:
- modelling the soil water balance at a field scale for irrigated areas and at a catchment scale for non-irrigated areas,
- linking an accurate estimation of crop water requirement for an irrigated area with the availability of water at a catchment scale,
- explicitly accounting for the impact of the performance of different irrigation systems on the hydrology and, ultimately, on the sugarcane yield of an irrigated area,
- assessing the impact of different supply constraints on sugarcane yield, and
- estimating both sugarcane and sucrose yield; and

(b) To illustrate the potential use of the integrated model in providing management advice to both water resource managers and irrigators by simulating output from various irrigation scenarios.

In this dissertation, the development, verification and implementation of the model are described. Chapter 2 contains a review of the literature related to the above-mentioned models. This was conducted in order to assess the feasibility of utilising the different concepts in order to develop the integrated model. The literature review is followed in Chapter 3 by a comprehensive description of the conceptual model developed and all the algorithms used in the development are documented. The conversion of the conceptual model into a working computer program is described in Chapter 4, followed in Chapter 5 by verifications of the cane and sucrose yield simulations by the model against observed yield data obtained from different irrigation experiments performed at both La Mercy in KwaZulu-Natal and at Chiredzi in Zimbabwe. In order to illustrate the integrated model's ability to be used as a management tool, a case study is documented in Chapter 6, in which a hypothetical catchment is simulated containing an irrigation operation which is subjected to different scheduling strategies, system types and performance levels. The results of the case study are used to highlight the ability of the model to simulate the impacts of the environment, levels of management, system hardware and water availability on the profitability of irrigated sugarcane. A discussion and conclusion of the project as well as recommendations for future research and improvements on the model is provided in Chapter 7.

2. A REVIEW OF EXISTING MODELS AND ALGORITHMS

There have been several independent simulation model developments that are pertinent to the objectives of this project. In this Chapter a review of selected and appropriate models is presented. The primary focus of the review is to highlight the distinguishing features of each model and to describe the manner in which processes relevant to this project are modelled. Two of the models mentioned in Chapter 1, namely, SWB and APSIM, are not included in the review. Although literature pertaining to these models was reviewed, the scope of this Chapter has been limited to only include models developed in southern Africa to which the author had ready access, including access to the developers of the models and the computer code.

2.1 The *ACRU* Model

The *ACRU* model was conceptualised during research on an agrohydrological and agroclimatological atlas for KwaZulu-Natal (Schulze, 1983). Since then it has been developed extensively into a multi-purpose, daily time step, physical-conceptual model (Schulze, 1995).

The model revolves around a daily, multi-layer soil water budget and has been developed into a versatile evapotranspiration model which is integrated with, *inter alia*, runoff generation, irrigation demand and supply, crop yield estimation and dam yields. The model requires daily rainfall input to facilitate computation of the daily water budget. Other less sensitive variables such as temperature data may, if not available at daily time steps, be input as monthly values and these are transformed internally in the model into daily values using Fourier analysis (Schulze, 1995).

The *ACRU* model's ability to simulate the hydrology of an entire catchment is a unique feature amongst the models reviewed and was a primary reason for its inclusion in the review.

2.1.1 Operation of the model for simulating catchment hydrology

The model may operate in either a "lumped" or "distributed" mode. When operating in lumped mode, small catchments with relatively homogeneous soil and land cover are modelled as a single response unit. When operating in distributed mode, catchments with heterogeneous soils and land covers are delineated into hydrologically homogeneous subcatchments which each subcatchment characterised by its own set of input parameters. Each subcatchment simulated may contain an irrigated area or an impervious area. Each subcatchment may also contain a dam that is located either at the exit of the catchment or internal to the catchment (Schulze, 1995).

The structure of the *ACRU* model is shown schematically in Figure 2.1. Rainfall and/or irrigation which is not intercepted by vegetation or runs off as stormflow, infiltrates the soil surface and is stored in the topsoil horizon. When the field capacity (FC) of the topsoil is exceeded, percolation to the subsoil horizon is initiated at a rate dependent on the textural characteristics and other drainage related properties of the soil horizon. If the FC of the subsoil horizon is exceeded, saturated drainage into the intermediate and ultimately groundwater stores occurs, from which baseflow is generated. Unsaturated soil water redistribution also occurs both upwards and downwards, but at a rate much slower than under saturated conditions, dependent on the relative wetness of adjacent horizons. Evaporation takes place from both intercepted water and from various soil horizons. Evaporation from the soil horizon is either separated into components of soil water evaporation and plant transpiration, or combined as evapotranspiration. Evaporation is estimated by accounting for atmospheric demand, water use characteristics of the crop and water availability in the soil. The roots of the crop extract soil water in proportion to their distribution of mass density in the soil horizons, except in conditions of low soil water content, when the wetter horizons provide higher proportions of soil water to the plant to prevent the onset of stress.

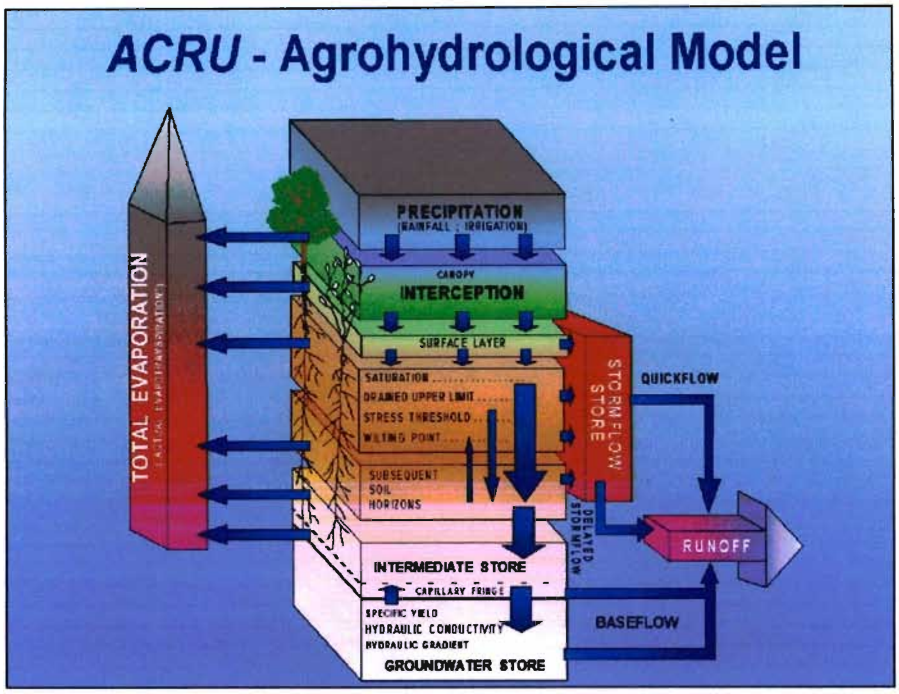

Figure 2.1 General structure of the *ACRU* agrohydrological modelling system (Schulze, 1995)

Within each subcatchment, the *ACRU* model simulates a soil water budget for both dryland and irrigated areas. The dryland water budget is based on the procedure described above, but the irrigation water budget has inherent differences.

2.1.2 Irrigation water budget and water supply

The irrigation routines in the *ACRU* model incorporate robust algorithms to simulate the major components of the water budget, namely:

- evaporation of water from the soil surface,
- transpiration in relation to,
  - atmospheric demand
  - available soil water and
  - rooting characteristics,
- stormflow and
- deep percolation (Lecler and Schulze, 1994).

The impacts of different modes of irrigation scheduling on the daily soil water budget are also represented.

Evaporation from the soil surface is simulated in a two-stage process. In the first stage evaporation from the soil is limited by atmospheric demand and crop shading. Atmospheric demand in *ACRU* is represented by A-pan equivalent evaporation. In the second stage when the soil begins to regulate the loss of water from the soil, evaporation is modelled with a square root of time relation after Ritchie (1972). Maximum transpiration, which occurs when soil water content is not limiting, is determined in *ACRU* using a refinement of concepts described by Ritchie (1971), Adams *et al.* (1976) and Ritchie and Johnson (1990). Transpiration is assumed to occur at a maximal rate until the soil water in the root zone decreases to a certain fraction, as defined by Slabbers (1980). The root zone is dynamic and accounts for root growth assuming a linear relationship between root depth and crop coefficients, according to the methodology described by Jensen *et al.* (1990).

Stormflow depth in an irrigated field is determined using the SCS approach developed by the Soil Conservation Service (USDA, 1985) and adapted for use in South Africa by Schmidt and Schulze (1987). The concept of this routine is based on the principle that stormflow potential is, *inter alia*, an inverse function of the soil's relative wetness (Schulze, 1994). A fundamental difference in the methodology used in the *ACRU* model is that a soil water deficit, instead of a curve number, is used to reflect the soil's runoff potential. In the irrigation water budget, a soil water deficit is determined for the top 0.3 m of soil.

The *ACRU* model allows the user to choose between the following four modes of irrigation scheduling that can be changed on a month-by-month basis:

- demand mode scheduling according to soil water depletion levels,
- fixed cycle/fixed amount,
- fixed cycle/variable amount and
- a predetermined schedule.

The irrigation water budget and scheduling options are displayed schematically in Figure 2.2.

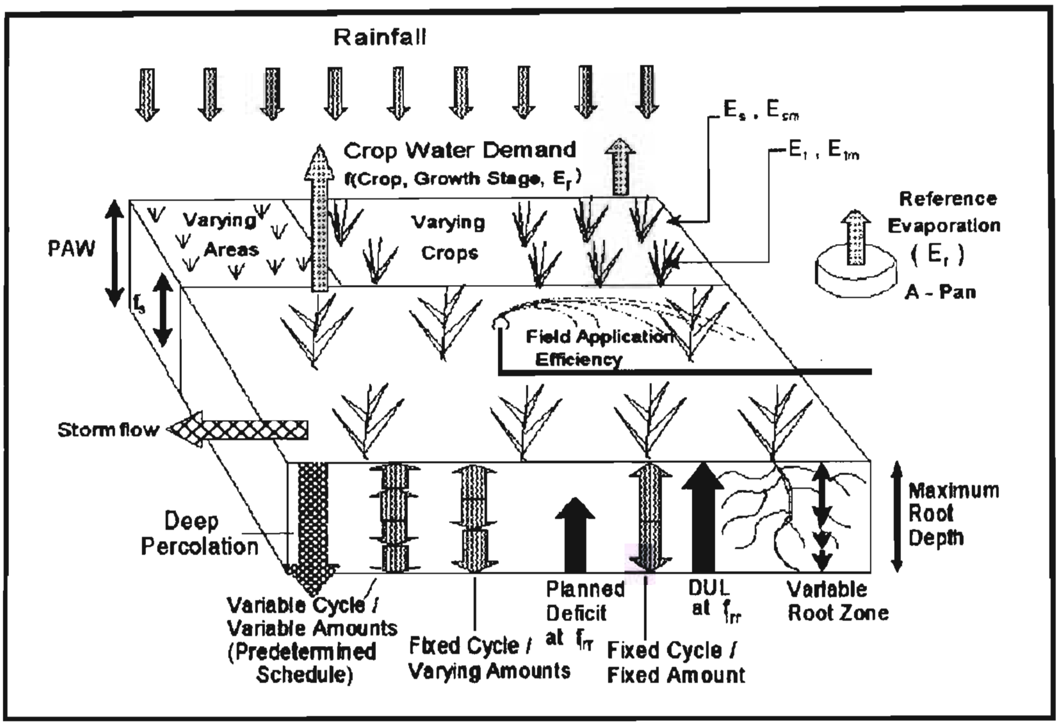

Figure 2.2 Irrigation water budget and scheduling options in *ACRU* (Lecler and Schulze, 1994)

When using demand mode scheduling, irrigation is scheduled in such a way that the plant is never subjected to stress. In this mode, a demand for irrigation is generated when the soil water reaches the fraction of plant available water at which stress sets in, and the irrigation is performed if the supply of water is adequate to meet the demand. When using fixed irrigation cycles, the application can either be a fixed depth, or a depth which varies depending on the current level of storage in the soil, the capacity of the irrigation system and the availability of water. When using deficit irrigation, the supply of water to the plant is deliberately limited to marginally reduce yield, but ultimately maximise profit (Lecler and Schulze, 1995).

ACRU allows the user to simulate various supply conditions when running an irrigation scenario. The irrigation supply dynamics in *ACRU* are shown schematically in Figure 2.3. Not included in the Figure is the option to simulate irrigation water used from an unlimited supply of water.

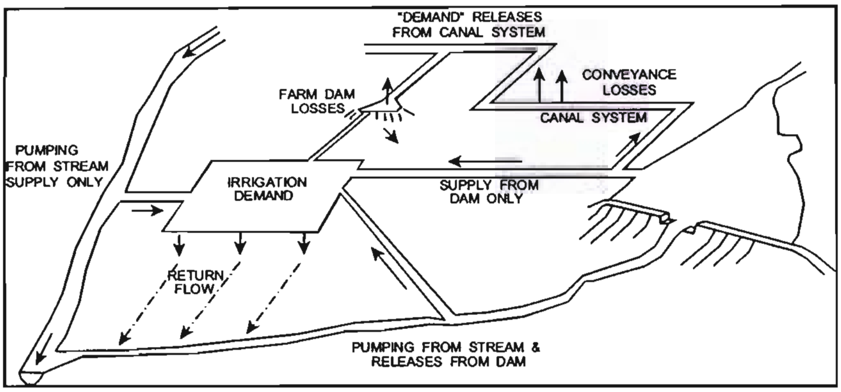

Figure 2.3 Schematic of irrigation supply options in *ACRU* (Lecler *et al.*, 1994)

Losses from the supply source to the root zone are simulated on a daily basis and included in the water budget. These losses include (Lecler *et al.*, 1994):

- canal conveyance losses, made up of evaporation, seepage and wastage due to poor management;
- balancing dam losses, which is water lost from temporary on-farm storage dams and
- field application losses, which are a consequence of poorly maintained field equipment, management and climatic factors such as wind drift.

In addition to simulating the water budget and supply dynamics of an irrigated area, the *ACRU* model also simulates crop yields using yield sub-models for maize, sugarcane and winter wheat (Schulze, 1995). The sugarcane yield sub-model is detailed in the following section.

2.1.3 Sugarcane yield estimation

Sugarcane yield is estimated in *ACRU* using a linear relationship between evapotranspiration and sugarcane developed by Thompson (1976). This relationship will subsequently be referred to as the Thompson equation. It must be noted that the current version of *ACRU* estimates an annualised cane yield for the period from July 1 to June 30 the following year. Furthermore, the linear nature of the equation means that there is effectively no upper limit on yield. The effects of stress are not accounted for explicitly, however, as it driven by evapotranspiration, yields are reduced as a result of a reduction in crop water usage. Lecler and Schulze (1994) concluded that it is a simple sugarcane yield model, operating on the assumption that the evapotranspiration process does not distinguish between soil water evaporation and transpiration. Using a research version of *ACRU*, Lumsden (2000) concluded that, on average, a conceptually improved version of the Thompson equation provided a more accurate estimate of yield than CANEGRO. This version of the Thompson equation used daily calculations of water use coefficients and catered for different growing cycle lengths, harvest dates and ratoons (Lumsden, 2000).

2.2 CANEGRO

The CANEGRO sugarcane yield model was initially developed with the intention of modelling the most pertinent physiological processes of sugarcane in order to answer questions put to scientists by growers in the South African sugar industry (Inman-Bamber, 2000). A further intention was to develop the model in such a way that a foundation would be laid for future model development (Inman-Bamber, 2000). The model's first inception in the 1970s was a result of equations developed to model photosynthesis and respiration of sugarcane, with particular reference to work done by Glover (1972) and Thompson (1976). It was first assembled into a simulation model by Inman-Bamber (1991). Since then there have been frequent developments to many components of the model and it has been included by Kiker and Inman-Bamber (1997) into the DSSAT suite of models as CANEGRO Version 3.10. The routines used in modelling the physiological processes, in particular sucrose yield estimation, make it attractive to include in an integrated modelling system.

2.2.1 Description of the model

The CANEGRO model is a deterministic model that simulates daily balances of carbon, energy and water, driven by daily climate observations. These observations typically include maximum and minimum temperature, precipitation, wind run, class A-pan evaporation, wet and dry bulb temperatures at 8:00 and 14:00 and sunshine duration (Bezuidenhout, 2000).

Evapotranspiration for a field of sugarcane is calculated in one of three ways, depending on the availability of input data, by either

- the Penman-Monteith model,
- the Priestley-Taylor model, or
- A-pan measurements (Bezuidenhout, 2000).

Evapotranspiration is separated into transpiration and soil water evaporation using Leaf Area Index, *LAI* (McGlinchey, 1998). Soil water evaporation is then assumed to occur in a two stage process from the first soil layer only, after Jones and Kiniry (1986).

The soil profile used in CANEGRO was based on concepts used in the CERES-Maize model (Jones and Kiniry, 1986). A soil profile comprises of ten horizontal layers, each with attributes for volumetric soil water content at wilting point (WP), FC, porosity (PO) and initial soil water content. Other physical characteristics are relative root distribution, bulk density and soil water conductivity (Bezuidenhout, 2000). These properties are used to simulate water runoff, soil water flow and evaporation.

CANEGRO simulates two types of runoff, *viz.* stormflow and saturated water runoff. Stormflow only occurs after irrigation or rainfall and is calculated by making use of the SCS curve number method, as described by Schulze *et al.* (1993). Saturated water runoff is caused by saturated conditions in the upper layers of the soil. Soil water dynamics in the various layers are simulated by modelling gravitational flow, soil water evaporation, capillary flow and water extraction by the root system (Bezuidenhout, 2000). Further details on the hydrological fluxes simulated by CANEGRO are contained in Bezuidenhout (2000).

CANEGRO uses daily temperature data to calculate daily Thermal Time (*TT* in °C.d), which drives leaf elongation, leaf appearance, stalk population and rooting depth. *TT* is calculated using Equation 2.1.

$$TT = \frac{T_{\max} + T_{\min}}{2} - T_{base} \qquad (2.1)$$

where

T_{max}	=	daily maximum daily temperature (°C),
T_{min}	=	daily minimum daily temperature (°C), and
T_{base}	=	base temperature (°C).

Note that the base temperature is a parameter that varies depending on the process being simulated. *TT* is determined for each day and the accumulated Thermal Time (TT_a in °C.d) is determined by summing the *TT* values obtained each day (Bezuidenhout, 2000). The dynamics of the relationship between *TT* and aspects of crop growth such as leaf elongation, leaf appearance and stalk elongation were quantified by Inman-Bamber (1994). The relationship between rooting depth and *TT* was derived from the CERES-maize model (Jones and Kiniry, 1986).

Tiller population is also driven by thermal time, whereby a daily change in tiller population is calculated based on empirical polynomial equations which relate the change in population to *TT*. Leaf development is simulated by the model, enabling the determination of mean leaf area per tiller. The number of tillers and mean leaf area per tiller are used to determine the *LAI* of the crop. Using a relationship derived by Inman-Bamber (1994), the portion of Photosynthetically-Active Radiation (*PAR*) intercepted by the crop's canopy can then be determined by *LAI*. This intercepted portion of *PAR* represents the driver of biomass accumulation within the model. Multiplying intercepted *PAR* by the crop's Photosynthetically-Active Radiation Conversion Efficiency (*PARCE*), gross daily photosynthate (P_g) is determined (Inman-Bamber and Thompson, 1989). P_g is subsequently reduced for maintenance and growth respiration as described by Inman-Bamber and Thompson (1989) to determine the daily biomass increment.

The daily biomass increment is partitioned into mass allocations to roots, foliage, stalk and trash. Stalk mass is simulated by assuming a constant daily partitioning fraction after thermal time since emergence exceeds a threshold value. Singels and Bezuidenhout (2002) assumed that stalk mass is further partitioned into either sucrose or fibre plus non-sucrose. Accumulation of sucrose in the stalk is determined by the canopy's ability to export net photosynthate to stalks. In CANEGRO, this is determined primarily by the daily biomass increment, water stress and temperature. An ideal sucrose mass is obtained by taking a genetically determined maximum sucrose content and decreasing it with factors related to the environment. A detailed description of biomass partitioning in the CANEGRO model is provided by Singels and Bezuidenhout (2002).

2.2.2 Model performance

In a comparison of three models, CANEGRO, APSIM (McCown *et al.*, 1996) and QCANE (Liu and Kingston, 1995), Keating *et al.* (1995) noted that CANEGRO was generally robust in the simulation of above ground biomass and soil water status. Millable stalk biomass was simulated with a root mean squared deviation (RMSD) of 0.95 $t.ha^{-1}$. A further observation was that the simulation of both water and nitrogen stressed and non-stressed conditions required further refinement.

In validating a new method of partitioning biomass in the model, Singels and Bezuidenhout (2002) noted that the simulation of aerial mass was satisfactory and yielded a root mean square error (RMSE) of 6.94 $t.ha^{-1}$. Significant improvements were obtained in both stalk mass and sucrose yield estimations. The RMSE of 5.48 $t.ha^{-1}$ for stalk dry mass compares favourably with the 28.7 $t.ha^{-1}$ obtained with the APSIM model (O'Leary, 2000). Similarly for sucrose mass simulations, the RMSE of 2.6 $t.ha^{-1}$ obtained by CANEGRO compares well with the 4.93 and 3.30 $t.ha^{-1}$ obtained by APSIM, reported by O'Leary (2000).

In addition to its detailed biomass partitioning and crop yield estimation capabilities, CANEGRO has also been used extensively as the basis for scheduling irrigation and predicting the components of an irrigation water budget (McGlinchey *et al.*, 1995; McGlinchey and Inman-Bamber 1996a). McGlinchey (1998) noted the detailed modelling approach of a model such as CANEGRO offers designers and managers scope for fine tuning irrigation design practices and scheduling systems.

2.3 CANESIM

Complex models like CANEGRO are data intensive and also require the user to have a good understanding of the physiological principles that drive the model. CANESIM, although semi-deterministic, was developed from CANEGRO as a more practical model for non-specialist sugarcane modellers (Bezuidenhout, 2003).

CANESIM, formerly called Irricane, was developed to provide the South African sugar industry with a simple, computerized, weather-based irrigation scheduling procedure (Singels *et al.*, 1998). A yield simulation component was added to CANESIM by Singels *et al.* (1999a), enabling it to be used as a strategy evaluation tool. After initial adoption of the model by stakeholders proved to be limited, CANESIM was made available via the internet and was linked to data from automatic weather stations (AWS) to promote use amongst industry stakeholders (Singels *et al.*, 1999b).

2.3.1 Description of the model

CANESIM is a daily time step model that revolves around a water balance for a single layered soil profile (Singels *et al.*, 1998). Effective irrigation and rainfall are determined by reducing the actual amounts by the amount intercepted by the crop. Evaporation of intercepted values is not allowed to exceed reference cane evapotranspiration, which is determined according to the method used by McGlinchey and Inman-Bamber (1996b). Interception is calculated as the smaller of actual irrigation or rainfall, and the potential interception amount by the vegetation. Potential interception is calculated as the product of 5 mm and a fraction of canopy cover (Singels *et al.*, 1998). The canopy development is simulated according to thermal time using algorithms described by Singels and Donaldson (2000). Drainage is calculated by assuming a rate of 40% per day of the surplus water above total available moisture (TAM), the difference between soil water at FC and WP. Runoff is determined as excess water above saturation, which is normally assumed to be 200% of TAM.

Cane yield is calculated using an empirical relationship derived by fitting a second order polynomial to CANEGRO simulated stalk dry matter and simulated cumulative transpiration for several widely varying situations (Singels *et al.*, 1999a).

By using pre-defined limits such as irrigation cycle, allowable depletion and refill levels as input, CANESIM can be used as a strategy evaluation tool (Singels *et al.*, 1999a). The user is able to simulate and analyse different scheduling scenarios. The model also generates daily output of water balance components and irrigation advice for the forthcoming week. When generating scheduling advice, the soil water content (*SWC* in mm) is compared with the upper (*Utl* in mm) and lower levels (*Ltl* in mm) of the specified *SWC* range. The timing of the next irrigation application is computed using Equation 2.2.

$$Fid = \frac{SWC - Ltl}{ET_{ave}} \quad \text{...(2.2)}$$

where

Fid = the estimated number of days to the next irrigation, and

ET_{ave} = is the average evapotranspiration rate for the previous seven days ($mm.d^{-1}$)

2.3.2 Model performance

Singels *et al.* (1998) concluded that, although simple, CANESIM produced results of similar accuracy to CANEGRO when estimating soil water content. The model was also shown to compare well with measured values at high water contents, but performed poorly at low soil water contents. Bezuidenhout and Singels (2003) used CANESIM in a forecasting system to verify mean productions on a mill level for the period 1980/81 – 2002/03. They concluded that there was good agreement between estimated and actual yields for most mills supplied by rainfed sugarcane, whereas yield estimation from irrigated areas were poor. The poor performance of the model in this regard was attributed to the model's weak simulations of historical water restrictions, as well as incorrect TAM values.

2.4 *ZIMsched* 2.0

ZIMsched 2.0 was first presented as *ZIMsched* by Lecler (2000) as a spreadsheet-based irrigation management and yield forecasting tool. It was developed using data from the Lowveld of Zimbabwe and the development included farmer participation to facilitate more widespread use compared to other available irrigation management tools. In general, the model favoured more robust algorithms over complex mechanistic methods to account for hydrological and physiological processes. *ZIMsched* was refined into a deterministic crop and irrigation systems simulation model, *ZIMsched* 2.0, by Lecler (2003). The motivation for the refinements was to quantify the impact of water management, system characteristics and irrigation performance indices on crop yields and water requirements (Lecler, 2003).

2.4.1 Description of the model

ZIMsched 2.0 simulates by a daily water balance, with evapotranspiration estimates based largely on the algorithms described by Allen *et al.* (1998). In *ZIMsched 2.0*, atmospheric demand is represented by A-pan evaporation. Although this differs from using reference grass evaporation as outlined by Allen *et al.* (1998), Lecler (2001) showed that there was very little difference between using A-pan data with appropriate pan factors and the Penman-Monteith equation in the Lowveld of Zimbabwe.

Crop transpiration, represented by the product of the basal crop coefficient and reference evaporation, differs from the Allen *et al.* (1998) methodology in that the crop coefficient is related to accumulated thermal time and not calendar days. The use of calendar days to represent crop development does not account for the variation in crop water use due to seasonal temperature variations associated with different planting dates. In order to account for this, Lecler (2003) used a polynomial relationship between thermal time and an average crop coefficient developed by Hughes (1989) that combines transpiration and evaporation from the soil. The basal crop coefficient was then related to the average crop coefficient using a linear interpolation relationship derived and validated by Lecler (2003).

The product of the basal crop coefficient and reference evaporation provides an estimate of the potential transpiration that would occur on each day. Transpiration does decrease below the potential rate when the crop is subjected to water stress. This is accounted for in *ZIMsched 2.0* by using a modified version of the equation described by Slabbers (1980), which predicts the fraction of TAM at which transpiration will drop below the potential rate. Once this fraction has been reached, the ratio of actual to potential transpiration is assumed to decrease linearly to zero when WP has been reached. Transpiration is also reduced below potential under conditions of excess soil moisture, using methodology described by Dijkhuis and Berliner (1988).

ZIMsched 2.0 calculates evaporation from the soil surface by the product of a soil water evaporation coefficient and reference evaporation. Evaporation from the soil surface takes place in two stages, and is based on the methodology outlined by Allen *et al.* (1998). In the first stage, evaporation the soil is maximal following a rainfall or irrigation event. The rate at which water leaves the soil during the first stage is limited by the atmospheric demand. The second stage of evaporation occurs when a certain amount of water has evaporated from the surface and consequently occurs at a much lower rate. Lecler (2003) made two changes to the Allen *et al.* (1998) methodology. The first was to include runoff in the water budget of the topsoil, which Allen *et al.* (1998) had assumed to be zero. The second change was to allow transpiration to occur from soil moisture stored in the upper soil layer, which Allen *et al.* (1998) had reserved for evaporation from the soil surface only. Utilisation of a water budget based on the methodologies described by Allen *et al.* (1998) has the advantage of, *inter alia*, accounting for the effects of wetting fractions of different irrigation systems on evaporation from the soil surface.

To account for shading effects *ZIMsched 2.0* simulates canopy development, a process that is driven by thermal time. In this way, variations in canopy development associated with different planting/ratooning times and seasonal temperature variations are automatically accounted for (Lecler, 2003). The proportion of the soil depth penetrated by roots is also driven by thermal time. The depth of the zone from which water uptake can occur is determined by assuming that the maximum rooting depth occurs when the canopy is fully developed, based on the approach used by Jensen *et al.* (1990).

Surface runoff, is accounted for in *ZIMsched 2.0* using the Soil Conservation Service (SCS) stormflow equation (USDA, 1985) as modified by Schulze (1995). Lecler (2001) noted that estimation of the amount of water that does not contribute to the soil profile is important for estimating rainfall effectiveness.

Drainage is also simulated in *ZIMsched 2.0*. Drainage is only initiated if, at the end of the day, the soil water content is above the FC. The rate at which drainage occurs is a function of the saturated drainage coefficient, antecedent soil moisture conditions and the magnitude of the rainfall/irrigation event. Drainage in *ZIMsched 2.0* can take place over a number of days, which Lecler (2001) noted as an advantage over many other water budgeting algorithms which tend to over-simply and shorten drainage from the soil profile, and consequently result in over-irrigation.

ZIMsched 2.0 uses a modified version of the relationship between sucrose and evapotranspiration derived by Thompson (1976) to determine an estimate of potential *ERC*. This estimate is adjusted according to the timing and magnitude of water stress, based on the procedures reported on by Doorenbos and Kassam (1979) and modified by De Jager (1994). This methodology uses growth stage specific yield response factors to reduce the potential yield to an estimate of actual yield.

To account for the effects of uniformity on system performance, *ZIMsched 2.0* determines a separate water budget and yield estimate for three equal areas of a field. One third of the field receives the mean water application, one third of the field receives the mean application plus a percentage (D%) of the mean, and the remaining third receives the mean application less D%. D% is determined as a function of the coefficient of uniformity (CU), statistical uniformity (SU) and distribution uniformity (DU) using equations derived assuming a normal distribution of irrigation water applications (Lecler, 2003).

2.4.2 Model performance

To verify *ZIMsched* 2.0, Lecler (2003) used historical data from the Zimbabwean Sugar Association Experiment Station. The data comprised of two trials that encompassed different irrigations systems, watering regimes, soil types and climatic data. Lecler (2003) focused on the model's ability to simulate relative differences in yields when comparing different scenarios, as opposed to comparing absolute estimates with observed yields. Thus yields were represented as a fraction of the highest yields obtained from the least stressed treatment in both the observed and simulated cases. A regression analysis showed that the model exhibited a high index of agreement of 0.96, where a value of 1.0 indicates perfect agreement. A RMSE of 0.056 was obtained, indicating that on average the predicted relative yields were within 5.6% of the observed relative yields (Lecler, 2003). Lecler (2003) concluded that the statistics obtained were indicative of very good model performance, especially when different management systems were compared to each other in relative terms.

2.5 Chapter Conclusions

To meet the objectives of the project, a model is required that provides the appropriate functionality for assessing the performance of different types of irrigation systems operating under different water allocations, management strategies, climate and surrounding environment. It should be able to supply best management information at both a local/on-farm and a catchment scale to both the suppliers and users of water.

The *ACRU* model provides an integrated representation of an irrigation system from the point of supply to the point of application. Several supply scenarios and their associated water losses can be simulated. The four irrigation scheduling options in ACRU have the potential to account for most scheduling methods used in practice. Furthermore, the latest version of *ACRU*, *ACRU2000*, was coded in object-oriented programming language JAVA with extensibility being one of the primary objectives of its development. These aspects make the *ACRU* model a viable option to use as a foundation for a catchment scale irrigation systems model for sugarcane. Although a detailed irrigation water budget already exists in the *ACRU* model, it is felt that there are limitations with regard to its ability to account for different irrigation systems and different levels of performance explicitly. For example, the effects of non-uniform irrigation applications are not accounted for and differences in evaporation from the soil surface that would manifest as a result of different types of irrigation systems wetting different fractions of the soil surface are not represented. Furthermore, the Thompson equation used in the model estimates tons of cane based solely on evapotranspiration and does not allow for a variable length of the growing season.

The CANEGRO model requires complex model inputs which detract from the model's usability and was reportedly weak in representing effects of soil water stress. In addition to these, it also does not represent the effects of non-uniform irrigation water applications. However, the sophisticated biomass accumulation and partitioning algorithms are very attractive features of the model. Using radiation as a driver for yield which is subsequently reduced for environmental conditions such as water and temperature stress represents an approach to yield modelling that is conceptually superior to other empirical yield models. Furthermore, and estimate of sucrose is provided. This is advantageous in that, apart from providing a valuable output, it is easier to attach a financial value to sucrose than it is to cane yield.

In order to facilitate its use amongst non-specialists, many of the hydrological processes used in CANESIM's water budget are simplified. For the purposes of this project, CANESIM's water budget is considered an oversimplification. The empirical equation used to estimate cane yield would, however, be simple to incorporate into the proposed model and would add value to yield outputs. Furthermore, its algorithms to simulate canopy development performed well in verification studies (Singels and Donaldson, 2000) and represent a viable means of simulating canopy development in the proposed model.

ZIMSCHED 2.0 uses a water budget based on the widely accepted algorithms of FAO 56 (Allen *et al.*, 1998). *ZIMSCHED 2.0* has the advantage of being the only model able to account for the impact of different irrigation systems on the water budget by accounting for, amongst other things, different wetting fractions. A further advantage is the fact the *ZIMSCHED 2.0* accounts for uniformity through the simulation of multiple water budgets. The ERC estimation algorithm used in *ZIMSCHED 2.0* would also add valuable output to the model.

It is felt that the use of a universally accepted approach to water budgeting in the proposed model, such as that used in FAO 56 and *ZIMSCHED 2.0*, represents the ideal means of simulating the hydrology of an irrigated area. The algorithms used to estimate evapotranspiration in FAO 56 are widely accepted internationally and the refinements to them made in *ZIMsched 2.0* to account, for example, for runoff and deep percolation are based on well researched algorithms from the *ACRU* model. The runoff and deep percolation algorithms used in *ACRU* and *ZIMsched 2.0*, are conceptually superior to the equivalent algorithms used in the CANEGRO and CANESIM models. Linking with *ACRU* would allow an irrigated area to be simulated within the context of a surrounding catchment, thus simulating the supply and demand interactions of water at a catchment scale. By utilising the concept of multiple water budgets as done in *ZIMSCHED 2.0*, application uniformity can be accounted for. By integrating the various yield algorithms reviewed into the proposed model, including the conceptually attractive radiation-based approach to estimate sucrose which is utilised in the CANEGRO model, it should thus be possible to assess the viability of different types of irrigation systems operating under different water allocations, management strategies, climate and surrounding environment. The development of this model/algorithm integration is described in Chapter 3 and the results of verification studies are given in Chapter 4.

3. MODEL DEVELOPMENT

It was concluded from Chapter 2 that, in order to develop the required modeling tool, an irrigation sub-model for sugarcane within the *ACRU* modeling system was required. This model will subsequently be referred to as *ACRUCane.*

ACRUCane simulates an irrigated area that is either part of, or external to, the catchment being simulated by the *ACRU* model. In *ACRU*'s input menu, an option is invoked to run *ACRUCane* concurrently with the rest of the *ACRU* model and can only be invoked if the *ACRU* model is set up to run an irrigation simulation. In this Chapter a description and explanation of the concepts and algorithms used in the *ACRUCane* model is provided. At this point it must be noted that this Chapter represents the integration of many of the concepts reviewed in Chapter 2. Consequently, descriptions of some concepts, algorithms and variables are repeated, but have been included in both Chapters for completeness.

3.1 Rainfall and Irrigation

Wetting events occur as a result of either irrigation or rainfall. The rainfall values used are those input to the *ACRU* model from a file containing climatic data, whereas irrigation requirements are generally determined internally by the model for the user selected scheduling option. However, in order to simulate a known watering regime actual irrigation amounts can also be read into the *ACRU* model via a composite data file which contains hydrometeorological data.

3.2 Runoff

In *ACRUCane,* both rainfall and irrigation can generate runoff. Runoff is determined using the same approach used in the *ACRU* model (Schulze, 1995) which is based on an algorithm originally developed by the Soil Conservation Service (USDA, 1985) shown in Equation 3.1.

$$Q = \frac{(PI - cS)^2}{PI - S(1-c)} \quad \text{.....(3.1)}$$

where

Q	=	stormflow depth (mm),
PI	=	daily wetting amount (mm), i.e. rainfall and/or irrigation,
c	=	coefficient of initial abstraction, and
S	=	potential maximum water retention of the top 0.3 m of soil, computed as the soil water deficit below porosity, prior to a wetting event (mm).

Rainfall and/or irrigation that does not generate stormflow is assumed to infiltrate into the soil immediately after the wetting event has occurred. Amounts, but not rates, of infiltration are not simulated in *ACRUCane*.

Correctly designed and well-managed irrigation systems typically do not generate substantial amounts of stormflow as water should be applied in such a manner that it all infiltrates. However, poorly timed or high intensity irrigation applications can potentially generate stormflow. To account for this, stormflow generated as a result of irrigation is a process that can be switched on or off according to the user's preference. If the option to simulate stormflow as a result of irrigation is not invoked, then all the applied irrigation is assumed to infiltrate until the soil becomes saturated. If saturation is reached, the remaining irrigation contributes directly to stormflow.

3.3 Evapotranspiration

Allen *et al.* (1998) define evapotranspiration as "the combination of two separate processes whereby water is lost on the one hand from the soil surface by evaporation and on the other hand from the crop by transpiration". In *ACRUCane*, evaporation from the cropped surface is determined largely on the widely accepted algorithms described in the Food and Agriculture Organisation (FAO) Irrigation and Drainage Paper No. 56 (Allen *et al.*, 1998), and incorporates several modifications made by Lecler (2003). This methodology uses dual crop coefficients to represent transpiration and evaporation from the soil independently, as shown in Equation 3.2.

$$ET = (K_{cb} + K_e).ET_0 \quad \text{...(3.2)}$$

where

ET	=	evaporation from a cropped surface (mm),
K_{cb}	=	basal crop coefficient,
K_e	=	coefficient controlling evaporation from the soil, and
ET_0	=	reverence grass evaporation (mm).

Using dual crop coefficients allows the separation of evaporation from a cropped surface into two processes, namely, transpiration (E_t in mm) and evaporation from the soil (E_s in mm). Treating these two processes separately is important because prior to the development of significant canopy cover, water losses are dominated by evaporation from the soil surface. Accurate estimation of this water loss is important, as it can vary for different types of irrigation and water management systems depending on the wetting fraction and frequency of wetting of the soil (Lecler, 2003).

Evaporation estimates in *ACRUCane* are driven by reference grass evaporation as defined by Allen *et al.* (1998), whereas the main catchment water budget in *ACRU* currently uses A-pan equivalent as a reference. A study undertaken by Jensen *et al.* (1990) of 20 different evapotranspiration estimation methods under widely varying conditions revealed the Penman-Monteith equation to be an accurate and consistent estimator of ET_0. It was consequently selected over other temperature, radiation and pan-based methods as the sole standard method of ET_0 estimation for the FAO (Allen *et al.*, 1998). Allen *et al.* (1998) also noted that the differences in aerodynamic, vegetation control and radiation characteristics resulted in difficulties in relating ET_0 to evaporation from an open body of water, such as an evaporation pan. Relating ET_0 to a specific crop has the inherent advantage of incorporating the biological and physical processes involved in ET. Consequently, reference grass evaporation, as defined in the FAO Irrigation and Drainage Paper No. 56 (Allen *et al.*, 1998), was used in *ACRUCane* to represent atmospheric demand for water.

3.3.1 Transpiration

Using the FAO 56 methodology, transpiration from a cropped surface is estimated by the product of K_{cb} and ET_0. K_{cb} is defined as the ratio of crop evapotranspiration over the reference evaporation (ET/ET_0) when the soil surface is dry i.e. soil water evaporation (E_s) is negligible but transpiration is still occurring at potential rate. The value of $K_{cb}ET_0$ includes a residual diffusive evaporation component supplied by soil water below the dry surface and by soil water from beneath dense vegetation (Allen *et al.*, 1998).

In *ACRUCane* a linear relationship between canopy development and K_{cb} is used to determine K_{cb} on a daily basis. K_{cb} is assumed to increase linearly between 0.15 and 1.2 as canopy development increases from 0 to 100%. The value of 0.15 is the recommended initial K_{cb} value for sugarcane given by Allen *et al.* (1998) and represents the residual diffusive evaporation component mentioned in the previous paragraph, which occurs even prior to canopy emergence. The value of 1.2 is the recommended maximum value for K_{cb} given by Allen *et al.* (1998), and indicates that under unstressed conditions a mature sugarcane crop can potentially transpire at a rate 1.2 times greater than ET_0. The relationship between canopy development and K_{cb} is shown in Figure 3.1.

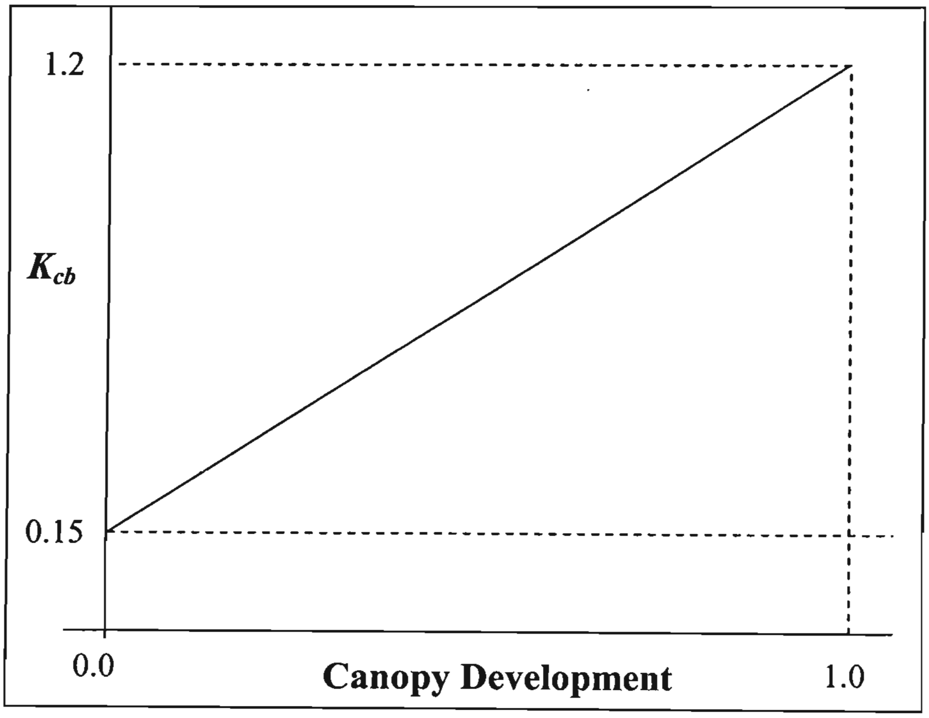

Figure 3.1 Relationship between K_{cb} and canopy development in *ACRUCane*

This relationship is expressed algebraically in Equation 3.3:

$$K_{cb} = 1.05 \times CD + 0.15 \qquad (3.3)$$

where

CD	=	canopy development expressed as a fraction of full canopy development

Canopy development is not determined explicitly in *ACRUCane*. However, a canopy model developed for CANEGRO to estimate light interception is used to represent canopy development. This model, known as the "Hill Model" (Haefner, 1996), determines the fraction of the ground shaded by the canopy. In this document, this fraction will be known as "canopy cover". The Hill Model is driven by thermal time, also referred to as "heat units", a characteristic of temperature commonly used in biological modelling. Thermal time is calculated using Equation 3.4:

$$TT = \frac{T_{\max} + T_{\min}}{2} - T_{base} \qquad (3.4)$$

where

TT	=	daily thermal time (°C.d),
T_{max}	=	daily maximum temperature (°C),
T_{min}	=	daily minimum temperature (°C), and
T_{base}	=	base temperature (°C).

In *ACRUCane*, T_{base} has a value of 10°C prior to emergence of canopy, which is assumed to occur after 403°C.d for a plant crop and 203°C.d for a ratoon crop (Bezuidenhout, 2000). After canopy emergence Singels and Donaldson (2000) found that a T_{base} value of 16°C provided the best simulation of canopy development. The components of the Hill model are shown in Equations 3.5 to 3.7.

$$CC = \frac{TTI^k}{0.5 + TTI^k} \qquad (3.5)$$

where

CC	=	canopy cover (dimensionless fraction),
TTI	=	thermal time index,
k	=	empirical shape constant, 2.453,

and

$$TTI = TT_{ae}/(TThalf) \quad (3.6)$$

where

TT_{ae} = accumulated thermal time since emergence (°C.d),

$TThalf$ = TT_{ae} required to half canopy development (°C.d),

and

$$TThalf = TThalf_{1.4} - r(1.4 - RS) \quad (3.7)$$

where

RS = row spacing (m),

$TThalf_{1.4}$ = half canopy thermal time at row spacing of 1.4 m,

= 250°C.d, and

r = response in $TThalf$ to unit change in row spacing ($°C.d.m^{-1}$),

= 125°C.d.

Singels and Donaldson (2000) used data from Pongola to calibrate the Hill model. Values for T_{base} were determined iteratively using different temperatures to obtain the highest value of correlation coefficient (r^2) for a linear regression between canopy cover and TT_{ae}. The value for k, the universal shape constant, was found in the same manner by relating CC to TTI data. Singels and Donaldson (2000) also concluded that thermal time required to reach half canopy changed by 50% for each one metre in row spacing. This response was assumed to be linear within the range of 0.5 to 1.5 m row spacing. The value of r was computed as half of $TThalf_{1.4}$, yielding the value of 125°C.d.

Full canopy development, i.e. canopy development corresponding to maximum ET, is assumed to occur when a Leaf Area Index (LAI) of 3 has been reached (Allen *et al.*, 1998). Equation 3.8 (after Inman-Bamber, 1991) yields a canopy cover of 0.8577 when LAI is 3.

$$CC = 1 - e^{(-0.65.LAI)} \quad (3.8)$$

Full canopy development, and thus the maximum value for K_{cb}, is therefore assumed to occur when canopy cover, as determined using the Hill model, is at 85.77% of its full value. Equation 3.3 can thus be represented as follows:

$$K_{cb} = 1.05 \times \{\min(1, CC/0.8577)\} + 0.15 \quad (3.9)$$

This effectively ensures that maximum canopy cover will occur when CC reaches a value of 0.8577, but limits K_{cb} from exceeding unity as CC increases. K_{cb} is thus determined indirectly as a function of thermal time and row spacing. This method represents an improvement to relating K_{cb} solely to calendar date, as is done in FAO 56, as account is taken of variations in canopy development with different planting dates and seasonal temperature variation (Lecler, 2003).

The product of K_{cb} and ET_0 estimates transpiration under ideal conditions (i.e. soil water is not limiting), as it is purely dependent on reference evaporation and thermal time. However, in practice a growing crop of sugarcane may frequently be subjected to a reduction in transpiration, either due to an excess or deficit of soil water.

3.3.1.1 Transpiration under soil water deficit

In drier soils, soil water has a low potential energy and is strongly bound by capillary and absorptive forces to the soil matrix making it difficult to be extracted by the crop (Allen *et al.*, 1998). If the demand for water by the crop exceeds the rate at which water can be supplied by the soil, the crop begins to transpire at a reduced rate, ultimately reducing crop growth. In *ACRUCane*, transpiration is assumed to decrease linearly from a potential value to zero, as soil water content decreases from a calculated fraction, f_s, of TAM to WP. f_s thus represents the fraction of TAM at which a reduction in transpiration occurs. It is determined using a relationship derived by Slabbers (1980) shown in Equation 3.10, *viz.*

$$f_s = 0.94 + 0.0026(\psi_{cl}/ET_0) \qquad (3.10)$$

where

ψ_{cl} = critical leaf water potential, assumed to be -1200 kPa for sugarcane.

Since ψ_{cl} is assumed to remain constant for sugarcane, this relationship adjusts the fraction of available soil water at which stress starts according to the atmospheric evaporative demand (AED), represented by ET_0. However, to express soil water stress purely in terms of soil water content is not entirely true as the energy required to extract water from the soil is also dependent on the soil type. To account for this, f_s is modified by a soil textural dependent percentage increase or decrease in the fraction of TAM at which stress starts. The modified f_s, $f_{s\ mod}$ is determined using Equation 3.11 (Allen *et al.*, 1998).

$$f_{s\ mod} = f_s \times (1 - f_{text}/100) \qquad (3.11)$$

where

f_{text} = soil textural dependent percentage increase or decrease in the fraction of TAM at which stress starts (%).

This concept is illustrated in Figure 3.2.

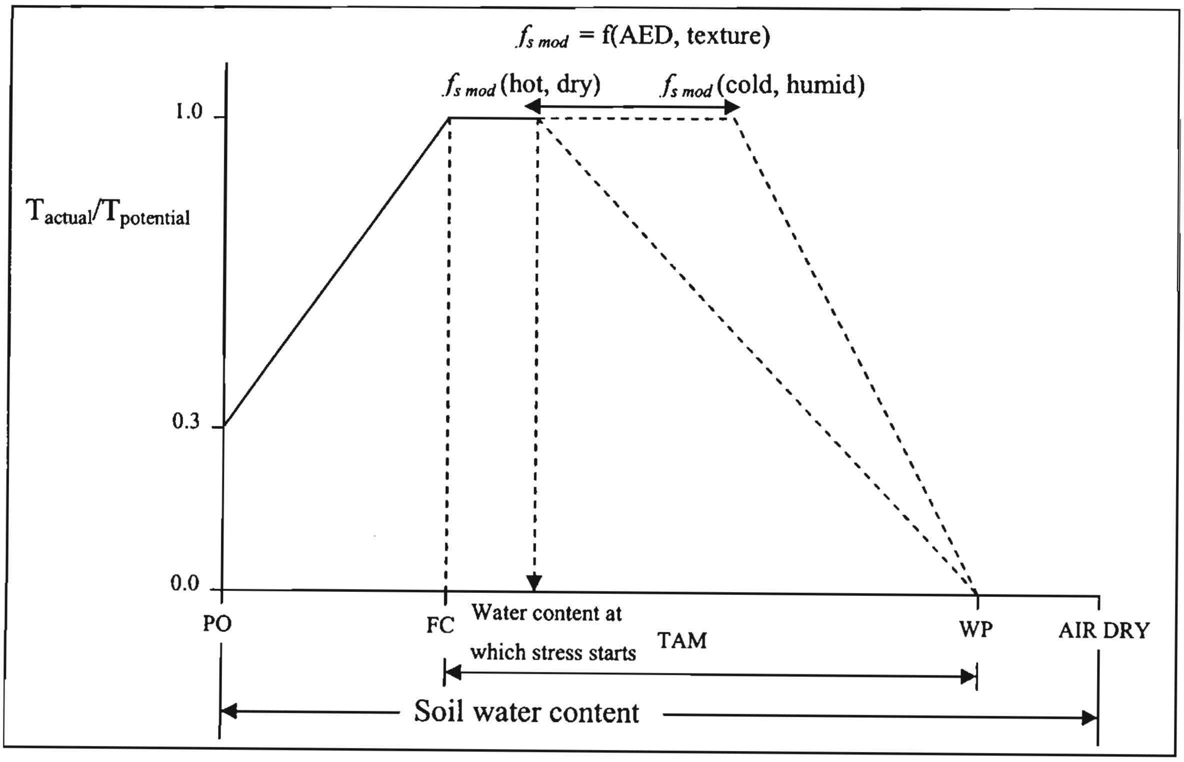

Figure 3.2 Relationship between T_{actual}:$T_{potential}$ and soil water content (after Schulze, 1995)

Default values for f_{text} are shown in Table 3.1.

Table 3.1 Default f_{text} values assigned to different soil textural classes (after Allen *et al.*, 1998)

Soil textural class	f_{text} (%)
Clay	-8.0
Clay Loam	-1.8
Loam	0.6
Loamy Sand	5.5
Sand	8.0
Sandy Clay	-1.8
Sandy Clay Loam	0.6
Sandy Loam	4.3
Silty Clay	-5.5
Silty Clay Loam	-3.1
Silty Loam	-0.6

If, for example, the soil type in a simulation was defined as a "sand", then the value for f_{text} would be set to 8%. An f_s value of 0.50 would then be modified to an $f_{s\ mod}$ value of 0.46. This makes stress set in at a lower fraction of TAM, and thus at a lower soil water content. Conversely, f_{text} for a clay is defaulted to –8%, resulting in stress being initiated earlier.

3.3.1.2 Transpiration under excess soil water conditions

Transpiration is also reduced below potential under excess soil water conditions as a result of poor aeration. Both the *ACRU* model and *ZIMsched 2.0* account for the impact of excess soil water using work reported on by Dijkhuis and Berliner (1988). The same concept is utilised in *ACRUCane* which assumes that the ratio of actual to potential transpiration decreases linearly from 1 at FC to 0.3 at PO. This concept is illustrated in Figure 3.2.

3.3.2 Evaporation from soil

The coefficient K_e in Equation 3.2 represents the soil water evaporation component from the cropped surface. Following a wetting event, K_e, and thus evaporation from the soil, is at a maximum. However, the sum of K_{cb} and K_e may not exceed the maximum crop coefficient, K_{cmax}, i.e. $K_{cb} + K_e \leq K_{cmax}$. Thus K_e is limited as follows: $K_e \leq K_{cmax} - K_{cb}$ (Allen *et al.*, 1998). Effectively, K_e is limited by the energy remaining after transpiration has taken place.

K_{cmax} represents an upper limit on evaporation and transpiration from a cropped surface and is governed by the amount of energy reaching the soil surface. K_{cmax} is determined using Equation 3.12 (Allen *et al.*, 1998):

$$K_{cmax} = \max\left(\left(1.2 + \left(0.4(u_2 - 2) - 0.004(RH_{min} - 45)\right)\left(\frac{h}{3}\right)^{0.3}\right), \left(K_{cb} + 0.05\right)\right) \text{............(3.12)}$$

where

u_2	=	wind speed (m.s^{-1}),
RH_{min}	=	minimum relative humidity (%), and
h	=	mean maximum plant height during the period of calculation, taken as 3 m.

Equation 3.12 ensures that K_{cmax} is always greater than or equal to K_{cb} + 0.05, implying that wet soil will always increase the value for K_{cb} by 0.05 following complete wetting of the soil surface, even at full canopy. The product of K_{cmax} and ET_0 represents the maximum possible evapotranspiration from a cropped surface.

Knowing K_{cmax}, K_e is determined as follows (Allen *et al.*, 1998):

$$K_e = K_r(K_{cmax} - K_{cb}) \leq f_{ew}.K_{cmax} \text{............(3.13)}$$

where

f_{ew}	=	fraction of soil that is both exposed and wetted, and
K_r	=	evaporation reduction coefficient dependent on cumulative depth of water depleted from the topsoil.

Evaporation from the soil is assumed to occur in two stages, an energy limiting stage and a falling rate stage. The onset of either stage is governed by the amount of water in the soil evaporation layer. The soil evaporation layer is the top portion of soil that is subject to drying by evaporation. Allen *et al.* (1998) recommend the depth of this layer to range from 100-150 mm. In *ACRUCane* this value is defaulted to 100 mm after Lecler (2003). The parameter K_r distinguishes between the two stages of evaporation. After rain or irrigation K_r is 1, and evaporation from the soil is limited by atmospheric demand. As the soil surface dries, K_r becomes less than one and evaporation is reduced.

3.3.2.1 Stage 1: Energy limiting stage

After the soil has been wet significantly by either rainfall or irrigation, evaporation from the exposed portion of the soil occurs at the maximum rate, limited by the evaporative energy availability at the soil surface. The soil water content in the topsoil is at, or above, the field capacity and the amount of water depleted by evaporation, D_e, is zero. K_r remains 1.0 during this stage until D_e exceeds the Readily Evaporable Water (*REW* in mm). *REW* depends on soil texture and usually varies from 5 to 12 mm. Defaults values of *REW* are provided in Table 3.2.

Table 3.2 Default *REW* values assigned to different soil textural classes (after Allen *et al.*, 1998)

Soil textural class	***REW* (mm)**
Clay	10
Clay Loam	9
Loam	9
Loamy Sand	6
Sand	4.5
Sandy Clay	8.5
Sandy Clay Loam	8.5
Sandy Loam	8
Silty Clay	10
Silty Clay Loam	9.5
Silty Loam	9.5

3.3.2.2 Stage 2: Falling rate stage

During stage 2, K_r decreases linearly from 1.0 to 0.0 as the soil water content decreases from *REW* to Total Evaporable Water (*TEW* in mm). Determination of *TEW* is as follows (Allen *et al.*, 1998):

$$TEW = 1000.(\theta_{FC} - 0.5\theta_{WP}).Z_e \qquad (3.14)$$

where

Z_e	=	depth of soil water evaporation layer (m), defaulted to 0.1 m,
θ_{FC}	=	soil water content at FC ($mm.mm^{-1}$), and
θ_{WP}	=	soil water content at WP ($mm.mm^{-1}$).

K_r is estimated by linear interpolation as shown in Equation 3.15.

$$K_r = \frac{TEW - D_{e,i-1}}{TEW - REW} D_{e,\, i-1} \qquad (3.15)$$

where

$D_{e,\, i-1}$	=	cumulative depth of evaporation from the soil surface layer at the end of day i – 1 (mm).

This two stage evaporation process is illustrated in Figure 3.3.

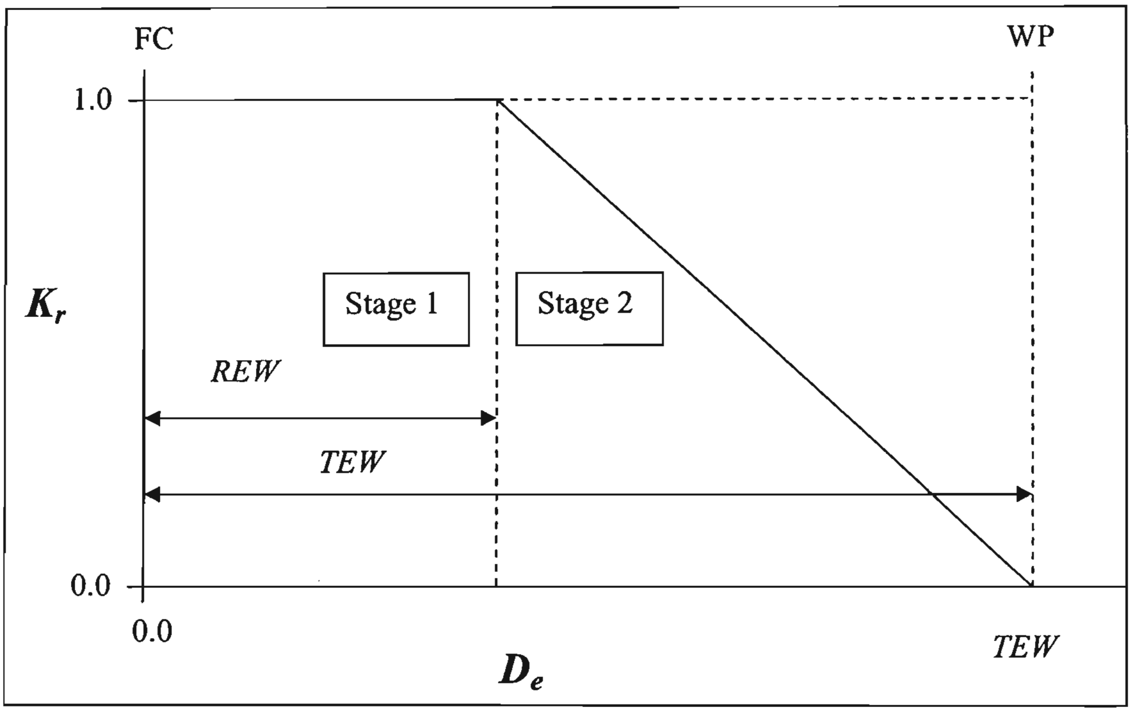

Figure 3.3 Two stage evaporation process (after Allen *et al.*, 1998)

The sloping section of the line shown in Figure 3.3 is represented by Equation 3.15.

3.3.2.3 Daily calculation of D_e

K_e is determined using Equation 3.13 which requires the estimation of K_r (Equation 3.15), which in turn requires the calculation of D_e. Determination of D_e requires the following daily water balance calculation:

$$D_{e,\,i} = D_{e,\,i-1} - (P_i - Q_i) - I_i/f_w + E_i/f_{ew} + T_{ew,\,i} + DP_{e,\,i} \quad \text{....................................(3.16)}$$

where

$D_{e,\,i}$	=	cumulative depth of evaporation following complete wetting from the exposed and wetted fraction of the topsoil at the end of day i (mm),
P_i	=	precipitation on day i (mm),
Q_i	=	runoff from the soil surface on day i (mm),
I_i	=	infiltrated irrigation depth on day i (mm),
f_w	=	fraction of soil wetted by irrigation,
E_i	=	evaporation from the soil surface on day i (mm),

f_{ew} = fraction of exposed and wetted soil,

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

$DP_{e,\,i}$ = deep percolation from the topsoil layer on day i (mm).

Note that values for $D_{e,i}$ are limited between 0 and *TEW*. Explanations of parameters f_w and f_{ew} are provided in Section 3.3.2.5.

Equation 3.16 is simplified in FAO 56, which assumes that all the water infiltrates and there is thus no runoff. A second assumption is that transpiration from the surface layer is negligible, i.e. $T_{ew} = 0$. *ACRUCane* however uses the methodology reported on by Lecler (2003), where runoff is calculated using the modified SCS stormflow equation (Equation 3.1) and the fraction of actual transpiration that is extracted from the topsoil is computed using Equation 3.17:

$$F_T = \max\left(0.0, \left(\frac{0.1}{R_{fac}.S_{dep}}\right).\left(\frac{TAM_{10} - D_{e,i-1}}{TAM_{10}}\right)\right) \quad \text{.....(3.17)}$$

where

F_T = fraction of actual transpiration extracted from the soil evaporation layer (mm),

R_{fac} = current proportion of maximum effective rooting depth in soil profile,

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

TAM_{10} = total available moisture in the topsoil layer of 0.1 m, i.e. 0.1 (θ_{FC} – θ_{WP}).

Equation 3.17 ensures that transpiration only occurs from the top 100 mm of soil while TAM_{10} is greater than $D_{e,\,i-1}$.

3.3.2.4 Exposed soil fraction, 1-f_c

Estimation of the exposed soil fraction requires a realistic and accurate estimation of f_c, the fraction of soil covered by vegetation. In *ACRUCane*, f_c is equal to the initial ground cover prior to emergence, after which it is affected primarily by canopy cover. This is shown in Equation 3.18 (Lecler, 2003).

$$f_c = Grd_{ini} \quad \text{for} \quad TT_a < TT_{emerge} \qquad (3.18)$$
$$f_c = \max(Grd_{ini}, \min(0.99, CC)) \quad \text{for} \quad TT_a > TT_{emerge}$$

where

TT_a = accumulated thermal time since the beginning of the season (°C.d)

Grd_{ini} = initial ground cover, e.g. due to surface mulching, and

TT_{emerge} = thermal time until emergence, taken as 403 °C.d for a plant crop and 203 °C.d for a ratoon crop.

3.3.2.5 Exposed and wetted fraction, f_{ew}

The parameter f_{ew} is used to account for the interrelated effects of the wetting characteristics of an irrigation system, and the fraction of the soil covered by vegetation. A centre pivot, for example, wets 100% of the area irrigated, in which case f_{ew} would depend on the fraction of the soil covered by vegetation. However, a drip irrigation system may only wet 36% of the soil while the fraction of exposed soil might be 50%. The parameter f_{ew} is thus determined as shown in Equation 3.19.

$$f_{ew} = \min(1 - f_c, f_w) \qquad (3.19)$$

where

f_c = fraction of soil covered by vegetation, and

f_w = fraction of soil wetted by irrigation.

A limitation imposed by Equation 3.19 is that it assumes that the fraction of wetted soil occurs within the fraction of soil exposed to sunlight and vegetation. This is generally the case, except with drip and in-row furrow irrigation. In instances where the majority of the wetted area is likely to be shaded, f_w is reduced by multiplying it by $[(1-(2/3)f_c]$ as proposed by Allen *et al.* (1998). In *ACRUCane*, f_w is input by the user.

3.4 Soil Water Dynamics

Water infiltrates the soil after a wetting event. Once in the soil profile, water leaves the soil through transpiration and/or soil water evaporation and/or deep percolation. Having discussed both transpiration and evaporation, the following subsections describe the manner in which water is redistributed within the soil profile and how it percolates through the soil profile in the *ACRUCane* model.

3.4.1 Drainage

Two soil layers are simulated in *ACRUCane.* The total thickness of both layers is limited by an input variable that specifies the maximum soil thickness. The top soil layer is defined by the portion of soil containing the roots of the crop and will subsequently be referred to as the "root soil layer". The second soil layer is made up of the remaining soil and will subsequently be referred to as the "sub-root layer". The soil is assumed to be uniform throughout the maximum soil depth, and thus both the root soil layer and the sub-root layer have the same physical properties. However, it is, for example, possible to input soil characteristics such that the drainage properties are that of a clay, while the water holding properties are that of a sand.

If, at the end of the day, the water content of the root soil layer is above FC, a fraction of the water above FC drains into the sub-root layer. The sub-root layer is then treated in an identical manner, and, if drainage occurs, it leaves the soil profile permanently as deep percolation.

The fraction of water above the field capacity that leaves the soil profile is dependent on the soil textural class and the fraction may be estimated using default values which are used based on the soil texture or, alternatively, a user can specify values.

With other, point-based models drainage simply represents the depth of water leaving the soil profile. However, as *ACRUCane* operates as a sub-model within the *ACRU* model, drainage can, depending on the configuration of the catchment, return to a dam or river and be re-used by irrigators. It is thus critically important to model drainage accurately as it allows one to quantify the amount of water that may erroneously be considered lost.

3.4.2 Root growth water redistribution

Root growth is simulated in *ACRUCane*, and results in the depth of the root soil layer increasing resulting in a decrease in the sub-root layer. A daily water content adjustment in each layer thus needs to be performed in order to account for the roots growing into soil which has a different water content. Before these calculations are explained, a description of how root growth is simulated is required.

Root growth modelling in *ACRUCane* is based on algorithms developed by Lecler (2003) for *ZIMsched*. R_{frac}, the proportion of maximum soil depth that is penetrated by the roots, is calculated as follows:

$$R_{fac} = 0.4/S_{dep} \quad \text{for } TT_a < TT_{emerge} \ldots\ldots\ldots\ldots (3.20)$$

$$= \min\left(1.0, \left(1 - \frac{0.4}{S_{dep}}\right) . \left(\frac{TT_a - TT_{emerge}}{980 - TT_{emerge}}\right) + \frac{0.4}{S_{dep}}\right) \quad \text{for } TT_a > TT_{emerge}$$

where

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

The structure of Equation 3.20 is such that, prior to emergence, root depth is 0.4 m. After emergence, R_{fac} increases linearly from $0.4/S_{dep}$ to a value of 1.0, which is assumed to occur once 980 °C.d have accumulated. When R_{fac} is 1.0 the crop has effectively reached its maximum rooting depth. Note that, as with canopy cover, a T_{base} of 10 °C is used prior to emergence and 16 °C after emergence when determining TT_a. The depth of the root soil layer can then be determined by finding the product of R_{frac} and S_{dep}. Note that Equation 3.20 also accounts for the difference in root depth from a plant to ratoon crop through the variable TT_{emerge}.

Once the roots start growing, the daily increase in root length (ΔL) is exposed to soil that was previously unoccupied by roots and potentially of different soil water content. In *ACRUCane* this is assumed to change the average soil water content in the root soil layer. It also becomes necessary to estimate the water content of the soil when the model makes the transition from the end of one season to the beginning of the next. The following solution proposed by Lecler

(2004) is implemented in *ACRUCane* and is illustrated with the aid of Figure 3.4 and Equation 3.21.

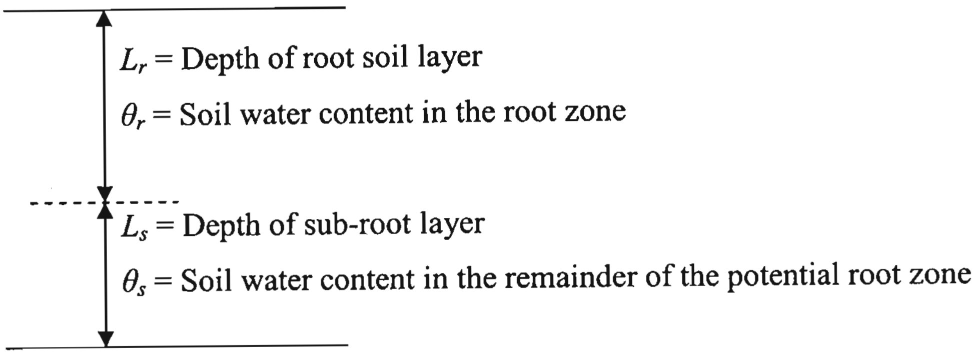

Figure 3.4 Schematic vertical section through soil profile

At the beginning of each day, if root growth has occurred, the soil water content is determined by finding the length-weighted averages of the soil water in the current soil and the new soil that has been "acquired".

$$\theta_{r,i} = \theta_{r,i-1}\left(\frac{L_r}{\Delta L + L_{r,i-1}}\right) + \theta_{s,i-1}\left(\frac{\Delta L}{\Delta L + L_{r,i-1}}\right) \quad (3.21)$$

where

$\theta_{r,\,i}$	=	soil water in the root zone on day i, (mm.mm^{-1}),
$\theta_{r,\,i-1}$	=	soil water in the root zone on day i-1, (mm.mm^{-1}),
$\theta_{s,\,i-1}$	=	soil water in the sub-root zone on day i-1, (mm.mm^{-1}),
$L_{r,\,i-1}$	=	root length on day i-1, (m),
ΔL	=	change in root length from day i-1 to day I (m).

The same principle of using length-weighted water contents is used to determine the soil water content in the transition from one season to the next.

3.5 Yield Estimation

To effectively be able to simulate the impact of different management practices, types of irrigation systems, water supply limitations and environmental conditions on sugarcane yield, it is necessary to estimate both the cane yield and quality of cane. In *ACRUCane*, several algorithms to simulate sugarcane yield and quality are used to provide a range of comparable outputs. A conceptually attractive radiation-based sucrose yield model is included, but this requires additional model inputs, such as daily solar radiation, that are occasionally unavailable. For this reason, a conceptually simpler transpiration-based *ERC* model is also included, as it provides a reliable surrogate for sucrose yield. Two transpiration-based cane yield models are also included. The following subsections discuss these in detail.

3.5.1 Sucrose yield model

To estimate sucrose yield, *ACRUCane* uses a conceptual, radiation driven model described by Singels and Bezuidenhout (2002). This model uses intercepted radiation to accumulate biomass, which is further partitioned to different parts of the plant and ultimately provides a prediction of sucrose yield. Unless otherwise specified, all aspects of this model have been incorporated into *ACRUCane* exactly as described by Singels and Bezuidenhout (2002). A description of this model follows.

Gross photosynthate (P_g in $t.ha^{-1}$) is accumulated on a daily basis using Equation 3.22.

$$P_g = (PARCE/100).L_i.PAR \quad (3.22)$$

where

L_i	=	light interception, (dimensionless fraction),
PAR	=	photosynthetically active radiation,
	=	0.5 × Solar Radiation ($MJ.m^{-2}.d^{-1}$), and
PARCE	=	*PAR* Conversion Efficiency, defaulted to 5.68 $g.MJ^{-1}$.

PARCE accounts for the plant's efficiency at converting intercepted *PAR* into gross photosynthesis and is divided by 100 to account for the different mass and area units used. Gross photosynthesis is then reduced to account for the photosynthate used by the plant for maintenance and growth respiration to yield the daily biomass (dry matter) produced. This is shown in Equation 3.23:

$$dW/dT = (P_g - R_m.W).(1 - R_{gr}).SWDF1 \quad (3.23)$$

where

dW/dT	=	daily biomass increment (t.ha^{-1}.d^{-1}),
R_m	=	maintenance respiration (0.004 g.g^{-1}),
R_{gr}	=	growth respiration (0.242 g.g^{-1}),
$SWDF1$	=	soil water deficit factor (dimensionless) and
W	=	current biomass (t.ha^{-1}).

Inman-Bamber and Thompson (1989) found R_m and R_{gr} to have values of 0.003 and 0.242g.g^{-1} respectively. In *ACRUCane* an R_m value of 0.004 is used, as suggested by Bezuidenhout (2000). dW/dT is also reduced by $SWDF1$, a soil water deficit factor that has a value of 0 at maximum water stress and 1 when there is no water stress. It is the less sensitive of two soil water deficit factors, the second factor being used to account for the effects of soil water stress on sucrose accumulation. A description of the calculation of these two factors follows.

$SWDF1$ is determined by calculating the ratio of actual to potential transpiration for a given day. Transpiration is assumed to reduce below the potential rate once a certain fraction of the TAM has been reached, as given by $f_{s\ mod}$ (Equation 3.11). Transpiration is also reduced below potential if soil water content exceeds FC and the soil becomes saturated. A detailed description of how actual transpiration is computed is given in Section 3.3.1.1. $SWDF1$ thus represents the y-axis value of any point on the line represented in Figure 3.2. $SWDF2$ is determined in the same manner but is assumed to reduce below a value of one at a higher fraction of TAM. This fraction is determined based on a set of initial conditions provided by Lecler (2005b) which require that when $f_{s\ mod} = 0.5$ for $SWDF1$, then $f_{s\ mod} = 0.7$ for $SWDF2$. Knowing these initial conditions a value for ET_0 is computed using Equation 3.10 to ensure that $f_{s\ mod}$ for $SWDF2$ meets the specified initial conditions. Thus a on given day, $f_{s\ mod}$ for $SWDF1$ would be calculated using the actual ET_0, while $f_{s\ mod}$ for $SWDF2$ would be determined using an artificially increased ET_0 to ensure that $SWDF2$ would "set in" earlier. This concept is illustrated in Figure 3.5

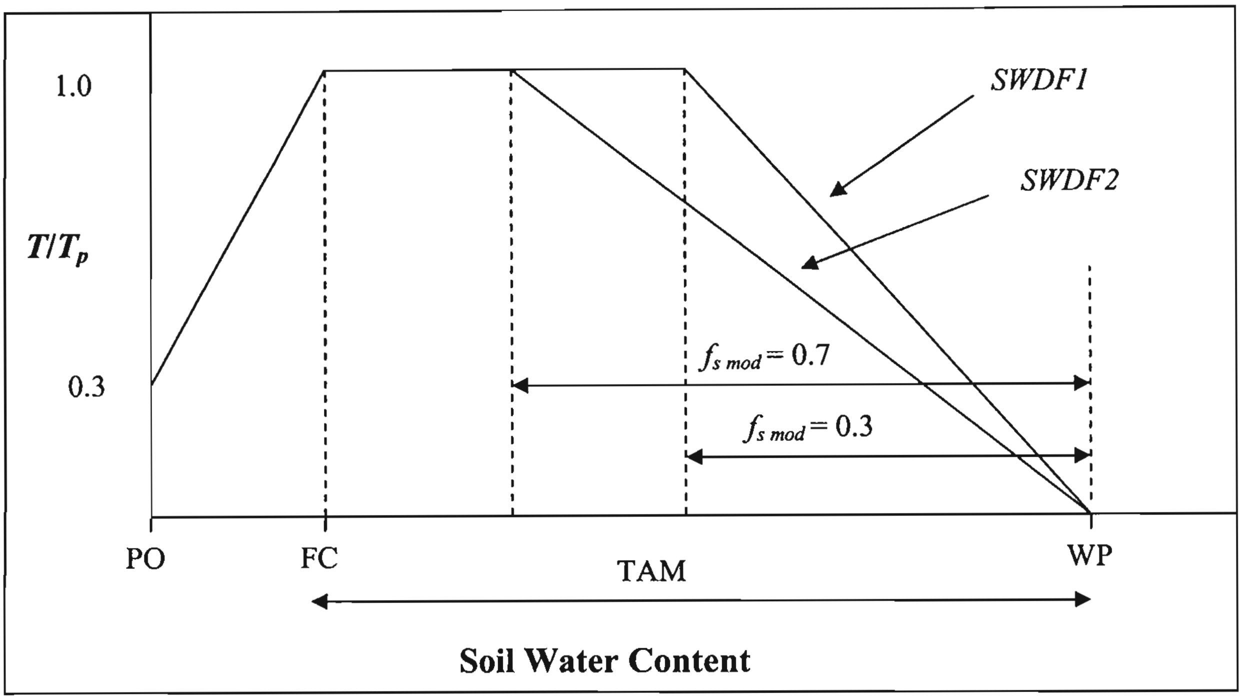

Figure 3.5 Determination of *SWDF1* and *SWDF2*

Note that *SWDF1* and *SWDF2* are assumed to behave identically for conditions of excess soil water. Referring back to Equation 3.23, *SWDF1* thus directly reduces accumulation of biomass according to the magnitude of stress experienced by the plant. An explanation of *SWDF2* will be provided in a subsequent section. A description follows of (i) partitioning of daily biomass to aerial mass, (ii) partitioning of aerial mass to stalk and (iii) partitioning of stalk mass to sucrose and fibre plus non-sucrose.

3.5.1.1 Partitioning of mass to aerial parts of plant

The daily biomass increment (*dW/dT*) is partitioned to aerial dry mass (*ADM* in $t.ha^{-1}.d^{-1}$) using an aerial dry matter partitioning fraction (*ADMPF*) as given in Equation 3.24.

$$ADMPF = ADMPF_{max}(1 - e^{(-bW)}) \qquad (3.24)$$

where

$ADMPF_{max}$	=	maximum *ADMPF*, 0.88 ($t.t^{-1}$),
W	=	total accumulated biomass ($t.ha^{-1}$), and

b = partitioning coefficient, 0.6.

The product of dW/dT and $ADMPF$ yields ΔADM (t.ha^{-1}.d^{-1}), the daily increment of aerial dry matter, as shown in Equation 3.25:

$$\Delta ADM = ADMPF \times dW/dT \quad \text{(3.25)}$$

3.5.1.2 Partitioning of mass to stalk

The daily stalk increment (ΔSK in t.ha^{-1}.d^{-1}) is determined by assuming a constant daily stalk partitioning fraction ($SKPF$ in t.t^{-1}) of 0.65 after thermal time since emergence has exceeded a value of 1050°C.d when using a T_{base} of 10°C.. Prior to this time no partitioning is simulated. This is expressed in Equation 3.26:

$$\Delta SK = \Delta ADM \times SKPF \quad \text{(3.26)}$$

3.5.1.3 Partitioning of stalk to fibre and fibre plus non-sucrose

In order to partition the daily stalk matter into sucrose and fibre plus non-sucrose, Singels and Bezuidenhout (2002) assumed the stalk to consist of one or two sections depending on the size of the stalk. The top of the plant is assumed to be an unripened section where sucrose content (SC in t.t^{-1}) decreases with increasing stalk length, while the lower section of the stalk is assumed to have a uniform maximum SC (SC_{max} in t.t^{-1}) throughout its length. These assumptions were applied to the "single big stalk" approach, i.e. the entire field is represented hypothetically by a single stalk. This is illustrated in Figure 3.6:

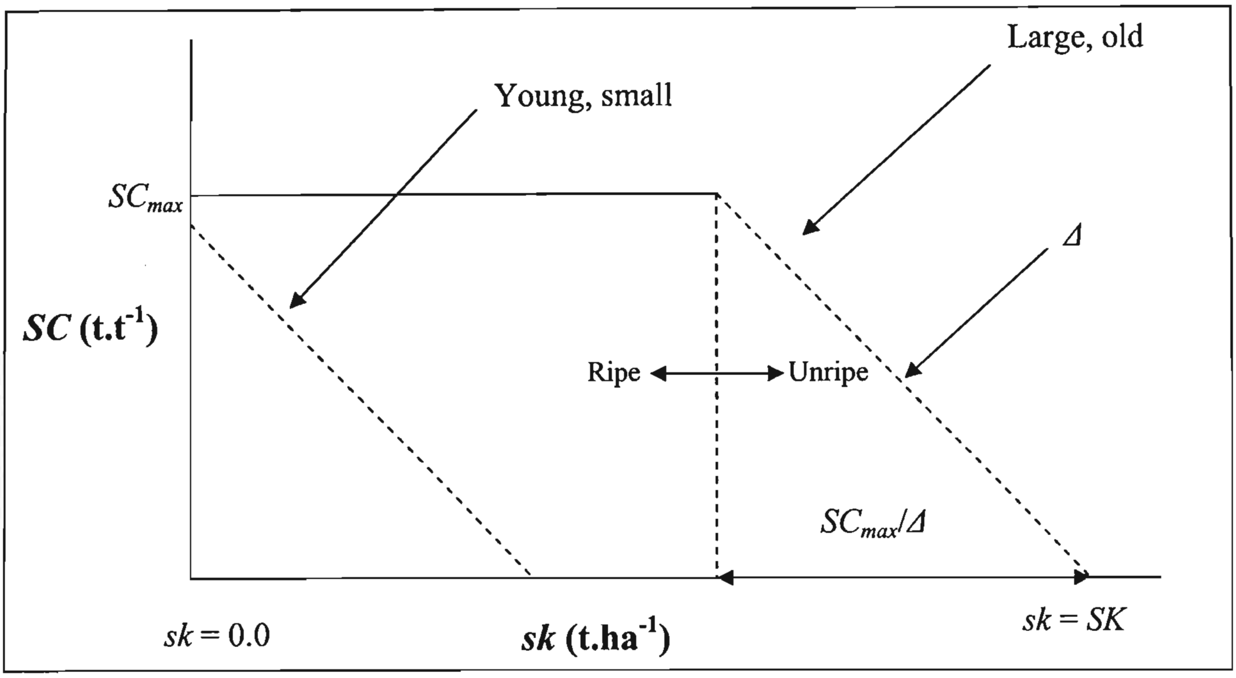

Figure 3.6 A schematic diagram of sucrose distribution within a single big stalk (after Singels and Bezuidenhout, 2002)

In Figure 3.6, sk is the cumulative stalk mass measured from the base, where sk = 0.0 t.ha^{-1}, to the top, where $sk = SK$, the current mass of the stalk (t.ha^{-1}). Figure 3.6 shows how a young, small stalk can be made of only the unripened section, whereas an older crop is comprised of both the ripe and unripened sections of stalk. The decrease in sucrose content in the unripe section is represented by the ripening gradient Δ, which has derived units of ha.t^{-1}. Determination of the ripening gradient is, in reality, determined by genetic characteristics and current condition such as temperature, soil water, nitrogen status and chemical ripening. In *ACRUCane*, as in CANEGRO, only the first three factors (genetic characteristics, temperature and soil water) are taken into account:

$$\Delta = \Delta_{max}(FW + FT - FW.FT) \qquad (3.27)$$

where

Δ_{max}	=	cultivar specific maximum ripening gradient, 0.7 (ha.t^{-1}),
FT	=	temperature control factor (eq 3.28), and
FW	=	water stress control factor (eq 3.29).

FT is a temperature control factor, and tends towards a value of 0 when temperatures increase and a value of 1 as temperatures decrease.

$$FT = 1/(1+e^{[FTCON(T_{mean} - T50)]}) \quad \text{...(3.28)}$$

where

$FTCON$	=	temperature response coefficient, 0.32,
T_{mean}	=	mean daily temperature, (°C), and
$T50$	=	temperature where the well watered ripening gradient is half of Δ_{max}, assumed to be 25°C.

FW is a crop stress control factor and has a value of 0 when the crop is unstressed and 1 when it is fully stressed.

$$FW = (1\text{-}SWDF2)^{FWCON} \quad \text{...(3.29)}$$

where

$FWCON$	=	soil water deficit sensitivity parameter, 0.5, and
$SWDF2$	=	soil water deficit factor.

SWDF2 thus affects sucrose partitioning indirectly through changing Δ. During periods of very high soil moisture stress *SWDF2* could potentially be as high as 1.0. If one were to fix *FW* at 0.5, for example, then an *SWDF2* of 1.0 would result in $\Delta = \Delta_{max}$. However, if *SWDF2* were equal to 0.0, then $\Delta = 0.5 \times \Delta_{max}$. A lower value of Δ effectively means a lower average sucrose content of the ripening section. In this way, the model simulates the concept of high sucrose accumulation during periods of soil moisture stress. Applying the same reasoning to Equation 3.28, if one were to hold *SWDF2* fixed at zero (i.e. no stress) then an *FT* value of 1 (corresponding to cold temperatures) would result in $\Delta = \Delta_{max}$. However, for higher temperatures *FT* tends to zero, making Δ tend to zero. In this way the model assumes cold temperatures to be favourable to sucrose partitioning.

Equation 3.27 serves to account for both the individual and combined effects of temperature and soil water on the potential ripening gradient. The ripening gradient is calculated on a daily basis and reflects the current temperature and soil water conditions. Once Δ has been determined, it is possible to determine the theoretical sucrose mass (SUC_{eq} in $t.ha^{-1}$) of the "stalk" by multiplying the average sucrose content (SC_{ave} in $t.t^{-1}$) by the current stalk mass, SK. This is determined differently, depending on whether the stalk is comprised of one or two sections, as shown in Equation 3.30.

$$SUC_{eq} = 0.5.\Delta.SK^2 \text{ for } SK < SC_{max}/\Delta \quad (3.30)$$
$$= SC_{max}(SK - 0.5.SC_{max}/\Delta) \text{ for } SK > SC_{max}/\Delta$$

where

SC_{max} = potential maximum sucrose content (t/t).

For young stalks that are compromised of only the ripening section, it is evident from Figure 3.5 that the stalk mass is less than SC_{max}/Δ. The value of this term is thus used to determine which option in Equation 3.30 to use.

The value obtained for SUC_{eq} represents the theoretical sucrose content that a stalk of mass SK would have achieved, if the conditions on the day for which it was calculated had occurred throughout the growing season. Thus, it incorporates the current day's growing conditions in Δ, and the cumulative effect of the previous days' growing conditions in SK. Knowing the theoretical sucrose mass, a theoretical mass of fibre plus non-sucrose (FNS_{eq} in $t.ha^{-1}$) can bc calculated as follows:

$$FNS_{eq} = SK_f - SUC_{eq} \quad (3.31)$$

where

SK_f = stalk mass at the end current day ($t.ha^{-1}$).

As with SUC_{eq}, FNS_{eq} is defined as the theoretical mass of FNS that would have been achieved at the end of the current day had the crop experienced uniform temperature and water stress conditions equal to the current day's conditions. The difference between FNS_{eq} and fibre plus non-sucrose at the beginning of the day (FNS_i in $t.ha^{-1}$) represents the potential structural growth of the plant for that day:

$$FCAP = FNS_{eq} - FNS_i \quad (3.32)$$

where

$FCAP$ = potential structural growth of the plant for that day (t.ha^{-1}).

Daily fibre plus non-sucrose (ΔFNS in t.ha^{-1}.d^{-1}) accumulated by the plant can then be determined as follows:

$$\Delta FNS = FCAP \times SSR \quad \text{...(3.33)}$$

where

SSR = sink activity, set to 0.99.

SSR represents the crop's ability to fill the sink capacity.

The stalk mass generated by the plant (ΔSK in t.ha^{-1}.d^{-1}) is first used to meet the fibre requirements of the plant for that day, i.e. ΔFNS. If ΔSK exceeds ΔFNS, then the remainder is used to generate sucrose, represented by ΔSUC (t.ha^{-1}d^{-1}). *FCAP* has the potential to yield a negative value, indicating that the plant has already met its theoretical structural requirements for that day. If this occurs, ΔSK contributes exclusively to ΔSUC. ΔSUC and ΔSK are summed over the course of the growing season to obtain yields of sucrose and stalk dry mass at the end of the season.

Using solar radiation as a driver for sucrose yield while further reducing yield due to environmental conditions makes this model conceptually superior to empirical transpiration-based models, which tend to be more robust. A range of transpiration driven models have been included in *ACRUCane*. A description of each follows.

3.5.2 *ERC* yield model

At the end of the growing season an estimate of Estimated Recoverable Crystals (*ERC* in t.ha^{-1}) is generated using the same methodology as that used by Lecler (2003) in *ZIMsched* 2.0. Lecler (2003) used a modified version of the methodology described by Doorenbos and Kassam (1979), which is described below:

Doorenbos and Kassam (1979) assumed that the decrease in relative yield is linearly related the relative evapotranspiration deficit. This relationship is described in Equation 3.34.

$$1-\frac{Y_a}{Y_p}=K_{yi}(1-\frac{ET}{ET_m}) \qquad (3.34)$$

where

Y_a	=	actual yield ($t.ha^{-1}$),
Y_p	=	potential yield ($t.ha^{-1}$),
K_{yi}	=	yield response factor for the i-th growth period,
ET	=	evapotranspiration (mm), and
ET_m	=	maximum evapotranspiration (mm).

Note that the linearity of the relationship exists within growth stages, where K_y represents the gradient of the relationship. This is significant in that it implies that stress, shown by a relative reduction in evapotranspiration, has varying impacts on yield depending on the plant's growth stage. Significantly, this relationship is valid for water deficits of up to approximately 50%, i.e. $1- ET/ET_m = 0.5$. De Jager (1994) stated that the transferability of the yield relationship shown in Equation 3.34 could be improved by using ratios of actual to potential transpiration (T_a/T_p) in place of evapotranspiration. In doing so, the influences of atmospheric vapour pressure deficits and climate-crop characteristics on (T_a/T_p) and hence Y_a/Y_p cancel out, thus making K_y a purely plant physiological entity determined by crop genetics and not climate (De Jager, 1994).

Doorenbos and Kassam (1979) suggest an overall yield response factor of 1.2 for sugarcane. In *ACRUCane*, as in *ZIMsched*, a value of 1.2 is used up until the ripening period, taken as 56 days before cutting, after which a K_y value of –0.01 is used (Lecler, 2003).

Substituting these values into a rearranged version of Equation 3.34, the yield relationship used in *ACRUCane* is thus represented by Equation 3.35.

$$\frac{Y_a}{Y_p}=(1-1.2(1-\frac{\Sigma T_1}{\Sigma T_{p1}})).(1+0.01(1-\frac{\Sigma T_2}{\Sigma T_{p2}})) \qquad (3.35)$$

where

ΣT_1 = accumulated actual transpiration for growth stage 1 (mm),

ΣT_{p1} = accumulated potential transpiration for growth stage 1 (mm),

ΣT_2 = accumulated actual transpiration for growth stage 2 (mm), and

ΣT_{p2} = accumulated potential transpiration for growth stage 2 (mm).

Y_p is computed using a modified version of the relationship derived by Thompson (1976) between actual evapotranspiration and tons of sucrose:

$$Y_p = \min(0,-22.65 + 4.923((\Sigma T_p/100)x1.05) - 0.149((\Sigma T_p/100)x1.05)^2) \qquad (3.36)$$

where

Y_p = potential *ERC* yield ($t.ha^{-1}$), and

ΣT_p = accumulated potential transpiration (mm).

The factor of '1.05' is based on a comparison between potential evapotranspiration (ET_p) and potential transpiration (T_p) assuming well scheduled 50 mm irrigation application amounts (Lecler, 2005a). Prior to significant canopy development, *ET* is dominated by evaporation from the soil surface. This is particularly true for systems that wet a large fraction of the soil or wet the soil very frequently. High soil water evaporation is not used beneficially by the crop as it returns directly to the atmosphere and results in artificially high yields simulated by ET-based algorithms. Thus by making Equation 3.36 purely transpiration-based, artificially high yields associated with high soil water evaporation are avoided.

3.5.3 Sugarcane yield models

In addition to the *ERC* yield estimation, two empirical transpiration-based algorithms are included to estimate tons of sugarcane produced per hectare. The first is the Thompson equation (Thompson, 1976):

$$Y_T = 9.53(\Sigma ET)/100 - 2.36 \qquad (3.37)$$

where

Y_T	=	tons of cane per hectare (t.ha^{-1}), and
ΣET	=	accumulated actual evapotranspiration (mm).

The second is an equation used in the CANESIM model, developed by fitting a second order polynomial to stalk matter and cumulative transpiration simulated by the CANEGRO model for several widely varying climates (Singels *et al.*, 1999a):

$$Y_c = -4 \times 10^{-5} (\Sigma T)^2 + 0.188\Sigma T - 30.737 \quad (3.38)$$

where

Y_c	=	tons of cane per hectare (t.ha^{-1}), and
ΣT	=	accumulated actual transpiration (mm).

Using the *ZIMsched 2.0* model to compare potential evapotranspiration and transpiration, Lecler (2005a) estimated the ratio between the two to be 1.05, as was described in section 3.5.2. Using this ratio, it is possible to compare the yield curves represented by Equation 3.37 and 3.38. This is shown in Figure 3.7.

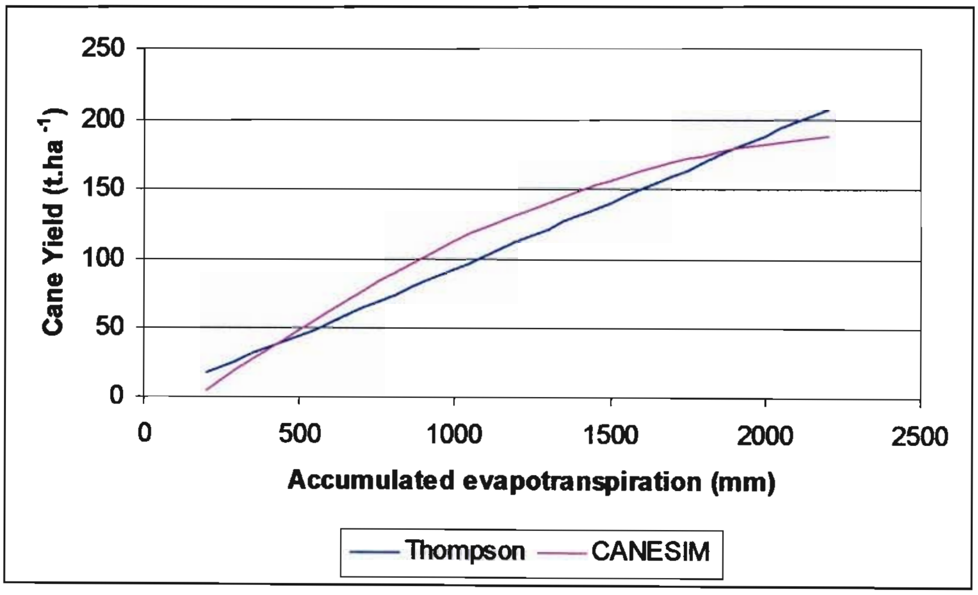

Figure 3.7 Comparison of Thompson and CANESIM yield curves

Figure 3.7 shows that the CANESIM equation predicts a slightly higher yield than the Thompson equation for a wide range of evapotranspiration values, but due to its polynomial nature, intersects the linear Thompson equation at two points. These two points correspond to a yields of 36.96 and 178.30 $t.ha^{-1}$. Hence it is evident that for the majority of yields estimated, a higher value will be simulated using the CANESIM equation.

3.6 Irrigation Scheduling

Different irrigation practices impact significantly on the hydrology of the area being irrigated. *ACRUCane* allows the user a choice of six different modes of irrigation scheduling, which are essentially a duplication of the four options available in the *ACRU* model (Schulze, 1995) as described in Sections 3.6.1 to 3.6.4, as well as two additional options (Sections 3.6.5 and 3.6.6) In *ACRUCane* the irrigation requirement is determined for the scheduling option selected by the user and is then applied at the beginning of the each day. Note that in all scheduling options described below, an irrigation requirement is determined. The amount that is actually applied to the crop is limited by water availability from the supply source, and in some cases, the system capacity.

3.6.1 Demand mode scheduling according to soil water depletion levels

In this mode of scheduling, a user input fraction of TAM is used to determine the maximum allowable depletion of water in the soil profile. Once this level has been reached, an irrigation requirement is generated to refill the soil profile to the field capacity, or to a water level below the field capacity and thus leaving a portion of the soil water store to be filled by precipitation. This irrigation requirement is supplied dependent on the availability of the source of water. Schulze (1984) noted that application of water just before the soil water content has reached a level at which plant stress will set in is a desirable scheduling strategy. It follows that a carefully chosen fraction of TAM will result in optimal irrigation scheduling. It is an efficient form of irrigation as irrigation is only initiated when it is necessary to prevent crop water stress.

3.6.2 Irrigation with a fixed cycle and fixed amount

For practical purposes, farmers often irrigate using fixed cycle and fixed application amounts for different times of the year. In *ACRUCane*, the user selects both the application depth and the interval between applications. The cycle length is assumed to continue throughout the growing season, unless a threshold amount of rainfall occurs which interrupts and causes the irrigation cycle to restart.

3.6.3 Irrigation with a fixed cycle and varying amounts of water application

This mode of irrigation scheduling results in irrigation applied using a fixed cycle length, but with varying amounts or irrigation applied. The user specifies the cycle length and the system capacity. At the beginning of each cycle the depth of water required to fill the soil profile up to the FC is determined. If the required amount is less than the system capacity then the irrigation requirement is met, otherwise the applied depth is limited by the system capacity. As with the demand mode scheduling described in Section 3.6.1, a certain portion of the soil water store can be left unfilled for potential rainfall events that may supplement irrigation. By specifying a potential rainfall store, the user can simulate irrigation that refills the soil at to a depth below the FC.

3.6.4 Irrigation according to a predetermined schedule

Using this option the user can simulate a known watering regime, which is read into the model from a user prepared hydrometeorological data file.

3.6.5 Irrigation with a fixed cycle and fixed amount with a summer and winter cycle

A fifth scheduling option was created for *ACRUCane* to enable the model to represent a common irrigation practice of having separate irrigation cycles for the summer and winter seasons. In this option, the user specifies the cycle length, application amount and the starting dates of the summer and winter cycles.

3.6.6 Demand mode scheduling according to water depletion levels using a fixed refill depth

The depth of the roots delimits the soil depth for which TAM is determined, and, since *ACRUCane* simulates root growth, this frequently results in small values of TAM in the beginning of the season. Consequently, use of the scheduling option described in Section 3.6.1 results in small and frequent irrigation applications early in the growing season. This is undesirable and necessitated the creation of a sixth option based on the soil water depletion demand driven mode described in Section 3.6.1. In this option, however, instead of specifying the fraction of TAM at which irrigation is to take place, the user specifies a fixed depletion level in mm below FC at which irrigation is to be triggered. In this way it is possible for the user to apply, say, 25 mm once the soil water has depleted 30 mm below FC, leaving 5 mm to be filled by precipitation.

3.7 Irrigation Uniformity

Irrigation systems with poor uniformity experience reduced yields due to either water deficiency or water logging. Poor uniformity can potentially have increased financial costs as excess water is often applied to overcome the effects of poor uniformity (Ascough and Kiker, 2002). To simulate the effects of non-uniformity, an irrigated field in *ACRUCane* is divided into several equal sized sub-areas (the number of which is specified by the user) and the model allocates a different irrigation depth, based on the mean depth of irrigation required, to each sub-area. The user inputs a value of either DU (Distribution Uniformity) or CU (Coefficient of Uniformity) or CV (Coefficient of Variation), where if either DU or CU are input, these are converted internally in *ACRUCane* to a CV value. Assuming a uniform distribution, Equation 3.39 is used to determine a "re-allocation fraction" for each sub-area (Ascough, 2001).

$$f_{r,i} = \left(\sqrt{3}\frac{CV}{100}\right)\left(\frac{2i-1}{wb}\right) + 1.0 - \left(\sqrt{3}\frac{CV}{100}\right) \quad \text{.......(3.39)}$$

where

$f_{r,i}$ = re-allocation fraction,

CV	=	coefficient of variation,
i	=	integer corresponding to sub-area 'i', and
wb	=	the total number of sub-areas.

Thus, if a user entered a CV value of 60 and specified that 3 irrigated sub-areas must be simulated, sub-area one (i.e. $i = 1$) would receive 0.343 of the mean application, sub-area two would receive the mean application and sub-area three would receive 1.636 times the mean application. Each portion of the field thus receives a different depth, although the same total volume is applied to the whole field as would have been applied if the mean irrigation requirement had been applied uniformly to the entire field. In this way, *ACRUCane* can simulate the effects of irrigation uniformity and the impacts on crop yield and the water budget.

3.8 Water Supply

The *ACRU* model simulates several water supply options, all of which are depicted in Figure 2.3. The *ACRUCane* model operates as a sub-model of *ACRU* and is thus internally linked to these supply options, making it capable of simulating the impact of different water supply constraints on the yield and water budget of an irrigated area. These supply options and other water supply dynamics are discussed in more detail in the following subsections. A full description is provided by Lecler *et al.* (1995).

3.8.1 Unlimited supply

Lecler *et al.* (1995) noted that in the planning and design phase of an irrigation project the need may arise to determine the irrigation requirements where there are no water resource limitations. Thus, if this option is invoked, it is possible to determine the total amount of water required to satisfy evapotranspiration as well as irrigation system and conveyance losses.

3.8.2 Irrigation water supply from a reservoir only

In this option, irrigation supply is simulated in conjunction with the simulation of a reservoir water balance. The reservoir may be located within the cathment or at the outlet of the catchment. All irrigation demands as well as supply losses are abstracted from the reservoir, provided that sufficient usable water is available in the reservoir.

3.8.3 Irrigation water supply from a river

When the option to simulate irrigation directly from a river is invoked, daily streamflow at the point of abstraction is reduced by the amount of daily irrigation requirement which can be met by flow in the river.

3.8.4 Water supplies to areas outside of the catchment system

In *ACRU* it is possible to simulate inter-catchment transfers of water. After the request has been supplied, the water which is transferred out is effectively "lost" to the catchment and plays no further role in the water budget of the catchment.

3.8.5 Irrigation supply losses

In *ACRU,* losses such as surface runoff and deep percolation are simulated in the water budget. However, losses due to the conveyance of water, storage and application of irrigation do require input from a user.

3.8.5.1 Canal conveyance losses

Canal conveyance losses may be defined as the fraction of irrigation water lost between water released at a canal headworks and the water delivered to the farmer (Schulze, 1995). These losses are made up of unavoidable losses such as evaporation and seepage, and avoidable losses as a result of poor management. The fraction of water lost in conveying it from the source to the point of application is a model input.

3.8.5.2 Balancing dam losses

Water may be lost from the balancing dam through either evaporation or seepage. A value specifying the fraction of storage that is lost is a model input.

3.8.5.3 Field application losses

Field application losses include surface runoff, deep percolation, evaporation and wind drift. Deep percolation and surface runoff are accounted for implicitly in the water budget. The fraction of applied irrigation lost to spray evaporation and wind drift is accounted for explicitly through a model input.

3.9 Chapter Conclusion

A conceptual sugarcane model has been developed to operate as a sub-model within the *ACRU* model which provides a link between irrigation demand and crop yields at a field scale and water supply at a catchment scale.

The irrigation demand is generated from an irrigation water budget which is based primarily on algorithms described by Allen *et al.* (1998). Refinements made to these algorithms made by Lecler (2003) have been included in the water budget, as have several algorithms from the *ACRU* model. To aid in the computation of the water budget, crop growth aspects such as root growth and canopy development are simulated using algorithms derived from the *ZIMsched 2.0* and CANESIM models. Unique algorithms have also been developed for the model in order to account for the varying soil water content of the dynamic root zone. This water budget can then be run for separate parts of the field in order to account for the spatial distribution of applied irrigation water.

Although it was concluded from Chapter 2 that the four scheduling options in the *ACRU* model had the ability to account for most scheduling methods that occur in practice, a further two options were added to *ACRUCane*. These two options, *viz*. irrigation using fixed summer and winter cycles, and refilling the soil profile at a fixed depletion depth, represent modifications to existing scheduling options and were added to improve flexibility of the model.

From the review in Chapter 2 it was concluded that a number of different sugarcane yield algorithms were available. In many cases these algorithms were simple empirical equations that could provide valuable yield information and they were all included in the model.

A conceptualised model has thus been developed. A description of how these algorithms were coded into the existing *ACRU* model is provided in Chapter 4.

4. THE *ACRU2000* MODEL

A description of the conceptual structure of the *ACRU* Model has already been provided in Section 2.1, and a comprehensive description of the model is provided by Schulze (1995). The *ACRU* model is reviewed in this Chapter from a computer programming perspective. A description of the structure of the object-oriented version (*ACRU2000*) written in the Java programming language, as well as a description of *ACRUCane*'s integration into this structure, is provided in this Chapter.

4.1 Background and Reasons for Restructuring

The *ACRU* model was originally written in the Fortran programming language. Since its inception, numerous additions and enhancements have been made to the model by numerous programmers with varying degrees of programming skills, making it more complex, to the point where changes to the model had become difficult to effect due to its structure. A particular limitation highlighted by Clark *et al.* (2001) was in the modelling of flows between river and dam reaches in different catchments or subcatchments. In *ACRU*, complex catchments are often simulated by delineating them into distributed subcatchments or conceptual Hydrological Response Units (HRU), each with their own set of input parameters. In this instance each subcatchment or HRU is simulated for the entire simulation time period before water is cascaded downstream to the exit of the simulated subcatchment. While this "serial processing" is computationally efficient, it does not easily enable the simulation of transfers and feedback of water between subcatchments within a particular simulation time step, as occurs in real subcatchments (Clark *et al.*, 2001).

It was thus required to have a more modular structure where the hydrological components are more explicitly defined to enable hydrological processes to be easily added or changed without affecting the rest of the model, and where new input variables could easily be accommodated. A new modular structure would also facilitate easier model development as users could work independently without causing conflicts within the model when their contributions were incorporated into the model.

According to Clark *et al.* (2001) the two main reasons for restructuring the *ACRU* model were to make it more extensible and to better represent the individual spatial elements of the model and the order of processing of components to facilitate the modelling of water flows and feedbacks between subcatchments more realistically. An object-oriented programming approach and the JAVA programming language were chosen to create the *ACRU2000* version of the model. A brief description of object-orientation follows, to form the basis of a description of the modifications to the *ACRU2000* undertaken in this project.

4.2 Object-Oriented Programming and the Unified Modelling Language

Object-orientation is defined by Silvert (1993) as being based on the idea that a model should represent the interaction between abstract representations of real objects rather than the linear sequence of calculations associated with sequential programming. Object-orientation is a relatively new way to represent reality using compute code. The increasing popularity of object-orientated approaches can be attributed directly to the fact that it is a more intuitive way of modelling real world systems, such as the hydrological system, in an improved conceptual manner. It allows complex systems to be designed without being distracted by implementation details.

An object, as defined by Quatrani (1998), is a representation of an entity, either real-world or conceptual. An object can thus be used to represent intangible objects, such as a bank account, or a real-world object, such as a car engine. Objects can also be comprised of several other objects, for example, an engine object would be made of piston objects, a carburettor object etc. Objects have both attributes and behaviour. Attributes describe physical characteristics or structure of an object, such as the amount of money stored in a bank account. Behaviour describes how one object interacts with another object (Clark *et al.*, 2001). Objects represent individual instances of classes, and are created in a process known as "instantiation", which occurs when a program, comprised of one or more classes, is executed.

Classes are used to classify objects into groups which have similar attributes, behaviour and relationships with other objects. For example, "channel" may be used to describe a class of objects that may include river, stream and gully type channels. These different channel objects may all have the same defining attributes (such as length and flow rate) and behaviour (such as flow), but the values associated with these attributes can be different for each object (Clark *et al.*, 2001). Classes are important in object-orientation not only as a means of grouping similar objects, but also as a means of creating a hierarchy of classes to facilitate inheritance of attributes and behaviour. Clark *et al.* (2001) illustrate this using an example of an abstract "spatial unit" class with the attribute "area". This class could contain two sub-classes, a land segment and a reach, both of which will inherit the "area" attribute. Objects created from classes can then exhibit different values for that attribute. Specialisation occurs with movement down the inheritance hierarchy, while generalisation occurs with movement up the hierarchy. This renders classes at the top of the hierarchy more powerful, and means that classes at the bottom can potentially be quite simple, making their addition easier to implement for less experienced model developers. The concepts of inheritance, aggregation and association are shown in Figure 4.1 and discussed below.

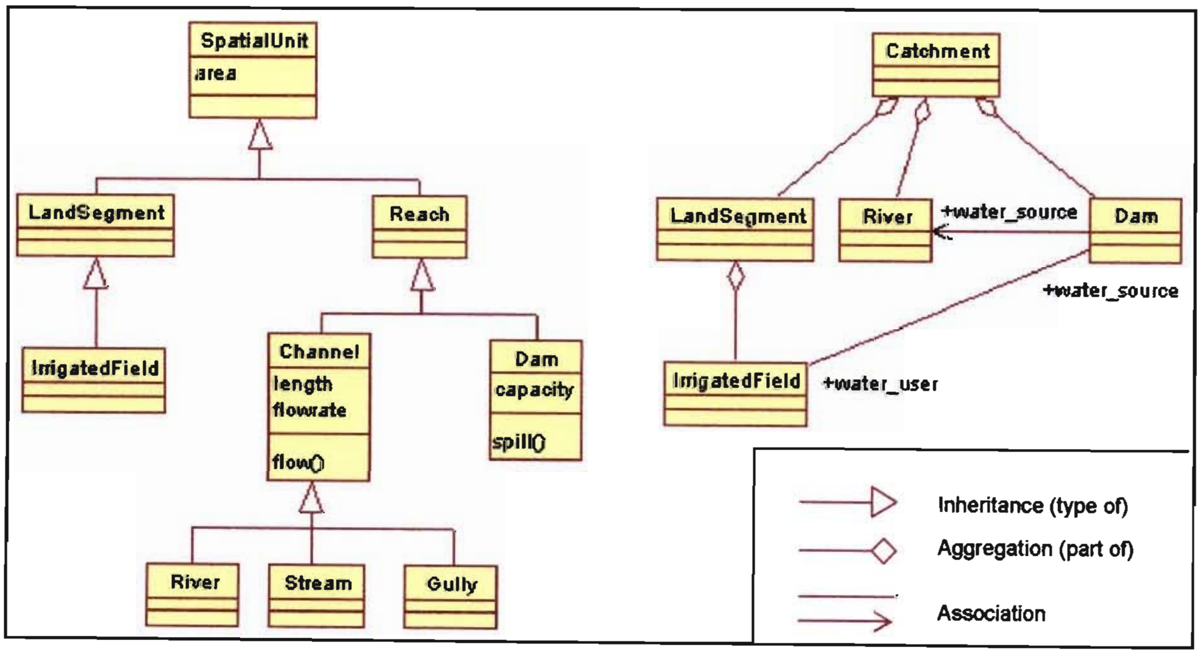

Figure 4.1 Class diagram showing inheritance, aggregation and association (Clark *et al.*, 2001)

The three main relationships which exist between classes, or instantiated objects, are inheritance, aggregation and association relationships. Inheritance represents a "type of" relationship, e.g. a river is a type of channel and thus inherits attributes and behaviour defined higher up the hierarchy. Aggregation, or "part of" relationships, allows objects to be made from other objects. For example, as illustrated in Figure 4.1, a catchment can be made of several land segment objects, a river object and a dam object. Association relationships are used to show interaction between objects, such as a dam object affecting the flow regimes of a river object (Clark *et al.*, 2001).

The notation used in Figure 4.1 is Unified Modelling Language (UML) which is a standard method used to specify, visualise and document the artefacts of an object-oriented system under development (Quatrani, 1998). UML represents classes using rectangular boxes, each containing the attributes and operations of that class. The notation used to represent inheritance, aggregation and association relationships is shown in Figure 4.1 (Clark *et al.*, 2001). UML is used extensively in this Chapter to illustrate the relationship between classes in both *ACRU2000* model and the *ACRUCane* sub-model.

4.3 Description of the Basic Structure of *ACRU2000*

ACRU2000 consists of seven different groups of classes, known as "packages", which are listed in Table 4.1.

Table 4.1 Packages used in *ACRU2000* (after Butler, 2001)

Package Name	Examples of classes in *ACRU2000*
Model	*MACRU2000Standard*
Control	*AACRU2000StandardProcesses*
Interface	*IWaterFlow*
Exception	*EFileNotFoundException*
Components	*CIrrigatedArea, CVegetation, CDam*
Processes	*PApplyIrrigation, PTranspiration*
Data	*DPrecipitation, DCropCoefficient*

Packages are thus comprised of classes grouped by their common function. A convention adopted in *ACRU2000* is that all class names start with the letter indicating their class type, or package to which they belong. For example, a component type of class would have the name prefixed by "C", for example *CIrrigatedArea*, or *CSugarcane*. In the same way, process classes would have the letter "P" as a prefix. In the case of Control classes, the letter "A" was used due to the commonality of the letter "C". This convention was adopted to facilitate easy recognition of particular class type, and to allow the programmer to have, for example, both *PRainfall* and *DRainfall* classes (Clark *et al.*, 2001). Four of the packages used in *ACRU2000* (i.e. Model, Control, Exception and Interface) operate largely out of sight of the programmer or model developer (Campbell *et al.*, 2001). Model classes are used as the basis or starting point from which all other objects are created. Control classes are responsible for coordinating input and output and for organising all the Component, Process and Data Objects in a simulation. Exception classes handle errors incurred during the running of *ACRU2000* and Interfaces can be described most simply as a means of grouping classes of similar behaviour (Clark *et al.*, 2001). The remaining three class types (i.e. Processes, Components and Data) are the most important class types with regard to hydrological modelling and are the classes most frequently dealt with by model developers.

Component classes, or objects, in *ACRU2000* represent the physical components of the hydrological system being modelled. In *ACRU2000*, a catchment or spatial unit being modelled is broken up into one or more *CLandSegment* components based on land cover and soil type (Clark *et al.*, 2001), as shown in Figure 4.2.

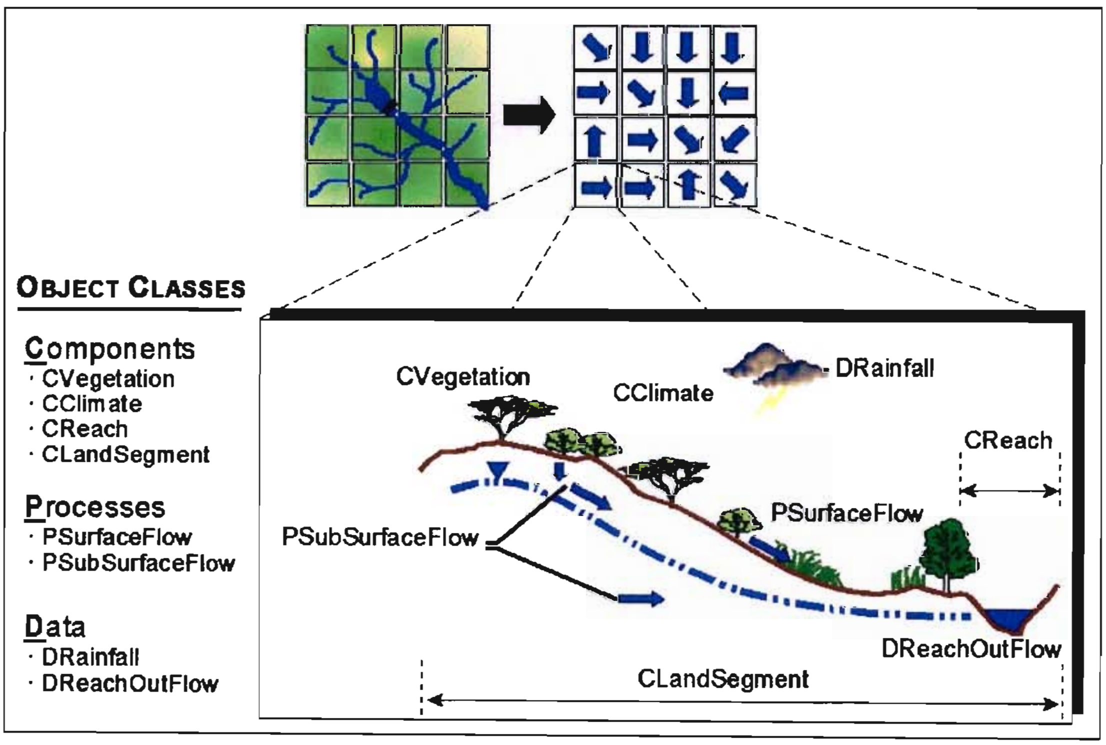

Figure 4.2 Object representation of the hydrological system in *ACRU2000* (after Kiker and Clark, 2001)

The *CLandSegment* class in Figure 4.2 also contains a number of Component classes related to it through aggregation. For example, *CVegetation* forms "part of" *CLandSegment*. As described in Section 4.2, objects have both attributes and behaviour. In the Java programming language, attributes and behaviour are expressed using variables and methods within the objects. In *ACRU2000*, this is taken a step further, in that attributes and behaviour are also expressed as objects. Each Component object contains a list of Data objects describing its attributes and a list of Process objects describing the behaviour associated with that Component (Clark *et al.*, 2001). From a UML perspective, Data objects are linked to Components using an aggregation relationship, while Processes are linked to Components through an association relationship. This concept, with respect to the *ACRU2000* model, is illustrated further in Figure 4.3 and explained in subsequent text.

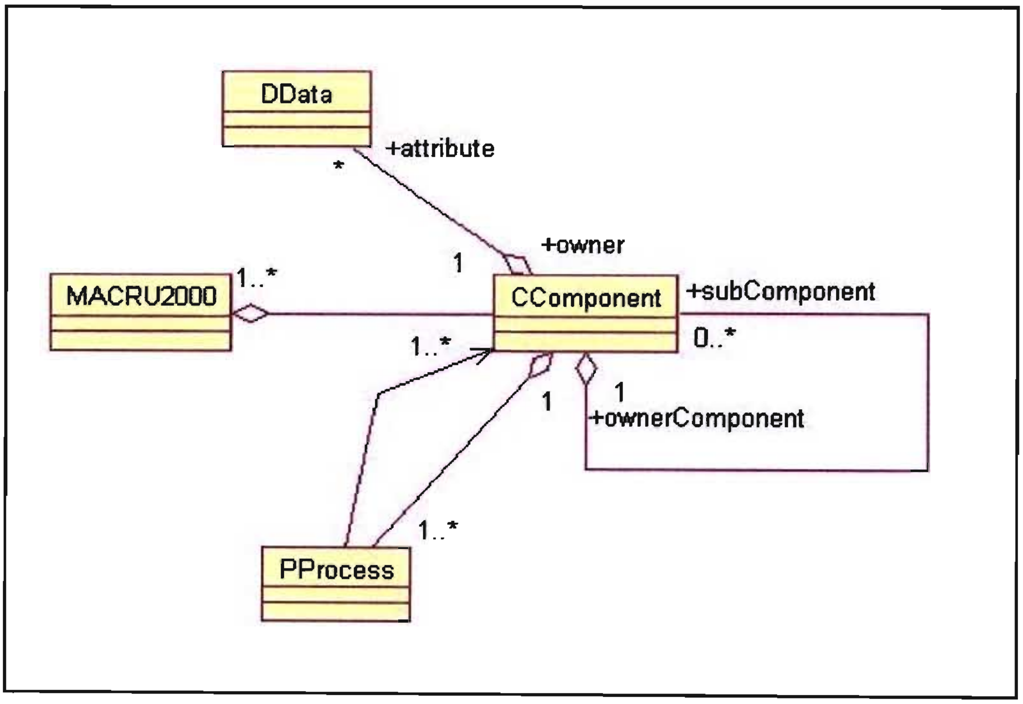

Figure 4.3 Class diagram of the relationship between Components, Data and Processes in the *ACRU2000* model

A Model object, represented by the *MACRU2000* class, contains one or more Component objects representing the hydrological system. Each Component can have one or more subcomponents which form part of the owner Component. Each Component can have a list of one or more Data objects describing its attributes, and a list of one or more Processes that act upon it.

The addition of the *ACRUCane* module into *ACRU2000* involved the creation of several Process classes to model the processes described in Chapter 3. To facilitate the storage and output of information, several Data classes were also created. The majority of Component classes required to describe the irrigated area had already been created in *ACRU2000*, e.g. *CIrrigatedArea* and *CSugarcane*.

4.4 Integrating *ACRUCane* into *ACRU2000*

A detailed description of the concepts and algorithms used in *ACRUCane* has already been provided in Chapter 3. In this section a description is provided of how the algorithms in Chapter 3, represented by *PProcess* classes, were integrated into *ACRU2000*. To avoid repetition this will be illustrated using examples. A flow diagram and comprehensive list and description of the processes created for *ACRUCane* are provided in Appendix A.

The catchment or subcatchment being modelled is comprised of one or more different spatial components or areas, represented by sub-classes of the *CSpatialUnit* class. For example, the area occupied by a catchment may be comprised of a portion of natural vegetation, an irrigated area, a river and a dam. In *ACRU2000* these would be represented by a *CLandSegment* object, a *CIrrigatedArea* object, a *CRiver* object and a *CDam* object respectively. The relationship exhibited between these and other similar classes within the *ACRU2000* model is shown in Figure 4.4.

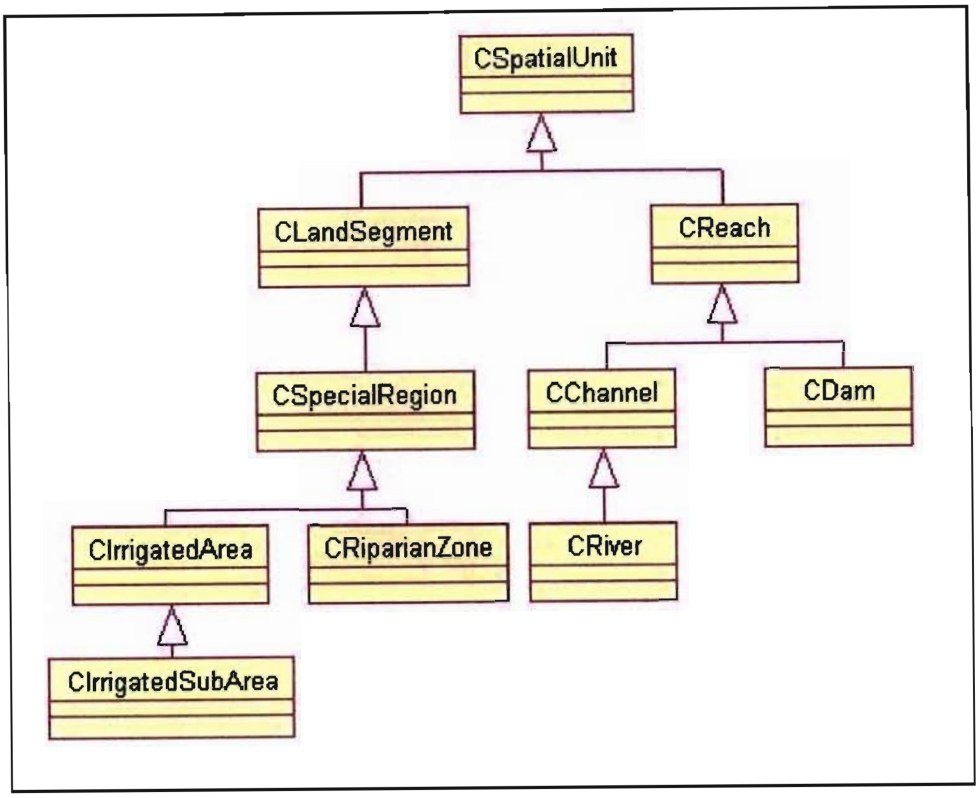

Figure 4.4 Class diagram showing relationships between different types of spatial units

All classes represented in Figure 4.4 are types of the *CSpatialUnit* class. However, owing to the relationship shown in Figure 4.3, it follows that these classes also form part of their super classes. Thus, the *CLandSegment* object would actually contain a *CIrrigatedArea* object to represent the portion of land under irrigation.

Each type of *CSpatialUnit* Component that is created has a list of *PProcess* objects associated with it which describe the agrohydrological processes occurring within that spatial unit. For example, a *CIrrigatedArea* object has, *inter alia, PApplyIrrigation* and *PIrrigTranspiration* associated with it. Since *ACRUCane* is an irrigation simulation model, model development primarily involved the creation and addition of processes to an irrigated area. However, in order to facilitate the concept of uniformity, the irrigated area being simulated was separated into "sub-areas", each of which receives a different quantity of water. The class *CIrrigatedSubArea* was created as both a "type of" and "part of" *CIrrigatedArea* in order to do so. Each *CIrrigatedSubArea* object has a separate water budget and subsequently a separate list of processes. A process written to estimate sucrose yield, *PSugarYieldEstimation*, which would thus be invoked for each sub-area when the process lists for each *CIrrigatedSubArea* object are executed. Since each sub-area is subjected to different irrigation applications and thus stress levels, a different sucrose yield would be obtained for each *CIrrigatedSubArea*. Although this value is averaged as an output in *ACRUCane*, individual values are stored in *DSucrose* objects, which represent one of many attributes of a *CSugarcane* object. A *CSugarcane* object in turn is one of many *CComponent* objects that form "part-of" a *CIrrigatedSubArea* object, a concept that was explained in Section 4.3. This is illustrated through the example shown in Figure 4.5.

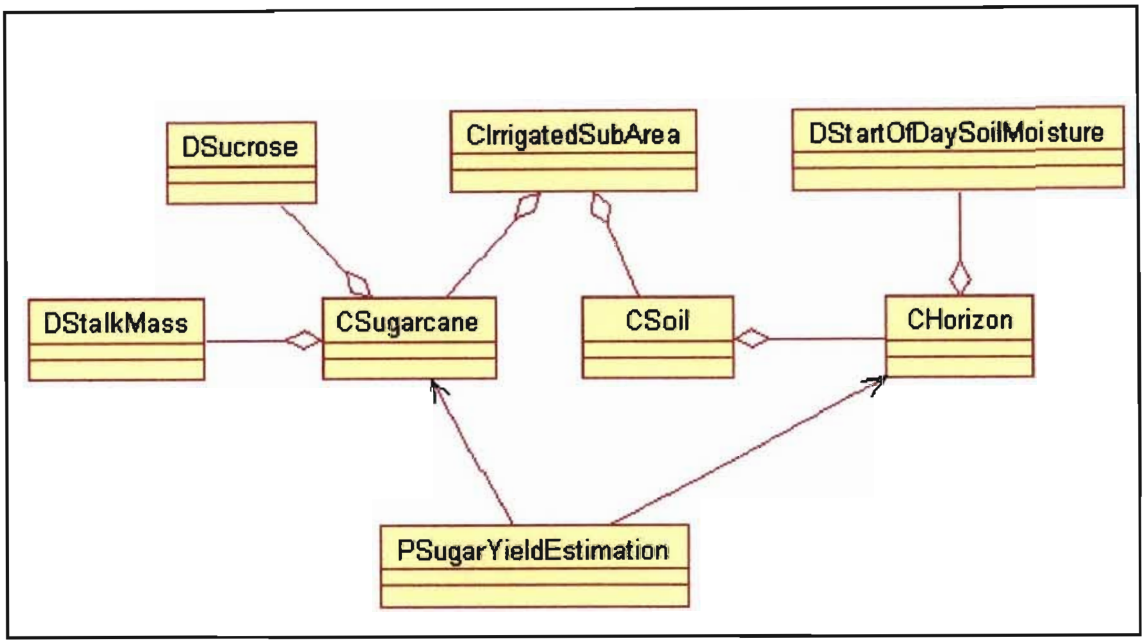

Figure 4.5 Class diagram of relationship between Process, Component and Data objects

As illustrated in Figure 4.5, *PSugarYieldEstimation*, a process belonging to the *CIrrigatedSubArea* process list, acts upon, *inter alia*, *CSugarCane* and *CHorizon*, which form part of *CIrrigatedSubArea*. Output that is generated or input that is required by *PSugarYieldEstimation* are stored in Data objects belonging to *CHorizon* and *CSugarCane*. For example, estimates of sucrose yield and stalk mass are stored in *DSucrose* and *DStalkMass* respectively. Similarly, *PSugarYieldEstimation* requires the soil water at the start of the day to determine the level of stress to which the sugarcane is subjected. This is obtained through the value stored in *DStartOfDaySoilMoisture*, belonging to *CHorizon*. Note that the Components, Processes and Data objects shown in Figure 4.5 are not an exhaustive list of those created for the *ACRUCane* sub-model, only an example to illustrate the relationship created between the three classes.

4.5 Chapter Conclusion

The restructuring of the *ACRU* model into the more extensible and modular *ACRU2000* modelling system enabled easy integration of the *ACRUCane* sub-model requiring minimal changes to existing computer code. The processes described in Chapter 3 were added to the model by creating several *PProcess* classes that run for a user specified number of *CIrrigatedSubAreas*. Data objects were created and used in conjunction with existing data objects in order to store either input values required by a process or output generated by a process. In effect, a sub-model to represent the hydrology of an irrigated field of sugarcane was coded into the *ACRU2000* model, using new and existing inputs, as well as generating many valuable outputs.

The completed *ACRUCane* model was then verified using data from three different irrigation trials, the details and results of which are shown in the following Chapter.

5. MODEL VERIFICATION

In order to asses integrated components included in *ACRUCane*, verification studies of the yield algorithms utilised by the model were conducted. Results from irrigation field experiments conducted at La Mercy on the coast of the KwaZulu-Natal province in South Africa and two separate field experiments conducted in the Lowveld of Zimbabwe were used to verify *ACRUCane*. An explanation of the methodology used to analyse the yield results and a description of the two sites and the verification results are presented in this Chapter.

5.1 Methodology of the Verification Analysis

A methodology based on that described by Willmott (1981) was used to analyse the yield results obtained. Simulated yields generated by the *ACRUCane* model were compared to observed yield data for each trial using a variety of indices which are presented, *inter alia*, in Table 5.1.

Table 5.1 Summary of statistical comparison information and indices

Output	Description
N	number of data points
O_{mean}	observed mean
S_{mean}	simulated mean
a	intercept of least of squares regression between simulated and observed values
b	slope of least of squares regression between simulated and observed values
d	index of agreement, 1.0 indicating perfect agreement, 0.0 indicating no agreement
r	correlation coefficient (Pearson's r).

5.2 La Mercy

A replicated trial was laid out at the South African Sugarcane Research Institute (SASRI) farm at La Mercy with the aim of comparing conventional irrigation scheduling methods using A-pan evaporation and canopy factors with other methods based on estimations of crop water use made using the CANEGRO model (McGlinchey and Inman-Bamber, 1996a).

5.2.1 Trial description

The site was located at 29°37'S, 31°05'E and was at an elevation of 50 m above sea level. The soil in the field was classified using the Binomial Soil classification for South Africa (MacVicar *et al.*, 1977) as a Swartland form and Gemvale series, with a maximum rooting depth of 1.65 m and an estimated TAM of 100 $mm.m^{-1}$ (McGlinchey and Inman-Bamber, 1996a). The sugarcane, of variety NCO 376, was planted on 08/09/94 and was harvested 08/11/95 after which 3 ratoons were harvested on an annual basis. Daily solar radiation, temperature, wind speed and relative humidity data were obtained from a weather station at Tongaat (SAWS number 0241214 S) located 4.86 km away. The five irrigation treatments applied to the plots at La Mercy were as follows (McGlinchey and Inman-Bamber, 1996a):

(i) Scheduled according to monthly mean class A-pan evaporation and crop factors determined for the southern areas of the sugar industry.
(ii) Using the CANEGRO model to calculate crop evapotranspiration based on climatic input data.
(iii) Using the CANEGRO model to ensure that irrigation is applied as soon as the model parameter SWDF2 drops below 1.
(iv) Using the CANEGRO model to ensure that irrigation is applied as soon as the model parameter SWDF1 drops below 1.
(v) No irrigation, i.e. rainfed.

Treatment (i), commonly referred to as a "Peg-Board" treatment, represented the wettest treatment with treatments becoming incrementally drier in the order presented. Water was applied using a drip irrigation system, and each treatment was replicated five times on plots of 8 × 10 m. The irrigation treatments were recorded and measured values of sugarcane yield ($t.ha^{-1}$) and sucrose ($t.ha^{-1}$) were obtained at the end of each growing season. A summary of the yields obtained is listed in Table 5.2.

Table 5.2 Summary of sucrose and cane yield from La Mercy irrigation trial results ($t.ha^{-1}$)

Treatment	Plant		1st Ratoon		2nd Ratoon		3rd Ratoon	
	Sucrose	Cane	Sucrose	Cane	Sucrose	Cane	Sucrose	Cane
(i)	15.2	112.6	18.0	131.9	18.7	139.7	16.6	113.4
(ii)	15.6	118.2	18.3	131.0	19.4	146.7	15.8	107.6
(iii)	15.1	115.6	18.1	129.8	18.9	141.9	15.6	106.4
(iv)	12.8	95.6	18.6	125.5	18.0	127.2	14.7	100.6
(v)	7.4	57.5	16.5	113.6	17.7	124.5	12.8	82.9

Ratoon crops make up the majority of the commercial sugarcane production cycle, as there are typically 6 – 8 ratoons after the crop is planted. The algorithms utilised in this study for yield estimation are based on ratoon and not plant crop information. Consequently, the results obtained from the ratoon crops were used in the verification of *ACRUCane*.

5.2.2 Simulation results

Separate input information files (menus) were created for each treatment and each ratoon (15 simulations in total) using the available climate, soils and irrigation data. Actual irrigation applications on specified dates were read into *ACRUCane* via a daily hydrometerological input file, and the drip irrigation system was assumed to wet 36% of the soil.

For each simulation, an estimate of sucrose yield, and two estimates of cane yield were obtained using the Thompson and CANESIM equations. To differentiate between the results from the two cane yield estimation equations, they are referred to AC-Thompson and AC-CANESIM respectively. No *ERC* yield simulations were conducted for La Mercy as this parameter was not documented during the trial.

5.2.2.1 Sucrose yield

Initial sucrose estimates obtained using the *ACRUCane* model were poor. The S_{mean} of 12.3 $t.ha^{-1}$ obtained from the 15 treatments simulated was significantly lower than the O_{mean} of 17.2

$t.ha^{-1}$. A root mean square error (RMSE in $t.ha^{-1}$) of 5.16 obtained in estimating yield compared poorly with the value of 2.6 $t.ha^{-1}$ obtained by Singels and Bezuidenhout (2002) using the CANEGRO model. A detailed statistical analysis of these results is not provided. The parameter *PARCE*, used in Equation 3.22 of Chapter 3, controls the efficiency at which Photosynthetically Active Radiation (*PAR*) is converted to gross photosynthate. The current CANEGRO model uses a value of 0.0568 $g.MJ^{-1}$ that was obtained through calibration (Singels and Bezuidenhout, 2002). Using a value of 0.082 $g.MJ^{-1}$ reported on by Inman-Bamber and Thompson (1989) for the same 15 simulations, results improved considerably. The results of these simulations is shown in Table 5.3.

Table 5.3 Statistical analysis of simulated versus observed sucrose yields using the *ACRUCane* model on La Mercy trial data

O_{mean}	S_{mean}	N	a	b	RMSE	d	r
17.2	18.9	15	6.3	0.732	2.6	0.65	0.55

The RMSE of 2.6 $t.ha^{-1}$ is the same as the value obtained by Singels and Bezuidenhout (2002). This indicates that, on average, the simulated yield was within 15% of the observed yield. The value of 0.65 obtained for the index of agreement, although not close to a perfect agreement of 1, still indicates a fair model performance. The correlation coefficient, Pearson's 'r' of 0.55 indicates a medium degree of correspondence between observed and simulated values. A scatter plot of simulated and observed sucrose yields and a "1:1" line are shown in Figure 5.1.

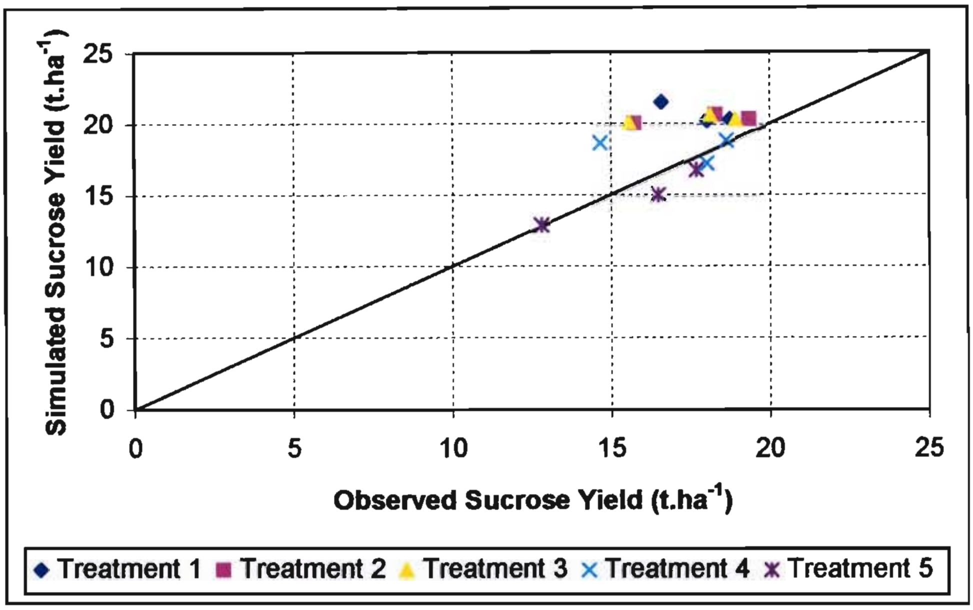

Figure 5.1 Observed and simulated sucrose yields obtained using the *ACRUCane* model on La Mercy trial data

It is evident from Figure 5.1 that the drier treatments, such as treatment 4 and 5, generally simulated sucrose yield well whereas for wetter treatments the sucrose yield was generally overestimated.

5.2.2.2 Sugarcane yield

Simulated sugarcane yields using AC-Thompson considerably underestimated the measured values. The results of the simulation are shown in Table 5.4.

Table 5.4 Statistical analysis of simulated versus observed sugarcane yield using AC-Thompson on La Mercy trial data

O_{mean}	S_{mean}	N	a	b	RMSE	d	r
121.5	103.0	15	29.1	0.61	21.7	0.66	0.74

The S_{mean} of 103.0 $t.ha^{-1}$ is much lower than the O_{mean} of 121.5 $t.ha^{-1}$. The RMSE of 21.7 $t.ha^{-1}$ indicates that, on average, yield was simulated to within 17.9 % of the observed value. The d and r statistics do indicate a fair index of agreement and correlation, respectively, between simulated and observed data, as shown in Figure 5.2.

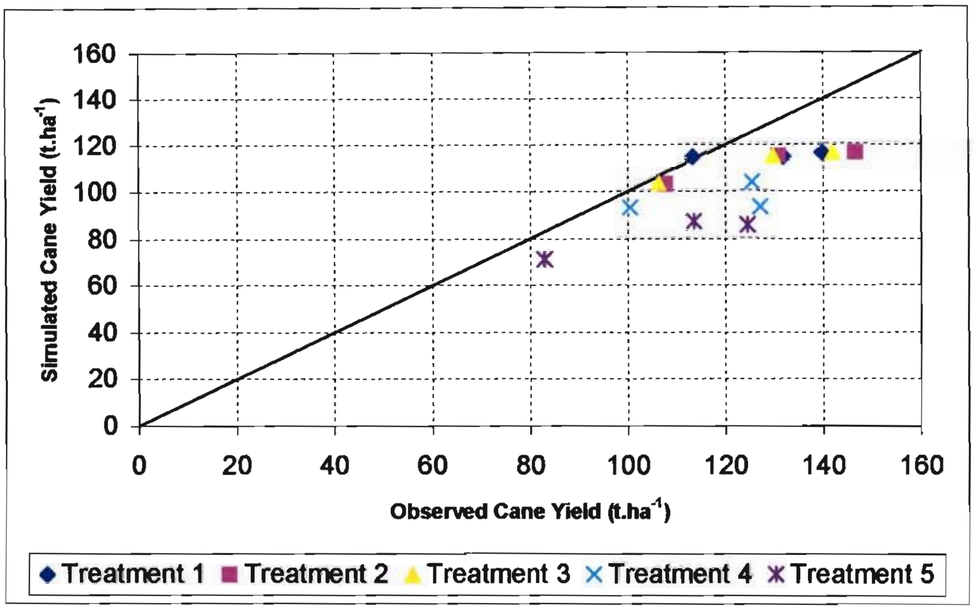

Figure 5.2 Observed and simulated sugarcane yields obtained using AC-Thompson on La Mercy trial data

It is clearly shown in Figure 5.2 that yields were underestimated. There appears to be no clear trends between wetter or drier treatments although higher yields were underestimated more than lower yields. This is confirmed by the gradient of the "best-fit" regression line of 0.608 and y-intercept of 29.1 t.ha^{-1}.

The results obtained using AC-CANESIM were much better, as shown in Table 5.5.

Table 5.5 Statistical analysis of simulated versus observed sugarcane yield using AC-CANESIM on La Mercy trial data

O_{mean}	S_{mean}	N	a	b	RMSE	d	r
121.5	116.8	15	19.3	0.80	11.2	0.88	0.81

The S_{mean} of 116.8t.ha^{-1} is considerably closer to the O_{mean} than values obtained using AC-Thompson. Both d and r are close to a value of 1.0, indicating a strong agreement between simulated and observed values. The RMSE of 11.2 t.ha^{-1} indicates that the simulated yields, although slightly underestimated on average, were generally within 9.2% of the observed values. The results are shown Figure 5.3.

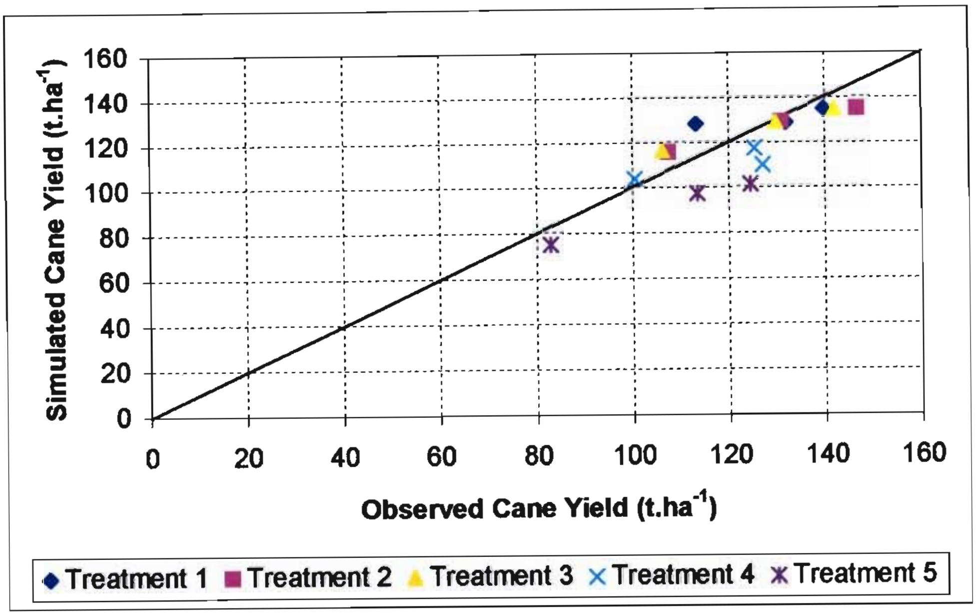

Figure 5.3 Observed and simulated cane yields obtained using AC-CANESIM on La Mercy trial data

There are no clear trends in the performance of the AC-CANSIM algorithms between wetter or drier treatments. All data points are closely aligned to the "1:1" line, confirming the high values of d and r. There does appear to be a slight trend to underestimate drier treatments as almost all data points for treatment 4 and 5 lie below the "1:1" line.

A noteworthy result from the cane yield estimation is that yields simulated by AC-CANESIM were higher than values simulated by AC-Thompson. This confirms the deduction made in Section 3.5.3, which stated that for yields between 36.9 and 178.3 t.ha^{-1}, AC-CANESIM would provide a higher simulation of yield.

5.3 Zimbabwe – Trial 4200/1

The first set of trial data from Zimbabwe used for verification came from an irrigation trial initiated at the Zimbabwean Sugar Association Experiment Station (ZSAES), which is located near Chiredzi in Zimbabwe. The trial plots were planted to sugarcane in 1966 and the experiments were terminated in 1972. The main objective of the trial was to determine the effects of various irrigation watering regimes on the yields of sugarcane and *ERC* (Lecler, 2005a). Information from the trials was obtained from the South African Sugar Industry Agronomists' Association trial archives located at Mount Edgecombe.

5.3.1 Trial description

The soils at the trial site were sandy clay loams, with a depth of approximately 1.09 m and TAM estimated at 95 $mm.m^{-1}$. The crop, of variety NCO 376, was planted on 24/11/66 and was harvested annually until 29/11/1971. Daily maximum and minimum temperature, rainfall and A-pan data were used as climatic inputs for *ACRUCane*. However, since *ACRUCane* uses reference grass evaporation to represent atmospheric demand, A-pan evaporation data were reduced by a factor of 1.2 based on the approximation made by Doorenbos and Pruitt (1977). Irrigation was applied using an overhead, hand-moved sprinkler irrigation system. A summary of the six irrigation treatments (ranging from wettest to driest) is provided below:

(i) A pan factor of 1.0 was used and 50 mm of water was applied following an accumulated A-pan evaporation of 50 mm.

(ii) A pan factor of 1.0 in summer and 0.5 in winter was used and 50 mm of water was applied following accumulated A-pan evaporation of 50 mm in summer, and 50 mm of water was applied after an accumulated A-pan evaporation of 100 mm in winter.

(iii) A pan factor of 0.84 was used and 50 mm of water was applied following accumulated A-pan evaporation of 59 mm.

(iv) A pan factor of 0.68 was used and 50 mm of water was applied following accumulated A-pan evaporation of 73 mm.

(v) A pan factor of 0.53 was used and 50 mm of water was applied following accumulated A-pan evaporation of 94 mm.

(vi) A pan factor of 0.38 was used and 50 mm of water applied following accumulated A-pan evaporation of 133 mm.

A summary of the observed yield results are shown in Table 5.6.

Table 5.6 Summary of ERC and cane yield results from trial 4200/1 at ZSAES (all yield values are in $t.ha^{-1}$)

Treatment	Plant		1st Ratoon		2nd Ratoon		3rd Ratoon	
	ERC	Cane	*ERC*	Cane	*ERC*	Cane	*ERC*	Cane
1	21.9	155.4	24.4	190.2	18.9	156.1	21.2	168.5
2	17.0	127.2	19.4	156.8	19.8	148.2	20.5	148.2
3	21.4	153.1	23.6	177.6	19.1	152.9	21.7	163.8
4	18.1	126.5	17.0	122.0	17.6	130.7	16.5	120.5
5	16.4	108.9	11.8	89.9	12.2	92.1	8.6	67.4
6	14.1	100.3	4.0	34.8	5.8	47.9	3.6	32.1

5.3.2 Simulation results

Separate input menus were created for each treatment and each ratoon, resulting in 24 simulations in total, using the available climate, soils and irrigation data. Actual irrigation applications on specified dates were read into *ACRUCane* via a daily hydrometeorological input file. The fraction of soil wetted by the sprinkler system was assumed to be 100%.

Both *ERC* and sugarcane yield were estimated using *ACRUCane* and compared against observed data. Due to the fact that no radiation data was available, sucrose yield was not estimated. It is significant that the land on which the trials were conducted had never been planted to commercial agriculture. As a result observed yields, in particular *ERC*, were exceptionally high. However, being a decision support tool, it is of primary importance that *ACRUCane* captures the relative differences and trends in yield between treatments and between seasons. For this reason, the concept of "relative yields" was used to analyse some of the results, where both simulated and observed yields are standardised and expressed as a fraction of the maximum simulated and observed yield for each treatment. Sucrose yield was not estimated, as the required radiation data were not available.

5.3.2.1 *ERC* yield

As mentioned, actual *ERC* yields were very high compared to the simulated values. The results of the ERC simulations are shown in Table 5.7.

Table 5.7 Statistical analysis of simulated and observed *ERC* yield for Trial 4200/1 at ZSAES

O_{mean}	S_{mean}	N	a	b	RMSE	d	r
16.4	13.8	24	3.16	0.62	3.70	0.87	0.93

The O_{mean} of 16.44 $t.ha^{-1}$ is significantly higher than the S_{mean} of 13.82 $t.ha^{-1}$ indicating that, on average, yields were underestimated by the model. The RMSE of 3.7 $t.ha^{-1}$ means that on average, yield was estimated within 22.5% of the observed yield. Both d and r, however, are quite close to a value of 1.0 and thus indicate a high level of agreement between simulated and observed values. A scatter plot of the results is shown in Figure 5.4.

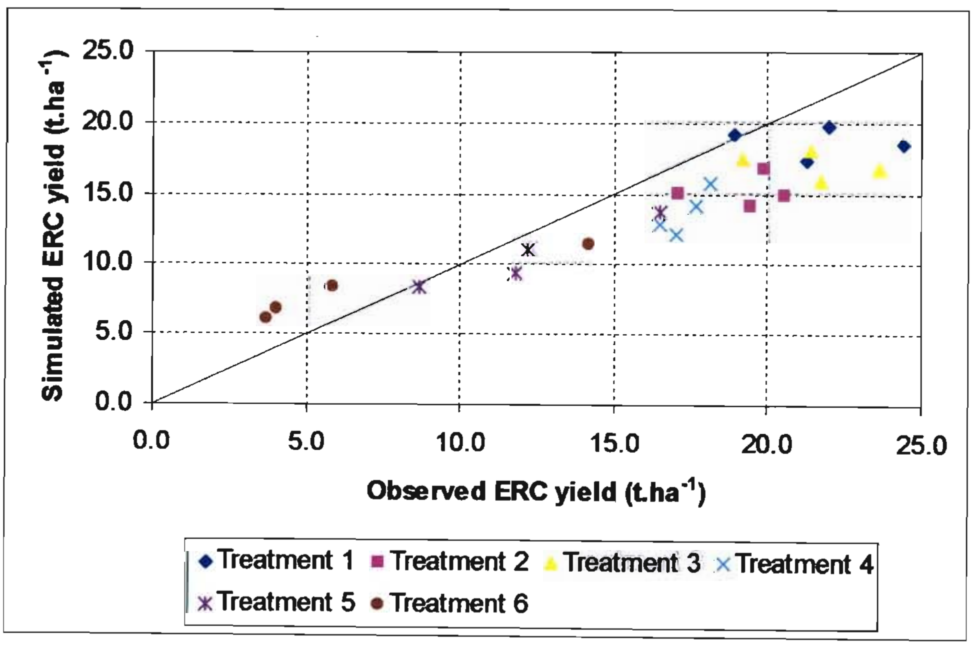

Figure 5.4 Observed versus simulated *ERC* yields for Trial 4200/1 at ZSAES

Figure 5.4 shows that, apart from three very low yields that were overestimated by the model, all yields were underestimated. It is postulated that these exceptionally high *ERC* yields can be attributed to the fact that this soil had never been planted to commercial agriculture prior to this trial and was thus of very high quality. For this reason, relative yields were used to analyse the *ERC* data. In the remainder of this chapter, when the magnitude of actual yields is simulated poorly, this will be stated and relative yield will then be used analyse the results. The purpose of doing so is to check that, even when actual yields are poorly simulated, the trends from one treatment and/or season to the next are still captured by the model.

The standardised results of the *ERC* simulations are shown in Table 5.8.

Table 5.8 Statistical analysis of standardised simulated and observed relative *ERC* yield for Trial 4200/1 at ZSAES

O_{mean}	S_{mean}	N	a	b	RMSE	d	r
0.77	0.74	24	0.19	0.73	0.097	0.96	0.96

The standardised S_{mean} and O_{mean} are very similar in value, and both d and r are very close to a value of 1.0, indicating a strong agreement between simulated and observed values. The RMSE of 0.097 obtained means that, on average, relative yield was estimated within 12% of the observed relative yield, which is comparable to the value of 6% obtained by Lecler (2003). A scatter plot of the results is shown in Figure 5.5.

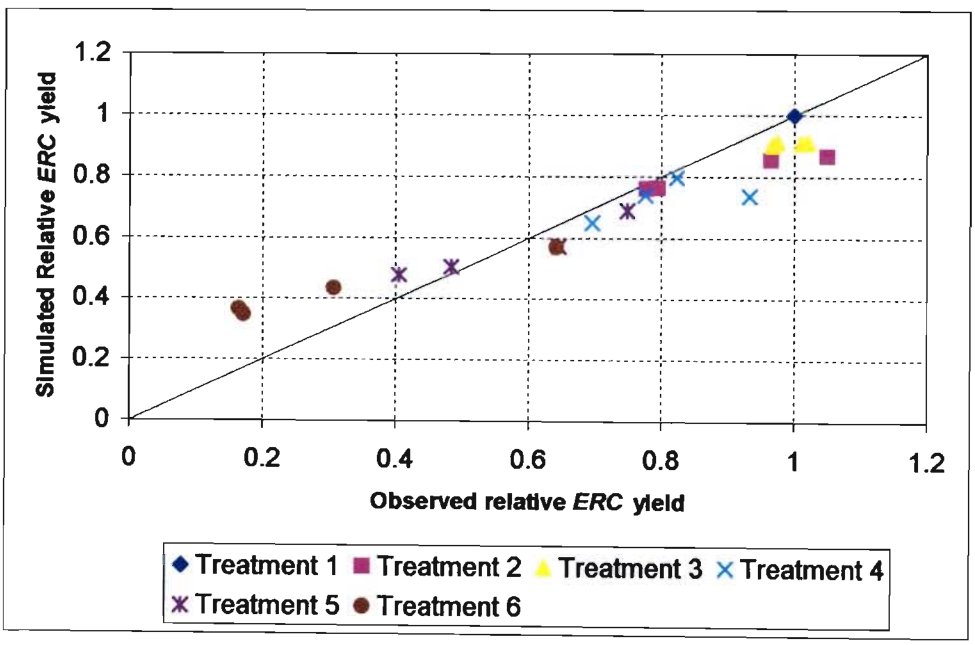

Figure 5.5 Observed versus simulated relative *ERC* yields for Trial 4200/1 at ZSAES

It is evident from Figure 5.5 that *ERC* is slightly underestimated at higher relative yields (wetter treatments) and overestimated for lower relative yields (drier treatments). It is postulated that the reason for the overestimation of lower yields is the fact the canopy model, which is used to "drive" transpiration, does not account for soil water stress. Since canopy development in *ACRUCane* depends primarily on temperature, each treatment would have the same simulated canopy and thus the same potential for transpiration. Thus, even very dry treatments would, when simulated, transpire at the same rate as wetter treatments after a wetting event. In practice, crops subjected to severe water stress would have stunted canopies and even after a wetting event would not transpire at the same rate as a crop that had been well irrigated (Lecler, 2005d). In addition to this, Doorenbos and Kassam (1979) noted that the relationship they derived was not valid for conditions where soil water stress was such that crop water use was reduced to less than half of the potential rate, potentially reducing the validity of simulated *ERC* yield subjected to a high level of stress.

5.3.2.2 Sugarcane yield

Sugarcane yield was estimated using both AC-Thompson and AC-CANESIM. In the case of cane yield, actual yields were simulated reasonably well and relative yields were not used to examine results. The results of simulated cane yield using AC-Thompson are shown in Table 5.9.

Table 5.9 Statistical analysis of simulated versus observed sugarcane yield from trial 4200/1 at ZSAES using AC-Thompson

O_{mean}	S_{mean}	N	a	b	RMSE	d	r
123.8	135.1	24	54.7	0.65	20.9	0.92	0.95

These results indicate that sugarcane yield was estimated well by the model. S_{mean} is slightly higher than O_{mean} and both d and r are very close to a value of 1.0, indicating a strong agreement between simulated and observed values. The RMSE of 20.9 $t.ha^{-1}$ means that, on average, yield was estimated within 16.8 % of the observed value. A scatter plot of observed and simulated values is shown in Figure 5.6.

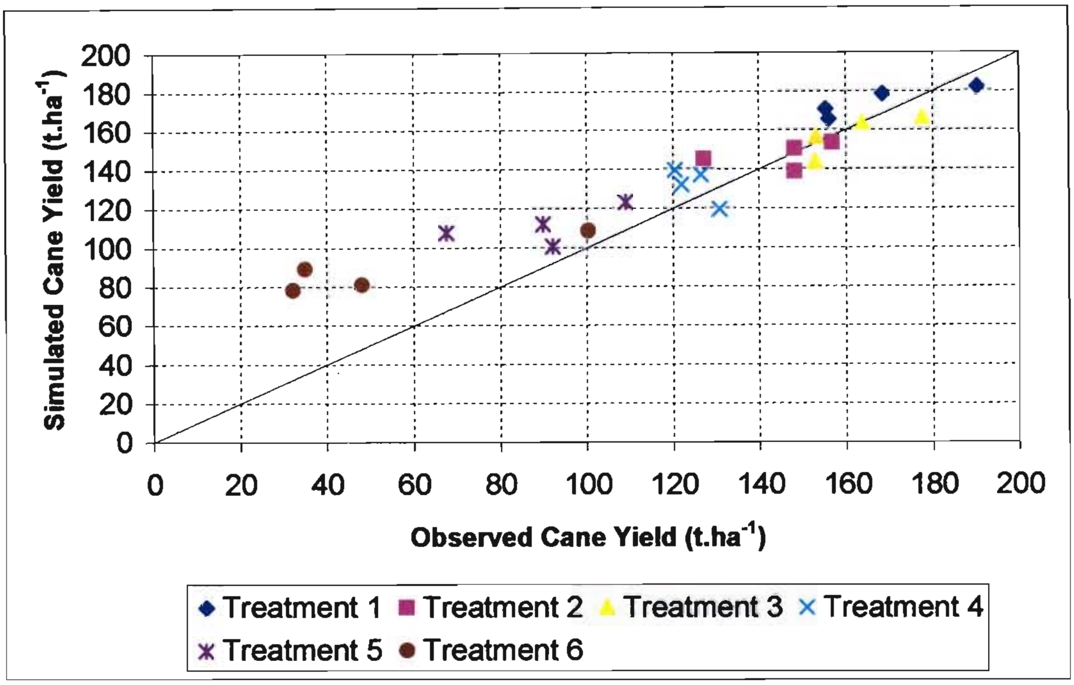

Figure 5.6 Observed versus simulated sugarcane yields from trial 4200/1 at ZSAES using AC-Thompson

In Figure 5.6 it is shown that high yields, typically resulting from wetter irrigation treatments, were simulated well by the model. As with *ERC* yield, lower yields from drier treatments were consistently overestimated by the model. This can be attributed to the fact that the simulated canopy does not account for soil water stress and hence overestimates transpiration for wetter treatments, as explained in the *ERC* yield analysis.

Importantly, the very dry treatments (Treatment 5 and 6) are not irrigation regimes that would be used in practice unless the irrigator was forced to under irrigate as a result of water shortages. Treatments 5 and 6 are the only treatments where the simulated values always exceed the observed values.

Yield estimates obtained with AC-CANESIM were very similar to those obtained with AC-Thompson. The results simulated cane yield using AC-CANESIM are shown in Table 5.9.

Table 5.10 Statistical analysis of simulated versus observed sugarcane yield from trial 4200/1 at ZSAES using AC-CANESIM

O_{mean}	S_{mean}	N	a	b	RMSE	d	r
123.8	144.9	24	73.8	0.58	28.9	0.84	0.96

The results shown in Table 5.10 indicate that sugarcane yield was estimated well using AC-CANESIM, although it performed slightly poorer than AC-Thompson. Both d and r are very close to a value of 1.0, indicating a strong agreement between simulated and observed values. The RMSE of 28.9 $t.ha^{-1}$ means that, on average, yield was estimated within 23.3 % of the observed value. In general, yields were overestimated, with the error in estimation being greater for drier treatments. A scatter plot of the data is shown in Figure 5.7.

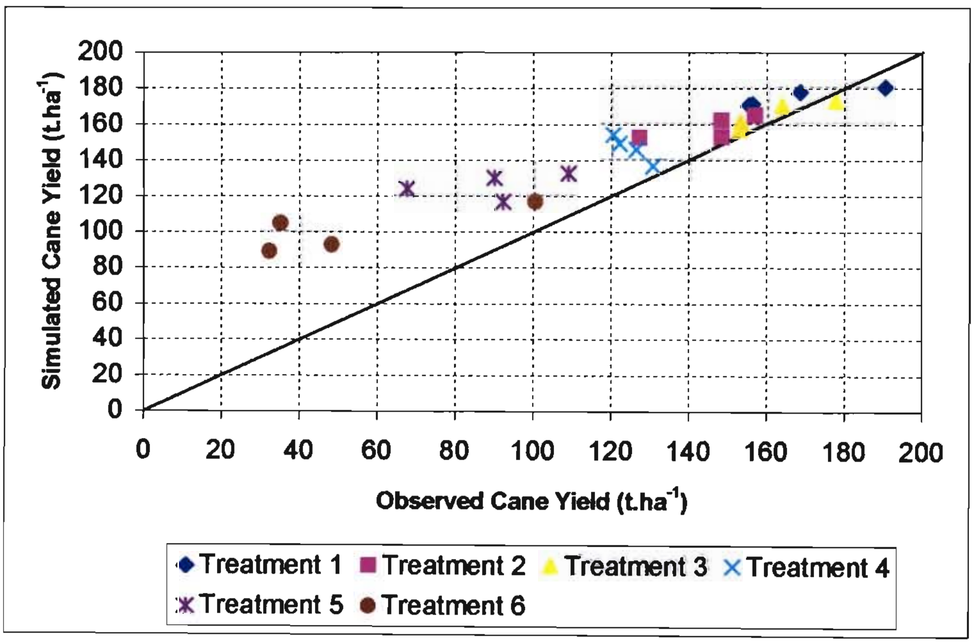

Figure 5.7 Observed versus simulated sugarcane yields from trial 4200/1 at ZSAES using AC-CANESIM

The similarities between Figure 5.6 and 5.7 are apparent and many of the same conclusions can be drawn. However, comparison of Figure 5.6 and 5.7 shows that the trend of overestimating lower yields is even more apparent in AC-CANESIM. Many of the higher yields were slightly overestimated and the S_{mean} of 144.9 $t.ha^{-1}$ is higher than the S_{mean} of 135.1 $t.ha^{-1}$ obtained using AC-Thompson. As with the La Mercy trial data, this observation confirms the deduction made in Section 3.5.3.

5.4 Zimbabwe – Trial 4200/12

The second set of trial data from Zimbabwe used for verification were from an irrigation trial conducted at ZSAES and is similar to Trial 4200/1. The trial commenced in 1985 and was terminated in 1991. As with the first trial, information from the trial was obtained from the South African Agronomy Association trial archives located at Mount Edgecombe.

5.4.1 Trial description

The soils at the trial site were sandy clay loams, with a depth of approximately 1.05 m and TAM estimated at 95 $mm.m^{-1}$ (Lecler, 2005a). Daily maximum and minimum temperature, rainfall and A-pan data for the first three ratoons were used as climatic inputs for *ACRUCane*. In the same manner as Trial 4200/1, A-pan values were divided by 1.2 to estimate reference grass evaporation. Irrigation treatments were applied using flood irrigation. A summary of the irrigation treatments are provided below (Lecler, 2005a).

(i) A pan factor of 1.0 was used and 50 mm of water was applied following an accumulated A-pan evaporation of 50 mm.

(ii) A pan factor of 1.0 was used and 100 mm of water was applied following an accumulated A-pan evaporation of 100 mm.

(iii) A pan factor of 0.85 was used and 50 mm of water was applied following an accumulated A-pan evaporation of 59 mm.

(iv) A pan factor of 0.70 was used and 50 mm of water was applied following an accumulated A-pan evaporation of 71 mm.

(v) A pan factor of 0.55 was used and 50 mm of water was applied following an accumulated A-pan evaporation of 91 mm.

(vi) A pan factor of 0.40 was used and 50 mm of water was applied following an accumulated A-pan evaporation of 125 mm.

A summary of the yield results for Trial 4200/12 are provided in Table 5.11. Both *ERC* and sugarcane yield were estimated.

Table 5.11 Summary of 4200/12 irrigation trial results (all yield values are in $t.ha^{-1}$)

Treatment	1st Ratoon		2nd Ratoon		3rd Ratoon	
	ERC	Cane	*ERC*	Cane	*ERC*	Cane
1	18.6	134.9	16.3	116.4	18.3	127.3
2	17.2	123.8	15.9	114.6	17.5	120.4
3	18.1	130.9	17.1	120.3	17.2	117.5
4	15.9	116.5	16.5	119.7	16.9	116.7
5	13.4	98.9	14.9	107.0	15.0	104.8
6	9.7	73.9	12.7	91.3	12.5	87.9

5.4.2 Simulation results

Separate input menus were created for each treatment and each ratoon, resulting in 18 simulations in total, using the available climatic, soils and irrigation data. Actual irrigation applications on specified dates were read into *ACRUCane* via a daily hydrometeorological input file. The fraction of soil wetted by flood irrigation was assumed to be 100%. Both *ERC* and sugarcane yield were estimated and compared against observed data. As with trial 4200/1, no radiation data was available and consequently no sucrose yield was estimated.

5.4.2.1 *ERC* yield

The results of the *ERC* simulations are contained in Table 5.12.

Table 5.12 Statistical analysis of simulated versus observed *ERC* yield for Trial 4200/12 at ZSAES

O_{mean}	S_{mean}	N	a	b	RMSE	d	r
15.4	15.8	18	6.2	0.62	1.60	0.92	0.93

Unlike the previous trial data (Section 5.3.2.1), *ERC* yields were well simulated for Trial 4200/12. The RMSE of 1.60 indicates that, on average, yields were simulated within 10% of the observed value. Both d and r are close to a value of 1.0, showing a very high level of agreement between simulated and observed values. A scatter plot of the results is shown in Figure 5.8.

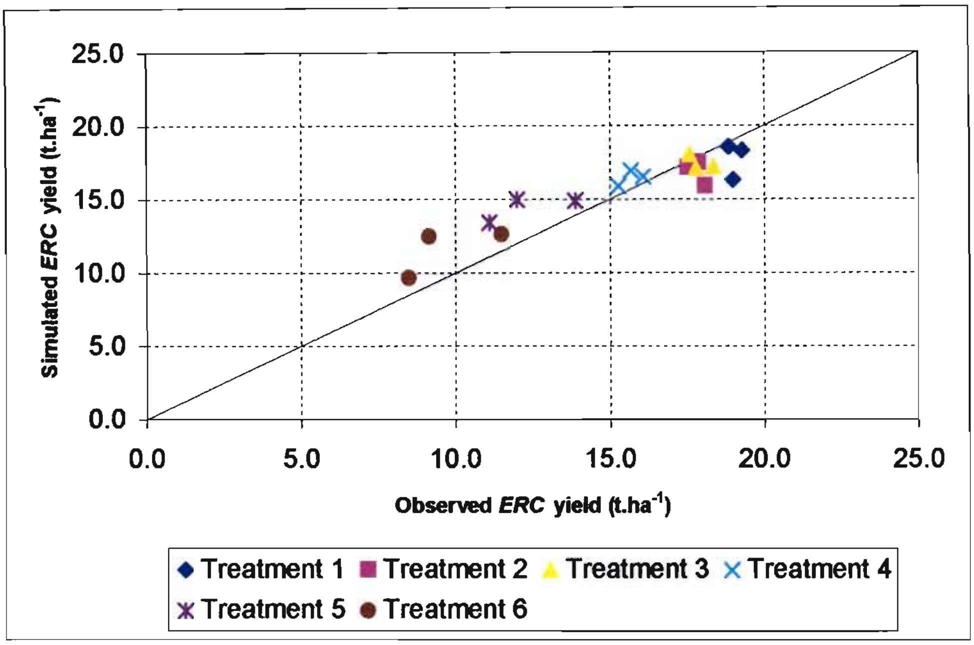

Figure 5.8 Observed versus simulated *ERC* yields from trial 4200/12 at ZSAES

Figure 5.8 shows that higher yields were slightly underestimated by the model and lower yields were slightly overestimated. The same observations made in Section 5.3.2.1 when analysing the relative *ERC* yields are appropriate for these results and appear to be a common trend in the model.

5.4.2.2 Sugarcane yield

Actual sugarcane yields were overestimated by AC-Thompson. The S_{mean} of 138.9 t.ha^{-1} was much higher than the O_{mean} of 112.4 t.ha^{-1}, and the RMSE of 28.5 t.ha^{-1} represents a large error relative to the observed mean. For this reason a detailed statistical analysis was not provided. However, a scatter plot of the results is shown in Figure 5.9.

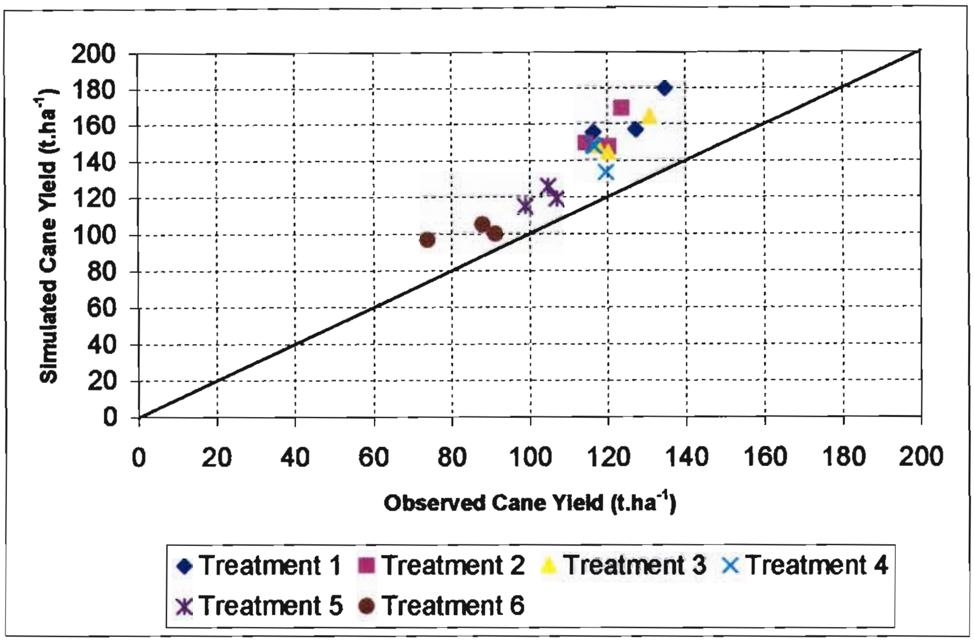

Figure 5.9 Observed versus simulated sugarcane yields from trial 4200/12 at ZSAES using AC-Thompson

As evident in Figure 5.9, all treatments for each season were overestimated. As expected, even larger over simulation errors were obtained when using AC-CANESIM, as this algorithm produces higher yield estimates between simulated yields of 36.9 to 178.3 $t.ha^{-1}$. An S_{mean} of 150.8 $t.ha^{-1}$ using AC-CANESIM was obtained. As with the results obtained using the AC-Thompson equation, a detailed statistical analysis was not provided. However, to determine if trends in yield were captured by the model, relative yields were used to analyse the results.

Table 5.13 Statistical analysis of simulated versus observed relative sugarcane yield from trial 4200/12 at ZSAES using AC-Thompson

O_{mean}	S_{mean}	N	a	b	RMSE	d	r
0.89	0.85	18	-0.029	0.99	0.074	0.92	0.90

When comparing relative yields, the results are significantly better. Both d and r are close to a value of 1.0 indicating a strong agreement between simulated and observed values. The RMSE of 0.074 means that, on average, relative yields were estimated within 8.3% of the observed relative value. A scatter plot of the relative yield values are shown in Figure 5.9.

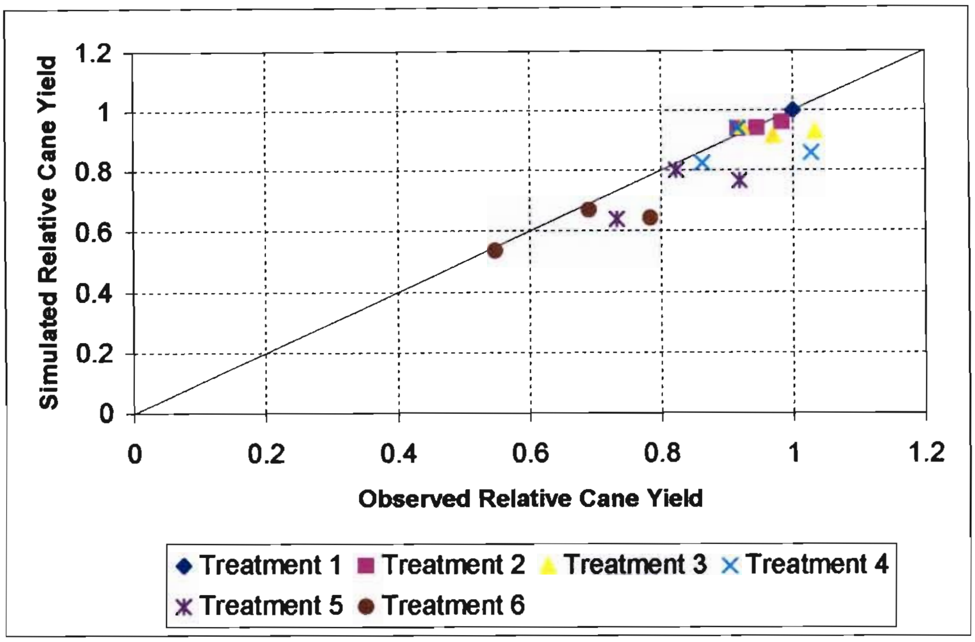

Figure 5.10 Observed versus simulated relative sugarcane yields from trial 4200/12 at ZSAES using AC-Thompson

Figure 5.10 shows that the relative yields, although well simulated, were generally underestimated. Results obtained using AC-CANESIM were also significantly improved when comparing relative yields. The results are shown in Table 5.14.

Table 5.14 Statistical analysis of simulated versus observed relative sugarcane yield from trial 4200/12 at ZSAES using AC-CANESIM

O_{mean}	S_{mean}	N	a	b	RMSE	d	r
0.89	0.88	18	0.16	0.82	0.066	0.93	0.87

As with AC-Thompson, the values of d and r are both close to 1.0 indicating a strong agreement between simulated and observed values. The RMSE of 0.066 means that on average relative yields were estimated within 7.4% of the observed relative values. A scatter plot of the data is shown in Figure 5.11.

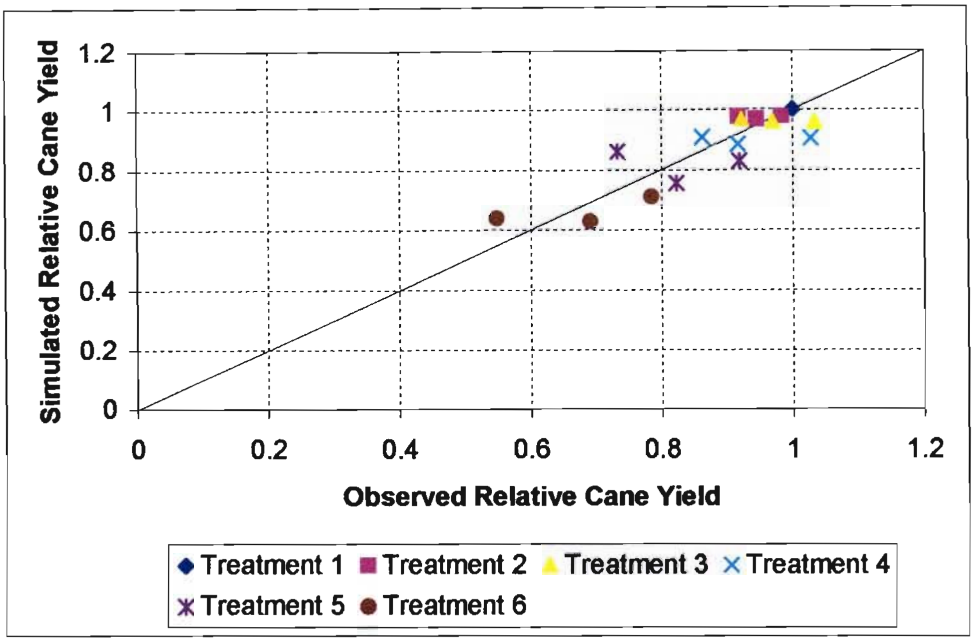

Figure 5.11 Observed versus simulated relative sugarcane yields from trial 4200/12 at ZSAES using AC-CANESIM

No clear trends between the simulated relative yields between wet and dry treatments are evident in Figure 5.11.

5.5 Results Summary and Chapter Conclusion

Table 5.15 Summary of yield estimation results for all three irrigation trials (all yields in t.ha^{-1} unless specified as being a relative yield).

Trial	Yield	O_{mean}	S_{mean}	N	a	b	RMSE	d	r
La Mercy	Actual Sucrose	17.2	18.9	15	6.3	0.73	2.6	0.65	0.55
La Mercy	Actual Sugarcane (AC-Thompson)	121.5	103.0	15	29.1	0.61	21.7	0.66	0.74
La Mercy	Actual Sugarcane (AC-CANESIM)	121.5	116.8	15	19.3	0.80	11.2	0.88	0.81
4200/1	Actual ERC	16.4	13.8	24	0.62	3.16	3.7	0.87	0.93
4200/1	Relative ERC	0.77	0.74	24	0.19	0.73	0.097	0.96	0.96
4200/1	Actual Sugarcane (AC-Thompson)	123.8	135.1	24	54.7	0.65	20.9	0.92	0.95

Trial	Yield	O_{mean}	S_{mean}	N	a	b	RMSE	d	r
4200/1	Actual Sugarcane (AC-CANESIM)	123.8	144.9	24	73.8	0.58	28.9	0.84	0.96
4200/12	Actual ERC	15.4	15.8	18	6.2	0.62	1.60	0.92	0.93
4200/12	Relative Sugarcane (AC-Thompson)	0.89	0.85	18	-0.029	0.99	0.074	0.92	0.90
4200/12	Relative Sugarcane (AC-CANESIM)	0.89	0.88	18	0.16	0.82	0.066	0.93	0.87

Prior to discussing the results obtained in this chapter, it must be noted that for all trials it was assumed that all yield data used were correct, i.e. no errors were made in observation.

Initially the simulation of sucrose by *ACRUCane* at La Mercy was poor. However, changing the *PARCE* value used in the model resulted in a significant improvement and results were obtained comparable to that reported on by Singels and Bezuidenhout (2002). The value for *PARCE* obtained by Singels and Bezuidenhout (2002) was obtained through calibration. Since adjusting this variable had a considerable impact on the yield results, it can be concluded that there is scope for further research on solar radiation conversion efficiency and potential to calibrate a unique *PARCE* value for the *ACRUCane* model (Singels, 2005). However, the need to calibrate a unique *PARCE* value may be linked to incorrect model inputs and/or poor simulation. Cane yield at La Mercy was underestimated by AC-Thompson, but was simulated well by AC-CANESIM, which was shown to typically produce higher simulated yields than AC-Thompson.

The results from Trial 4000/1 in Zimbabwe showed that *ACRUCane* estimated relative *ERC* well, obtaining results comparable to those obtained by Lecler (2005a). Actual cane yields were estimated well by both the AC-Thompson and AC-CANESIM algorithms. The results from Trial 4000/12 in Zimbabwe showed that the model estimated actual *ERC* yields well whereas actual cane yields were simulated poorly. When comparing relative yields, however, results were improved significantly.

A common trend noted with both *ERC* and cane yield estimation is that lower yields, associated with drier treatments, were often overestimated. A possible explanation for the overestimation of lower yields, as postulated by Lecler (2005d) and described in Section

5.3.2.1, is the fact the canopy model, which is used to "drive" transpiration, does not account for soil water stress. Since canopy development in *ACRUCane* depends primarily on temperature, each treatment would have the same simulated canopy and thus the same potential for transpiration. Thus, even in very dry conditions simulated transpiration would be at the same rate as under wetter conditions after a wetting event. In practice, crops subjected to severe water stress would have stunted canopies and even after a wetting event would not transpire at the same rate as a crop that had been well irrigated. Furthermore, Doorenbos and Kassam (1979) noted that the relationship they derived was not valid for conditions where soil water stress was such that crop water use was reduced to less than half of the potential rate. Excluding simulated *ERC* yields that were subjected to such high levels of stress would have resulted in improved statistical results as these yields were frequently simulated quite poorly. Taking the aforementioned two aspects into consideration, it can be concluded that the current version of *ACRUCane* is limited in its ability to account for the impact of severe stress levels on both *ERC* and sugarcane yield.

Relative yields were frequently used in the verification study due to the fact that the magnitudes of the actual yields were occasionally simulated poorly. Although *ACRUCane* models the irrigation water budget in detail, there are many aspects that contribute to crop yield that are not simulated by the model. Aspects such as soil quality (e.g. Nitrogen content) and the existence of nematodes represent some of the many non-modelled variables impacting on crop yield that are not modelled by *ACRUCane*. However, capturing the relative differences in yield due to different irrigation treatments and seasonal climatic changes was considered the most important aspect of the verification study, as it is this feature of the model that enables it to provide decision support information. In all instances in this verification study, yields were simulated accurately in either actual or relative terms. It can thus be concluded that *ACRUCane* can adequately predict the relative yield differences due to different wetting strategies and can thus be used to evaluate impact of different management, irrigation systems and scheduling strategies.

Having made this conclusion, an illustration of how *ACRUCane* can be used to provide decision support information regarding different management, irrigation systems and scheduling strategies is provided in Chapter 6.

6. CASE STUDY

This Chapter is used to illustrate how *ACRUCane* can be used to provide decision support information to irrigators and water resource managers, by being able to account for different types of irrigation systems performing at different levels, with different scheduling strategies and different supply constraints. In order to illustrate this, a scenario consisting of a dragline irrigation system with supply constraints in northen KwaZulu-Natal (Pongola) was simulated using observed climatic data for a hypothetical catchment. The irrigator, wanting improve his profit, could benefit considerably from economic comparisons of his current system to new "what if" scenarios. The new scenarios, representing potentially beneficial changes he could implement, were created by varying:

- application uniformity, represented by an improvement in DU;
- scheduling, represented by using an improved demand-based schedule, and
- system type, represented by a subsurface drip irrigation system.

6.1 Description of Hypothetical Catchment and Irrigated Area

The primary objective of this case study is to illustrate *ACRUCane*'s usefulness as a decision support tool and not to model and verify the simulated hydrology of an existing catchment. Numerous verification studies of the *ACRU* modelling system are documented by Schulze (2004). Hence it was decided to create a hypothetical catchment based on realistic input parameters, rather than configuring a real catchment and irrigation systems for the *ACRU* modelling system. Several simplifying assumptions were made and are presented below.

The land cover of a hypothetical 200 km^2 catchment was assumed to be veld in good condition. Daily values of maximum and minimum temperature and relative humidity, rainfall, and solar radiation data from Pongola (27°24'S, 31°18'E) were used to represent the climate of the catchment. The soil type, assumed to be uniform throughout the catchment, was a sandy clay loam with a depth of 0.75 m. Stormflow and baseflow generated by this catchment flow into a dam constructed at the outlet of the catchment. The dam was assumed to have a capacity of 14 000 000 m^3 and dead storage of 10% of the full supply capacity. This dam was assumed to supply water to an 800 ha irrigation scheme located outside of the catchment. No other abstractions from the dam were assumed. Thus, although the dam was at the outlet of the catchment, the position of the irrigated area was such that stormflow and baseflow generated by irrigated area did not return to the dam. The soil in the irrigated area was also assumed to be a sandy clay loam with a depth of 1.2 m. The entire 800 ha of irrigation were planted to sugarcane with a row spacing of 1.5m. It was assumed that once the cane had been planted it was harvested for a further 6 ratoons before being replanted. The irrigator was assumed to irrigate his cane with a dragline sprinkler system, using fixed summer and winter cycles to irrigate, *viz.* 48 mm each week in summer, and 48 mm every two weeks in winter, which is a typical irrigation schedule in Ponogla (Lecler, 2005c). It was assumed that spray evaporation and wind drift losses were approximately 10% of the irrigation depth applied. It was assumed that an infield evaluation of the dragline system revealed the system to have a DU of 50 %. Under the specified conditions, the supply of water to the irrigated fields was frequently inadequate to meet the irrigation requirement as the level of water in the dam was often below the dead storage level. A time series of 30 years of dam storages simulated for the current scenario outlined above is shown in Figure 6.1.

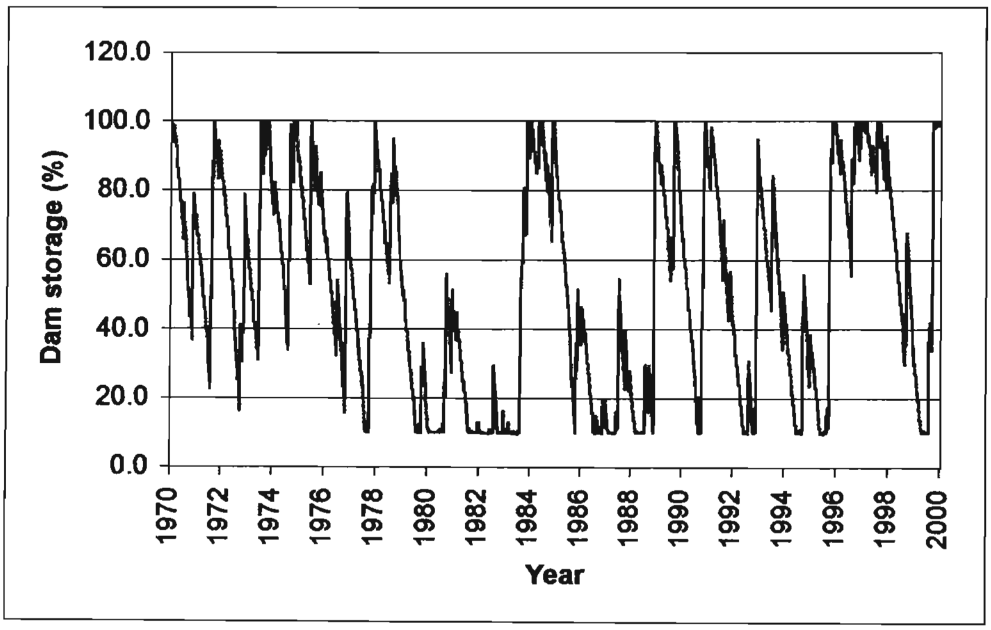

Figure 6.1 Time series of dam storage using current irrigation scheduling

6.2 Methodology

Input information (menus) for the *ACRUCane* model were generated to represent the above-mentioned hypothetical catchment and irrigation scenario, which will subsequently be referred to as the Current Scenario. By making adjustments to the Current Scenario, such as system uniformity, system type or scheduling, new input menus were created to represent potentially beneficial changes that the irrigator could implement in his operation. A description of each scenario follows in the subsequent text.

6.2.1 Scenario 1: Uniformity

The Current Scenario operated at a low DU of 50%, caused primarily by low operating pressures, poor dragline spacing and nozzle wear. By making the necessary changes, for example by replacing worn nozzles, it would be possible to have the system operating at the recommended value of 75%, as specified by Pitts *et al.*(1996). Scenario 1 was thus used to represent a system that was essentially identical to the Current Scenario, except for the improved DU.

6.2.2 Scenario 2: Scheduling

Alternatively, if the irrigator did not wish to finance the changes required to obtain the recommended DU, he could improve his irrigation scheduling through the use of a water budgeting model such as CANESIM (Singels *et al.*, 1998) or *ZIMsched 2.0* (Lecler, 2003). This was represented by scheduling the irrigation such that 40 mm was applied once the soil water had reached a depletion of 45mm below the FC, leaving 5 mm storage to be filled by potential precipitation.

6.2.3 Scenario 3: Scheduling and uniformity

In Scenario 3, the improvements in both DU and scheduling of the previous two scenarios were combined to represent an "ideal" dragline system, *viz.*: DU = 75% and 40 mm applied once a depletion of 45mm below FC was reached.

6.2.4 Scenario 4: Subsurface drip irrigation

A further option available to the irrigator was to change his system type to a more efficient irrigation system such as a subsurface drip irrigation system. Application of water directly to the root zone has the potential to optimise irrigation water applied, as very little water is lost to evaporation from the soil surface. For this Scenario, an "ideal" subsurface drip irrigation system was represented by using a DU of 85%, as recommended by Pitts *et al.* (1996), and by scheduling irrigation such that 6 mm of water was applied once a depletion of 15 mm below FC was been reached. Importantly, spray evaporation and wind drift losses were assumed to be zero for this form of irrigation. Furthermore, the fraction of soil wetted by irrigation was assumed to be 3% for the subsurface drip system, whereas it was assumed to be 100% for all dragline scenarios.

These four scenarios and the Current Scenario are summarised in Table 6.1.

Table 6.1: Summary of scenarios used in case study.

Scenario	Uniformity (%)	Scheduling	System
Current	50	48mm per week cycle (summer) 48mm per 2 week cycle (winter)	Dragline
1	75	48mm per week cycle (summer) 48mm per 2 week cycle (winter)	Dragline
2	50	Apply 40 mm once a depletion of 45 mm below FC has been reached. 5 mm reserved for rainfall.	Dragline
3	75	Apply 40 mm once a depletion of 45mm below FC has been reached. 5mm reserved for rainfall.	Dragline
4	85	Apply 6 mm once a depletion of 15 mm below FC has been reached. 5 mm reserved for rainfall.	Subsurface Drip

6.2.5 Techniques for scenario comparison

By comparing Scenarios 1-4 to the Current Scenario, the feasibility of making the suggested change could be assessed. Scenarios were compared in four ways, *viz*. impact on dam storage, on *ERC* yield, on seasonal irrigation efficiency (*SIE*) and net return per hectare (*NRH* in $t.ha^{-1}$) using 30 years of historical data from Pongola.

SIE is defined in Equation 6.1 as the ratio of accumulated transpiration (mm) to the total irrigation and rainfall (mm) (Ascough and Lecler, 2005).

$$SIE = \frac{\Sigma T}{\Sigma I + \Sigma R} \qquad (6.1)$$

where

ΣT	=	transpiration accumulated over the course of the season (mm),
ΣI	=	irrigation accumulated over the course of the season (mm),
ΣR	=	rainfall accumulated over the course of the season (mm).

SIE represents the fraction of water reaching the crop that was used "beneficially" by the crop. It is often a valuable way to represent what proportion of different irrigation applications is used beneficially.

NRH is defined in Equation 6.2 (Lecler *et al.*, 2005):

$$NRH = R - BPC - IWC - EC - HC - LC - CapC - MC \qquad (6.2)$$

where

R	=	Revenue ($R.ha^{-1}$),
BPC	=	Base Production Cost ($R.ha^{-1}$),
IWC	=	Irrigation Water Cost ($R.ha^{-1}$),
EC	=	Electricity Cost ($R.ha^{-1}$),
HC	=	Haulage Cost ($R.ha^{-1}$),

LC	=	Labour Cost ($R.ha^{-1}$),
$CapC$	=	Capital Cost ($R.ha^{-1}$) and
MC	=	Maintenance Cost ($R.ha^{-1}$).

R was computed as the product of *ERC* yield in $t.ha^{-1}$ and yield price, assumed to be $R1350.t^{-1}$ in this study. *BPC*, which includes fertilizer and seed cane, was assumed to be equal for all scenarios and a value of $R4000.ha^{-1}$ was used, based on values presented by Lecler *et al.* (2005). *IWC* was assumed to be comprised of a constant water price of $R0.123.m^{-3}$ and a constant Catchment Management Agency (CMA) levy of $R0.01.m^{-3}$. *EC* represents the cost of pumping, and a constant cost of $R0.3kWh^{-1}$ was assumed. The power used was calculated from the total volume of water pumped, the required operating head and the pump efficiency, assumed to be 70% in all cases. The required operating head was determined assuming a static head of 5 m, 500 m of pipe per hectare, and a friction loss of 1.5 m per 100 m, i.e. 1.5 % (Ascough and Lecler, 2004). *HC* represents the cost of harvesting and transporting cane. This parameter was determined from the product of sugarcane yield and the fixed haulage cost of $R45.t^{-1}$ derived from Lecler *et al.* (2005). *LC* was determined using system specific values of $ha.person^{-1}$ obtained from Koegelenberg and Breedt (2003), and a fixed labour salary of $R8803.year^{-1}$ (Gillit, 2005). *CapC* was computed using Equation 6.3 (Koegelenberg and Breedt).

$$CapC = K_k \frac{int(1+int)^n}{(1-int)^n - 1} \qquad (6.3)$$

where

int	=	current interest rate, assumed to be equal to 10.5 %,
K_k	=	total capital costs ($R.ha^{-1}$), with system specific value extracted from Koegelenberg and Breedt (2003), and
n	=	term of repayment (year), taken as the life of the system, obtained from Koegelenberg and Breedt (2003).

MC was estimated by the product of total capital costs and a system specific maintenance percentage which was obtained from Koegelenberg and Breedt (2003). Economic differences associated with different systems and scenarios are accounted for in Equation 6.2, thus making *NRH* a means of assessing the viability of different irrigation options.

System specific input requirements such as system life and labour requirements are shown in Table 6.2.

Table 6.2 Cost input variables for dragline and drip irrigation systems

Variable	Input value	
	Dragline system	**Subsurface drip system**
Labour requirement ($ha.person^{-1}$)	25	30
Total capital cost ($R.ha^{-1}$)	12000	22000
System life (years)	10	10
Maintenance cost (%)	4	3

6.3 Results

Graphical comparisons of the Current Scenario with Scenarios 1 - 4 are shown and discussed in sections 6.3.1 – 6.3.4 respectively.

6.3.1 Scenario 1: Uniformity

Percentiles of exceedence for annual periods were determined for *ERC* yield, *SIE* and *NRH* and are shown in Figures 6.2, 6.3 and 6.4 respectively. Note that dam storage of the two systems is not compared as in *ACRUCane*, changes in uniformity have no impact on water supply.

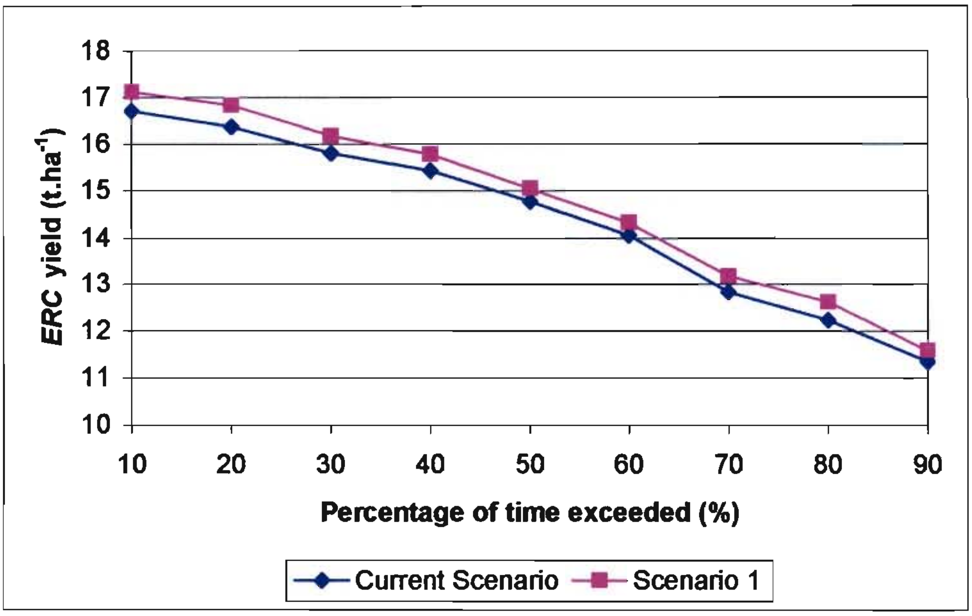

Figure 6.2 Exceedence percentiles of *ERC* yield for the Current Scenario and Scenario 1

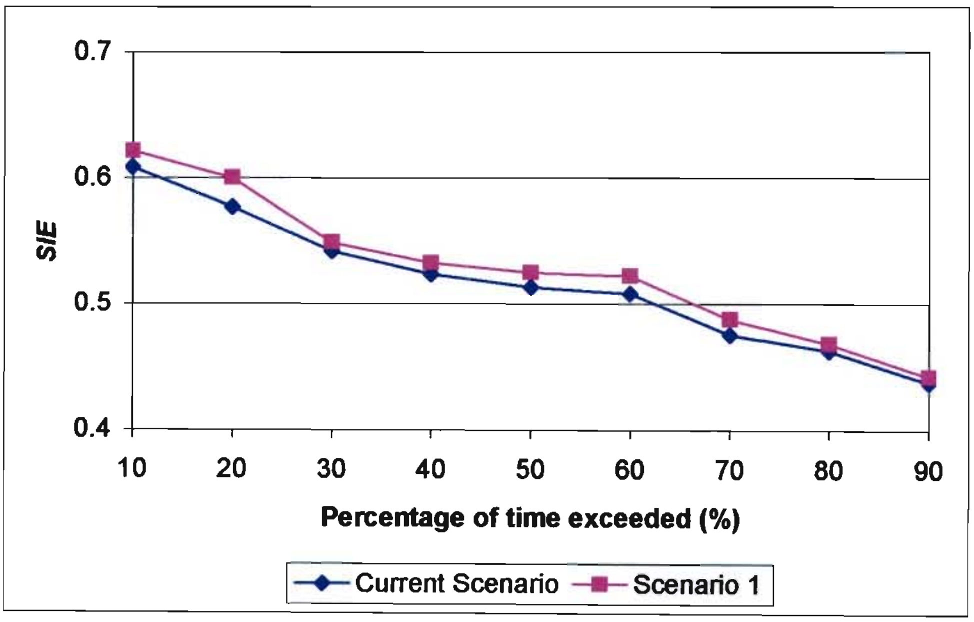

Figure 6.3 Exceedence percentiles of *SIE* for the Current Scenario and Scenario 1

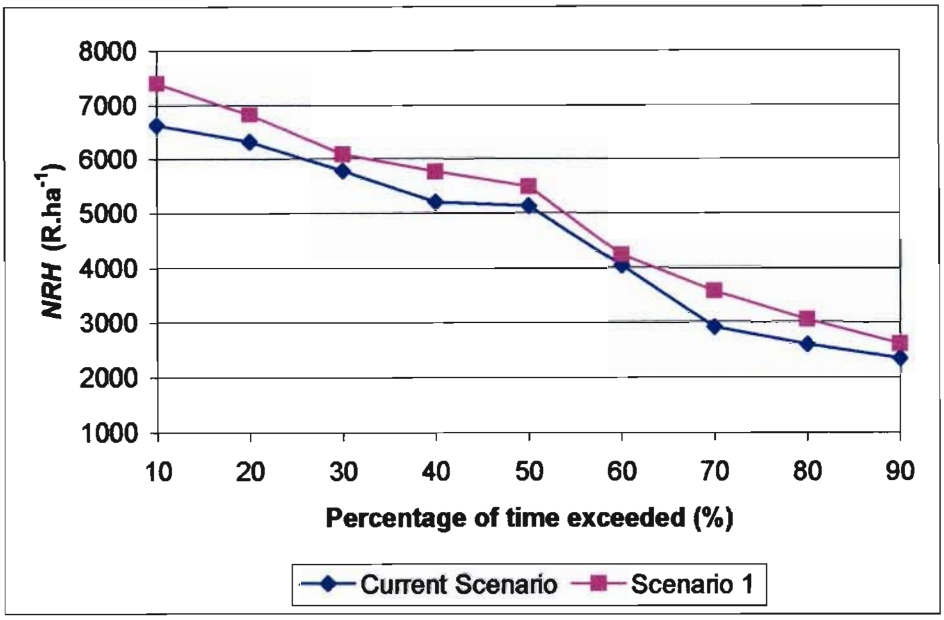

Figure 6.4 Exceedence percentiles of *NRH* for the Current Scenario and Scenario 1

Examination of Figures 6.2 to 6.4 shows that increasing DU to the recommended value of 75% resulted in a relatively small increase in yield (3.1 % increase on average) and *SIE* (2.2 % increase on average) and a more significant increase in *NRH* (10.5 % increase on average). More uniform irrigation applications resulted in higher transpiration per mm of water applied, which is reflected in the increase in *SIE*. As the *ERC* yield algorithm is a transpiration-based algorithm, this increase in transpiration is also reflected in the increase in yield. Apart from a minor increase in harvest and haulage costs due to increased yield, all other costs were identical when comparing the two systems. Consequently, the revenue generated from the increased *ERC* yield resulted in an irrigation practice that generated on average R502 more profit per annum per hectare, which translates to R401 600 for the 800 ha system. This provides valuable information to the irrigator, as he is now able to compare the cost of making the required maintenance to achieve a DU of 75% with the expected profitability associated with these changes.

6.3.2 Scenario 2: Scheduling

In this instance two different scheduling scenarios were being compared, making it necessary to compare the impact of improved scheduling on dam storage and water usage in addition to a comparison of *ERC*, *SIE* and *NRH*. For illustrative purposes, a time series graph of the 30 years of simulated dam storages is shown in Figure 6.5.

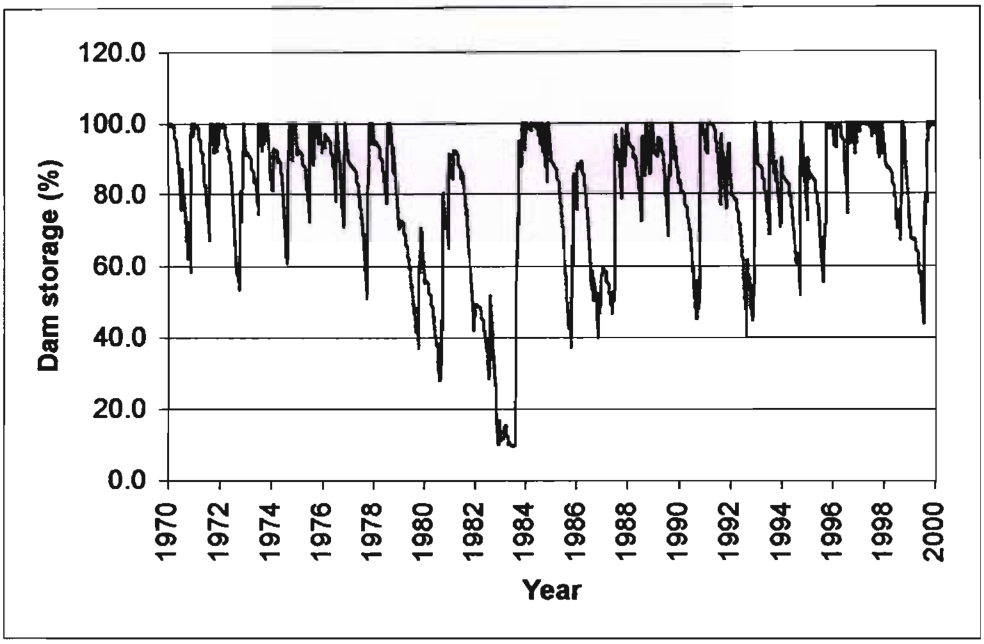

Figure 6.5 Time series graph of dam storage using Scenario 2

Using the improved scheduling practice of Scenario 2, significantly less water was used each season and as a result the dam only reached the dead storage level once in the 30-year period of simulation. This represents a significant improvement on the dam storage shown in Figure 6.1 for the Current Scenario. The seasonal irrigation water applications for the two scenarios are compared in Figure 6.6.

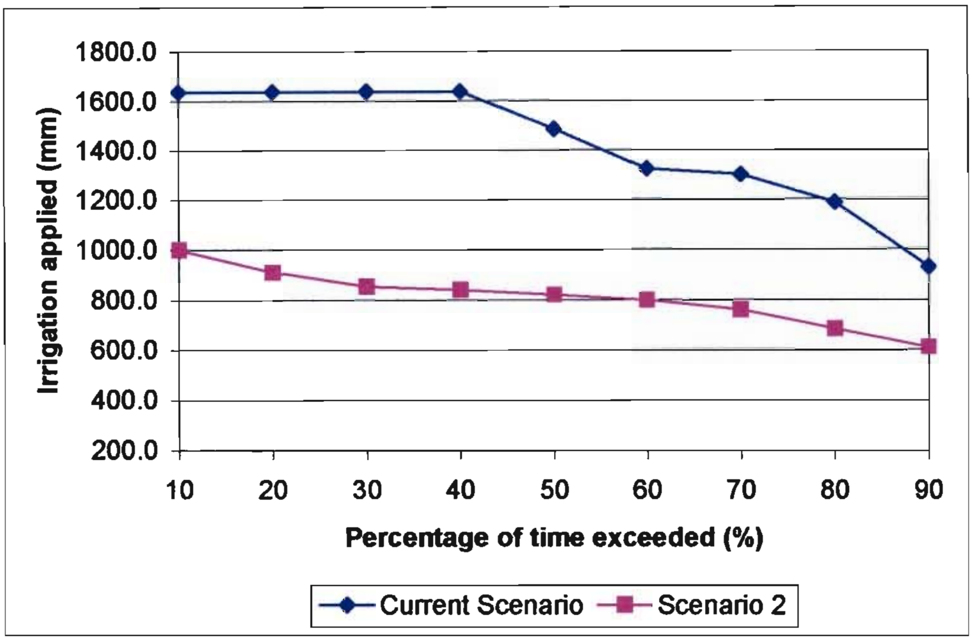

Figure 6.6 Exceedence percentiles of irrigation water use for the current system and the well-scheduled system

Figure 6.6 illustrates the considerable difference in water applied per season when comparing the Scenario 2 and the Current Scenario. With the Current Scenario, 1638 mm is applied per season if water supply is not restricted, which occurred 40% of the time. On average, however, 1428 mm was applied per season. In comparison, the Scenario 2 used only 816 mm on average per season, which equates to a water saving of R 815.ha^{-1} or R652 000 for the 800 ha irrigated area. A major implication of the improved water usage shown in Figure 6.5 and 6.6 is that the irrigator can potentially irrigate a much larger area without suffering severe water shortages.

Comparisons of *ERC* yield, *SIE* and *NRH* are shown in Figures 6.6, 6.7 and 6.8 respectively.

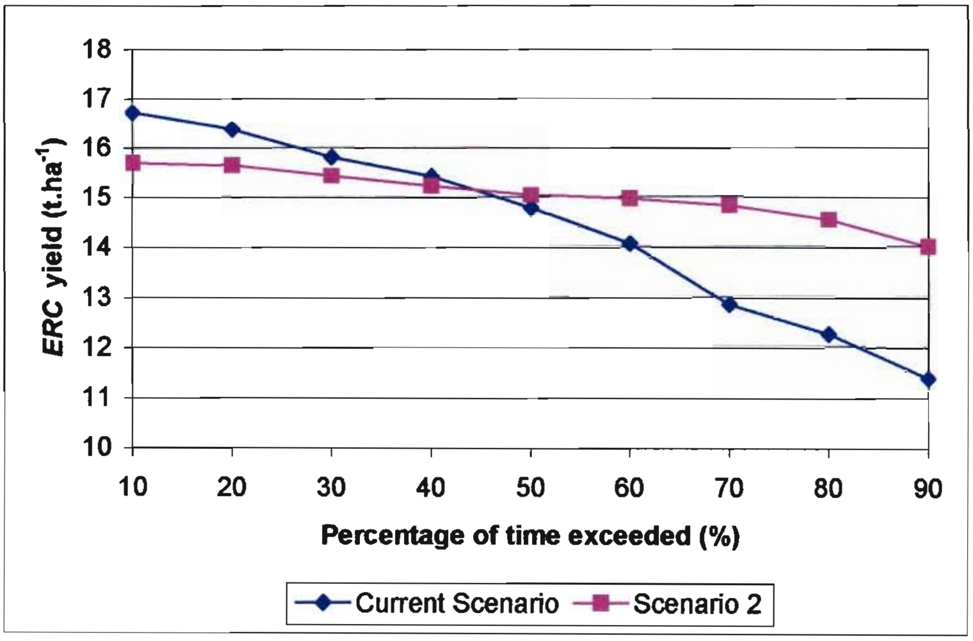

Figure 6.7 Exceedence percentiles of *ERC* yield for the current system and the well-scheduled system

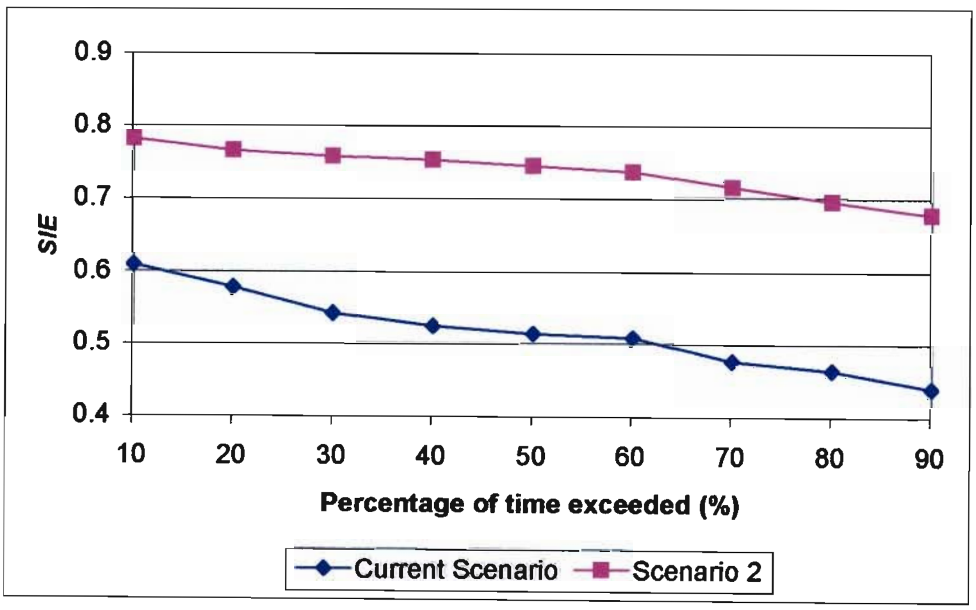

Figure 6.8 Exceedence percentiles of *SIE* for the current system and the well-scheduled system

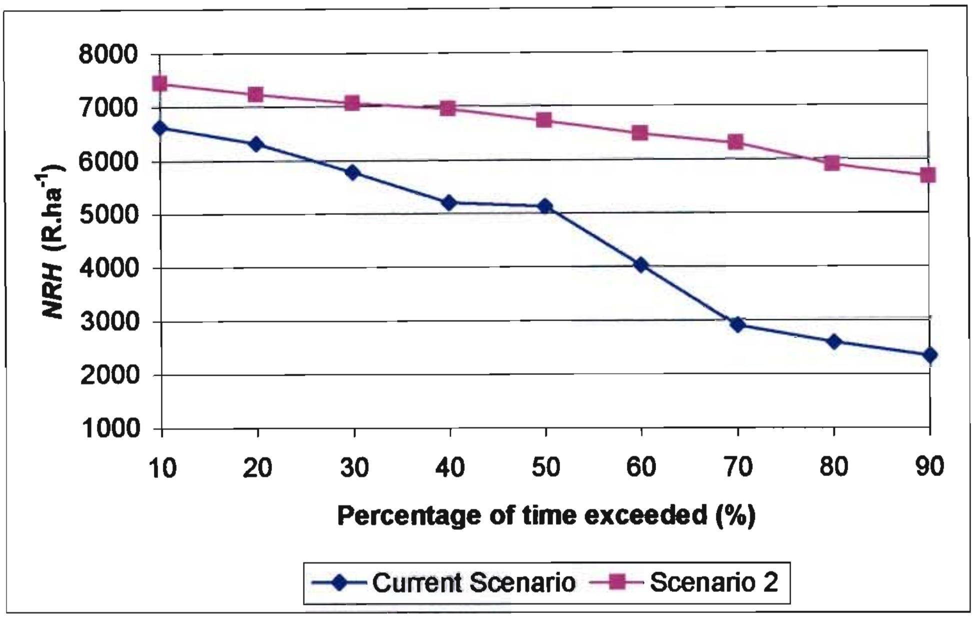

Figure 6.9 Exceedence percentiles of *NRH* for the Current Scenario and the Scenario 2

Examination of Figures 6.7 to 6.9 shows that higher yields were obtained with the Current Scenario on 40% of the years compared to yields obtained using the Scenario 2. On average however, marginally higher yields (2.5 %) were obtained with Scenario 2. The reason for this is that, with the current schedule, the irrigator used far more water than with the improved schedule and yields frequently suffered as a result of the dam emptying. This resulted in a wide range of yields. Furthermore, the benefits of improved scheduling were, in this scenario, somewhat negated by the poor DU. Portions of the field were frequently under-irrigated, resulting in stress and reduced yield, whereas the current system applied excessive amounts so that even the drier portions of the field received adequate water. However, the improved timing of the irrigation applications resulted in a much higher *SIE* (40% on average), as is shown in Figure 6.8. The slightly higher average yields and considerable reduction in water use resulted in an *NRH* that was, on average R1850.ha^{-1} higher per season which translates into R1 480 000 for the 800 ha irrigated area. As was concluded in the previous section, this improvement in profit is a value the irrigator can use to assess the feasibility of making the associated improvements in scheduling.

6.3.3 Scenario 3: Scheduling and uniformity

Comparisons between Scenario 3 and the Current Scenario of *ERC* yield, *SIE* and *NRH* are shown in Figures 6.10, 6.11 and 6.12 respectively. Comparison of water use/dam storage is not necessary in this case as the amount of water used by this system is identical to that used by in Scenario 2.

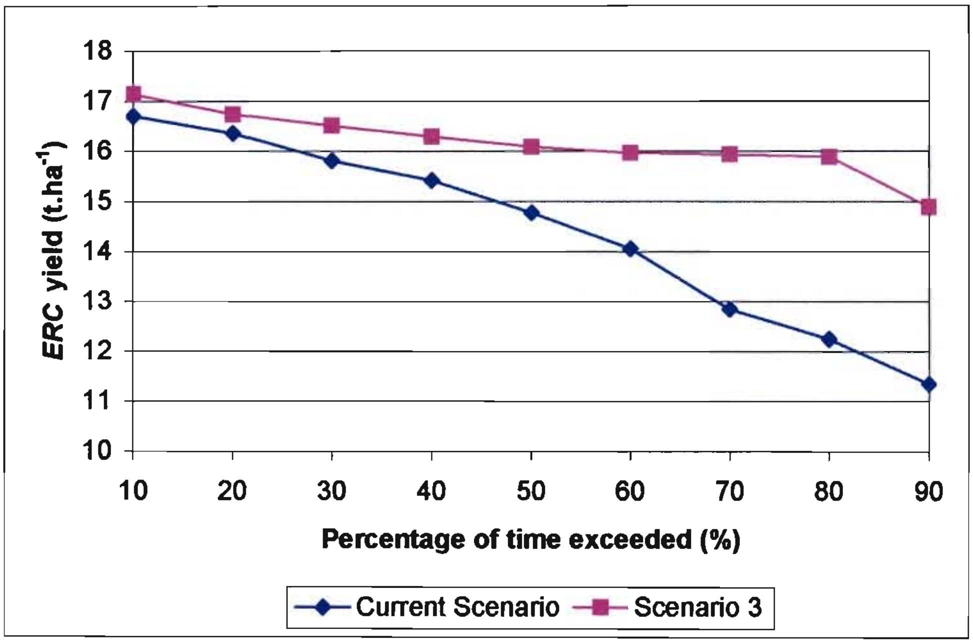

Figure 6.10 Exceedence percentiles of *ERC* yield for the Current Scenario and Scenario 3

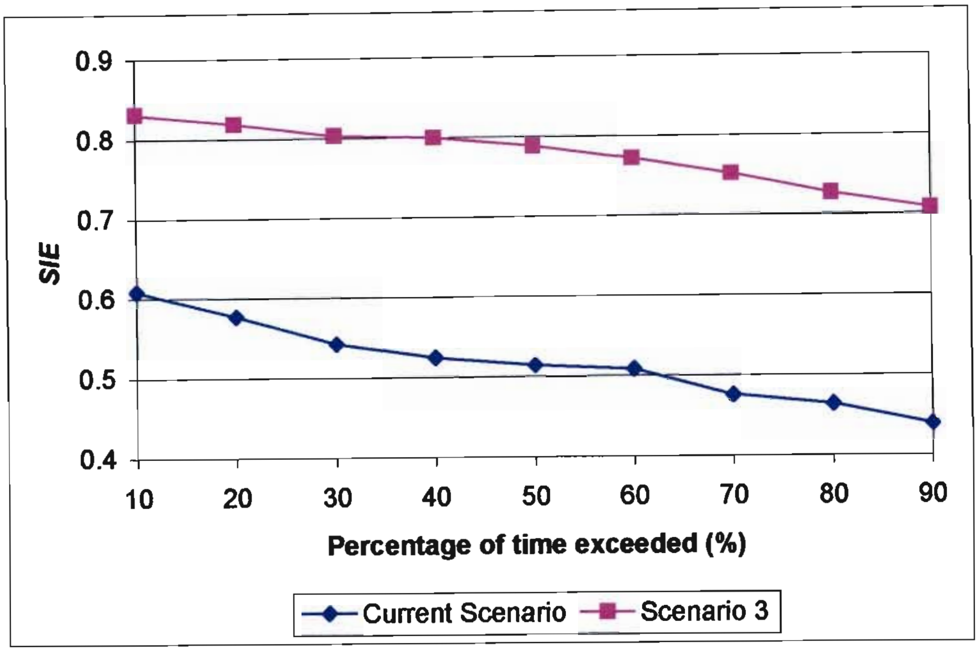

Figure 6.11 Exceedence percentiles of *SIE* for the Current Scenario and Scenario 3

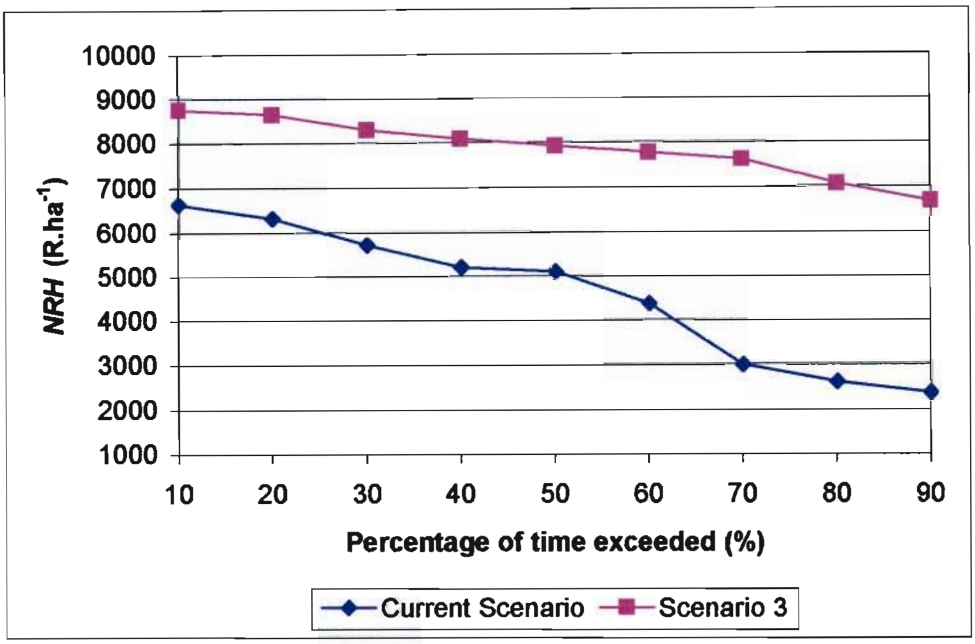

Figure 6.12 Exceedence percentiles of *NRH* for the Current Scenario and the Scenario 3

It was shown in Scenario 2 that the benefits of the well-scheduled system were somewhat negated by poor uniformity. Furthermore, in Scenario 1 the effects of uniformity were also, albeit to a lesser extent, negated by a poor irrigation schedule. However, this comparison shows that the "ideal" system (Scenario 3) performed significantly better in all aspects when compared to the Current Scenario. Yields were higher and more consistent. Although higher yields (represented by values with a low exceedence probability) obtained with the current system were only marginally lower than for the current system, yields were generally considerably lower for all percentiles > 50%. This can be attributed partially to the fact that for the Current Scenario the dam was frequently unable to supply the irrigation requirement. Importantly, as was shown in Section 6.3.2, much less water was used to obtain higher yields. The improved timing and uniformity of application resulted in more beneficial water use, reflected in Figure 6.11, where *SIE* was on average 48% higher than that in the Current Scenario. The consistent, high yields and more efficient water use obtained with Scenario 3 resulted in an *NRH* that was, on average, R3067.40 .ha^{-1} higher than the Current Scenario. This equates to a R2 453 920 increase per annum for the entire 800 ha of irrigated area.

6.3.4 Scenario 4: Subsurface drip irrigation

As with Scenario 1, it was necessary to compare the impact of the different scheduling scenarios on water supply/water usage, as well as *ERC*, *SIE* and *NRH*. Exceedence percentiles of seasonal irrigation applications were compared for all three systems, the results of which are shown in Figure 6.13.

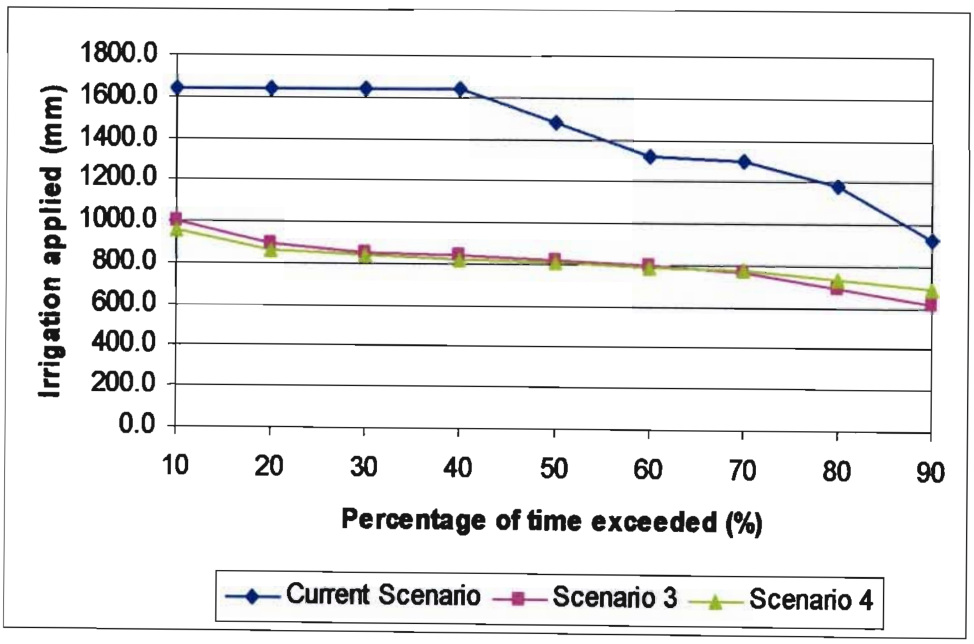

Figure 6.13 Exceedence percentiles of irrigation applied for the Current Scenario, Scenario 3 and Scenario 4

Figure 6.13 shows that the ideal subsurface drip system (Scenario 4) used marginally less water than the ideal dragline (Scenario 3) and considerably less water than the Current Scenario. Intuitively one would have expected there to have been a greater difference in water use between Scenario 3 and 4 as subsurface drip irrigation has the advantage of minimising evaporation of water from the soil surface. However, Scenario 4 was scheduled to refill the soil profile at a much lower depletion than Scenario 3. Consequently, crops grown under Scenario 4 were never subjected to soil water stress and consistently transpired at potential rate. Scenario 3 occasionally subjected the crops to mild stress in order to meet the specified depletion level, thus utilising slightly less water during those periods. Since the equation to estimate *ERC* yield is transpiration-based, this deduction is confirmed by the higher yields obtained by the Scenario 4, shown in Figure 6.14. A comparison of *SIE* and *NRH* is shown in Figures 6.15 and 6.16 respectively.

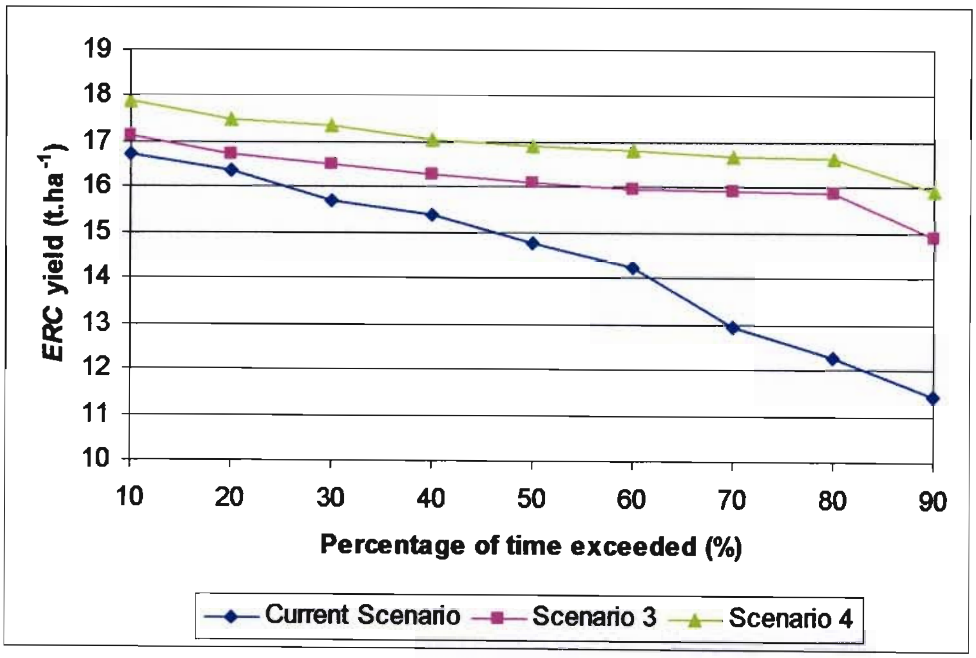

Figure 6.14 Exceedence percentiles of *ERC* yield for the Current Scenario, Scenario 3 and Scenario 4

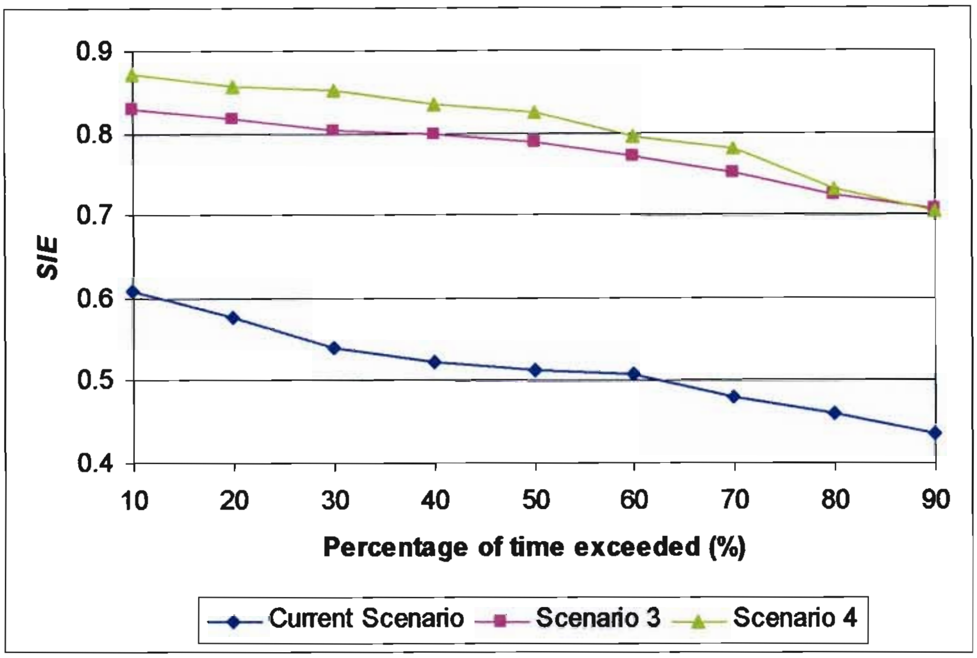

Figure 6.15 Exceedence percentiles of *SIE* for the Current Scenario, Scenario 3 and Scenario 4

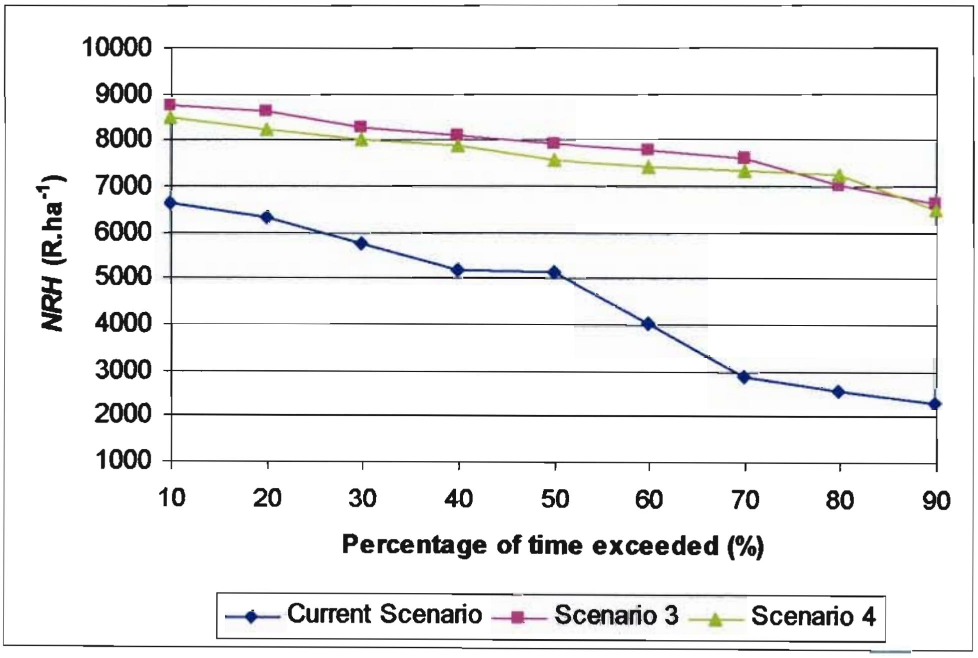

Figure 6.16 Exceedence percentiles of *NRH* for the Current Scenario, Scenario 3 and Scenario 4

Examination of Figures 6.14 to 6.15 show that the ideal drip system (Scenario 4) provided the highest yields with a seasonal average of 16.92 $t.ha^{-1}$, compared with $16.08t.ha^{-1}$ and $14.62t.ha^{-1}$ obtained for the two dragline systems. Furthermore, Scenario 4 used water more efficiently, as is reflected in the highest *SIE* values shown in Figure 6.15. Ultimately this indicates that Scenario 4 made the most beneficial use of applied irrigation water, as it utilised the least water and obtained the highest transpiration per season. As was deduced from Figure 6.13, this can be attributed to the fact that Scenario 4's irrigation was scheduled at a much lower depletion level than that of Scenario 3. As a result, in Scenario 3 transpiration was occasionally reduced below the potential rate before the soil profile was refilled.

However, even though Scenario 4 obtained the highest yields and used irrigation water most beneficially, the increased capital costs associated with a subsurface drip system negated these benefits and resulted in the system being marginally less profitable than Scenario 3. In this instance, the average *NRH* obtained using Scenario 4 was R7561.ha^{-1}, slightly lower than the R7841.ha^{-1} obtained using Scenario 3.

6.4 Chapter Conclusion

In this Chapter the results from several simulated scenarios were used to illustrate the financial benefit of making improvements to irrigation system hardware and/or management which can be used by an irrigator to assess the feasibility of implementing the simulated changes. It was shown in Section 6.3.1 that a large improvement in uniformity resulted in only small improvements in yield, *SIE* and *NRH*. However, it is felt that the benefits of improving uniformity were masked by the poor irrigation schedule used to compare the two systems. Comparison of Scenario 2 and Scenario 3 shows the impact of uniformity on well scheduled systems. Although these two scenarios were not compared graphically, the mean yield obtained for Scenario 2 was 14.9 t.ha^{-1}, considerably lower than the mean yield of 16.1 t.ha^{-1} obtained for Scenario 3. Thus for well scheduled systems, it can be concluded that considerable benefits can be obtained by improving application uniformity.

The reduction in water costs incurred as a result of improved scheduling resulted in significant potential financial gains to the irrigator as was illustrated in Section 6.3.2. However, it is felt that the benefit of improved scheduling was somewhat negated by poor uniformity, as average yields were only marginally higher for Scenario 2. Savings made by large reductions in water use, however, resulted in considerable increase in *NRH*.

The combined effects of improving scheduling and uniformity were illustrated in Section 6.3.3 through Scenario 3. Marked improvements in yield, *SIE* and *NRH* were noted when compared with the Current System and clearly illustrate the benefit of running a well managed and maintained irrigation system.

In Section 6.3.4, Scenario 3 was shown to be the most financially viable option of all the scenarios that were simulated. Although the ideal drip system (Scenario 4) provided higher yields and utilised applied irrigation more effectively, the high capital costs associated with Scenario 4 made it less financially viable. However, both scenarios out-performed the Current Scenario and resulted in considerable financial gains to the irrigator. Furthermore, all the scenarios that were simulated in the Chapter resulted in financial benefits to the irrigator. Ultimately, the model has provided him with a figure (*NRH*) that he can use to compare to the cost of making the associated changes.

It has been shown in this Chapter that *ACRUCane*, in combination with the *ACRU* model has the capacity to provide valuable decision support information to irrigators.

7. DISCUSSION AND CONCLUSIONS

As a consequence increasing demands for water and of the implementation of the National Water Act (1998) in South Africa, water allocations to irrigated agriculture, the largest water user in the country, are likely to be affected. Sugarcane is a major land use in KwaZulu-Natal and Mpumalanga and competes with other crops as well as with domestic and industrial users for water resources (Schmidt, 2001). Consequently, growers are facing increasing pressure to use water more efficiently and to justify existing water use. It was thus deemed necessary to develop a catchment scale modelling tool for sugarcane, capable of providing reliable management information to both water resource managers and water users. In the following sections of this Chapter aspects of this project are discussed with respect to the objectives, which are reiterated below for completeness:

(a) The development, validation and verification of an integrated modelling tool capable of:
- modelling the soil water balance at a field scale for irrigated areas and catchment scale for non-irrigated areas,
- linking an accurate estimation of crop water requirement for an irrigated area with the availability of water at a catchment scale,
- explicitly accounting for the impact of different irrigation systems on the hydrology and, ultimately, the sugarcane yield of an irrigated area,
- assessing the impact of different supply constraints on sugarcane yield, and
- estimating both sugarcane and sucrose yield.

(b) Illustrate the potential of the model to provide management advice to both water resource managers and irrigators by simulating various irrigation scenarios.

7.1 Model Development

Model development involved two tasks, *viz.* development of a conceptual model, and integration of the conceptual model into the *ACRU2000* modelling system.

The development of the conceptual model involved a review of available models to the South African sugar industry with respect to their potential to meet the objectives of the project. The

ACRU model is able to simulate the hydrology of a catchment, provides a detailed representation of different irrigation supply scenarios, including the associated losses and inefficiencies, has limited crop yield simulation options and has embedded links between irrigation demand and supply. Hence the *ACRU* model was selected as the most suitable model to use as a framework for the model developments required for this study.

In *ACRUCane*, the irrigation water budget adopted followed very closely the concepts used in the *ZIMsched 2.0* model. The *ZIMsched 2.0* model is tailored specifically for sugarcane and is able to differentiate between different types of irrigation systems and different levels of performance with regard to application uniformity. Although the water budget in *ACRUCane* is based almost exclusively on that used in *ZIMsched* 2.0, it must be noted that *ZIMsched 2.0* in turn makes use of many internationally accepted algorithms and concepts to simulate the water budget of an irrigation field. These include, *inter alia.*, the dual crop coefficient approach utilised by Allen *et al.* (1998) and the modified SCS-based approach to stormflow generation used by the *ACRU* model (Schulze, 1995). The simulation of two soil layers, *viz.* the root soil layer and sub-root layer, represents the major conceptual difference between the water budget algorithms in *ZIMsched 2.0* and *ACRUCane*. Other differences include *ACRUCane*'s use of reference grass evaporation as opposed to A-pan to represent atmospheric evaporative demand, and the methodology used to represent canopy development.

The simulation of sucrose yield was necessary in the model as it is one of the best indicators of the quality of the crop and is linked directly to income generated. For this reason, the complex biomass partitioning algorithms used in the CANEGRO model were integrated into *ACRUCane*. In addition to simulating the yield of sucrose, total daily dry biomass as well as stalk mass are simulated. Algorithms to simulate *ERC* and two sugarcane yield models were also included in *ACRUCane*. The empirical nature of the yield models made their inclusion easy and the yield information provided adds significant value to the model development.

The model development performed in this study represents a unique link between a sophisticated deterministic crop and irrigation systems simulation model and the water resources available from a catchment. This functionality was not available in any of the models reviewed. Although the *ACRU* model does have the ability to simulate the yield from a field of irrigated sugarcane, the yield model was simplistic and assumed an annual growing season from July 1 to June 30. *ACRUCane* uses complex thermal time-based sugarcane crop growth algorithms whereas the current *ACRU* model uses monthly crop factors to represent crop water use for sugarcane. The *ACRU* water budget does not account for the impact of different wetting fractions associated with different irrigation systems on soil water evaporation. As this is a value that can vary considerably prior to significant canopy development, it was explicitly accounted for in *ACRUCane* and represents an improvement in the water budget. Furthermore, two new irrigation scheduling options have been added to *ACRUCane* in addition to the current four employed by the *ACRU* model. The added functionality of being able to simulate multiple water budgets to account for system uniformity represents a significant advancement in the modelling of irrigation systems, as it allows the impact of varying degrees of application uniformity on the hydrology and yield of an irrigated area to be quantified.

It is concluded that the objectives of the research were met. However, it is acknowledged that some conceptual weaknesses remain in the *ACRUCane* model. Among these is the manner in which the model accounts for different types of irrigation systems. Currently, the only manner in which *ACRUCane* differentiates between different systems is through changing the specifics of different scheduling options, such as the amount and frequency with which water is applied, and the fraction of the soil wetted by irrigation. It is felt that the model's inability to account for the interception of water from overhead irrigation applications is a shortcoming in the model. A further limitation is that, currently, only one mode of irrigation scheduling, *viz.* irrigation with a fixed cycle and varying amounts, accounts for system capacity. Further conceptual weaknesses will be highlighted in the discussion of the case study.

Incorporation of the conceptual version of *ACRUCane* into a working model involved programming the required algorithms into the *ACRU2000* modelling system in the Java programming language. Once familiar with the Java language and the structure of the *ACRU2000* model, addition of code was easy due to the extensible manner in which *ACRU2000* was created. Classes added to the model were independent of the rest of the model and minimal addition to existing code was required. Furthermore, as a result of the object-oriented nature of the Java programming language, classes created for the *ACRUCane* model can be used in other parts of the *ACRU2000* model. This represents significant value added to the *ACRU2000* model, as many complex processes, such as the determination of reference grass evaporation are now available to the rest of the *ACRU2000* model. Wherever possible, classes were made generic. To clarify this, although *ACRUCane* is tailored specifically for sugarcane, processes such as transpiration and evaporation from the soil surface were programmed in such a way that they can be used for any crop grown on any land segment modelled by the *ACRU2000* model. However, some limitations were encountered when creating the *ACRUCane* model. In some instances it was impossible to make classes generic, for example, as the algorithms utilised for canopy growth were created specifically for sugarcane. A further limitation was encountered when simulating irrigation scheduling. In *ACRUCane*, the irrigation requirement is determined at the end of one day of simulation and the required amount is applied at the beginning of the next day. This happens as the irrigation amount applied depends on the availability of water from its source, and thus on the hydrology of the non-irrigated portion of the catchment which then needs to be simulated in order to determine whether the irrigation requirement can be met. The implication of this is that, when using the option of simulating a known irrigation regime, water applications will only occur a day after the date specified in the input file. However, this is considered to be a minor problem and will not have major repercussions on the functionality of *ACRUCane*.

7.2 Model Verification

All the yield algorithms used in the *ACRUCane* model were verified against observed data from either La Mercy and/or the Zimbabwe Lowveld. The sucrose yield model initially provided poor results. However, a slight modification to the value of one of the parameters used in the sucrose yield model, justified by results from the literature, resulted in significant improvements, with the results comparable to those previously reported on for the model. The sucrose yield model is conceptually superior to the other yield models included in *ACRUCane* in that it utilises solar radiation to accumulate biomass, which the model further partitions to sucrose and other constituents according to soil water conditions, temperature and genetic properties. However, this model is complex and requires daily solar radiation as an input. As daily solar radiation is not always available, it is not the ideal tool to provide robust decision support information and is better suited as a research tool. The *ERC* yield and cane yield models provided simulations to an acceptable degree of accuracy. In most instances actual yields were simulated well and when they were not, relative yields were. This means that the actual and/or relative differences in yield magnitude resulting from different wetting treatments were captured well by the model. The significance of this is that it shows the ability of *ACRUCane* to differentiate between different wetting treatments and hence provide important decision support information.

A common trend noted for the *ERC* and cane yield simulations was the tendency to over-simulate low yields, which are generally associated with the drier treatments. As explained in Chapter 5, Lecler (2005d) postulated that these over-simulations are related to the inability to simulate the impact of stress on canopy development and thus transpiration demand. This aspect is considered to be conceptual flaw in the model and has implications regarding the model's ability to compare irrigated and rainfed scenarios in very dry areas, as it will potentially over-estimate yields under rainfed conditions, thereby masking the potential benefits of irrigation.

7.3 Model Implementation

Implementation of the model as a decision support tool was demonstrated in the hypothetical case study presented in Chapter 6. Simulating several irrigation scenarios and comparing them to the current scenario demonstrated the financial feasibility of the farmer making changes in management or systems. Importantly, the impact of different types of systems and different scheduling regimes was demonstrated. The ability of the model to link the irrigated area to the water generated from the surrounding catchments and to asses the associated impact on yield was also demonstrated.

Simulating hypothetical irrigation scenarios represents the primary way in which information can be generated for irrigators. However, several uses of the model were not demonstrated in the case study. Being linked to the *ACRU* model, *ACRUCane* has the facility to: perform reservoir yield simulations; asses the impact of a proposed irrigation scheme on the surrounding catchment hydrology; be used as an irrigation planning tool with regard to both water requirement and available water supply; be used as a water resource optimisation tool; resolve conflicting demands on water resources and asses environmental consequences associated with deep percolation and stormflow.

7.4 Recommendations for Future Research

In developing the required model, it is concluded that the objectives of the research have been achieved. However, during the course of this discussion, several model shortcomings were identified and it is these shortcomings that, *inter alia*, form the basis of the recommendations for future research as listed below:

(i) The canopy model utilised in *ACRUCane*, as has been mentioned, does not account for the effect of water stress. This was identified in Chapter 5 as the reason for the over-simulation of yields under low rainfall conditions. It is proposed that if the impacts of soil water stress on canopy development could be adequately modelled, both transpiration and canopy development will be more accurately represented.

(ii) Many of the concepts and algorithms used in the *ACRUCane* model are based very closely on the methodology outlined by the FAO (Allen *et al.*, 1998). In doing so, the foundations for future FAO-based developments have been laid. It is believed that further model development to enable *ACRU* to simulate the growth of all crops listed by Allen *et al.* (1998) would be of value, as currently only sugarcane is simulated.

(iii) The economic analysis of the output as described in Chapter 6 provided valuable information regarding the viability of different system and scheduling options. These results were all computed by processing output from *ACRUCane*. It is suggested that having such economic analyses automatically generated by the *ACRU* model would provide beneficial information and save time for users of the model.

(iv) Currently, a simple means of allocating dam water to irrigated areas is employed in the *ACRU* model. More complex operating rules and supply scenarios, such as fractional water allocation and capacity sharing, as a means of allocating water generated in a catchment to a range of users could be valuable additions to the manner in which water is made available for the irrigator in the *ACRU* model.

(v) The environmental impacts of the different irrigation management scenarios used in the case study were not assessed. It is felt that further research on the impacts these scenarios had on aspects such as stormflow and deep percolation would be valuable research.

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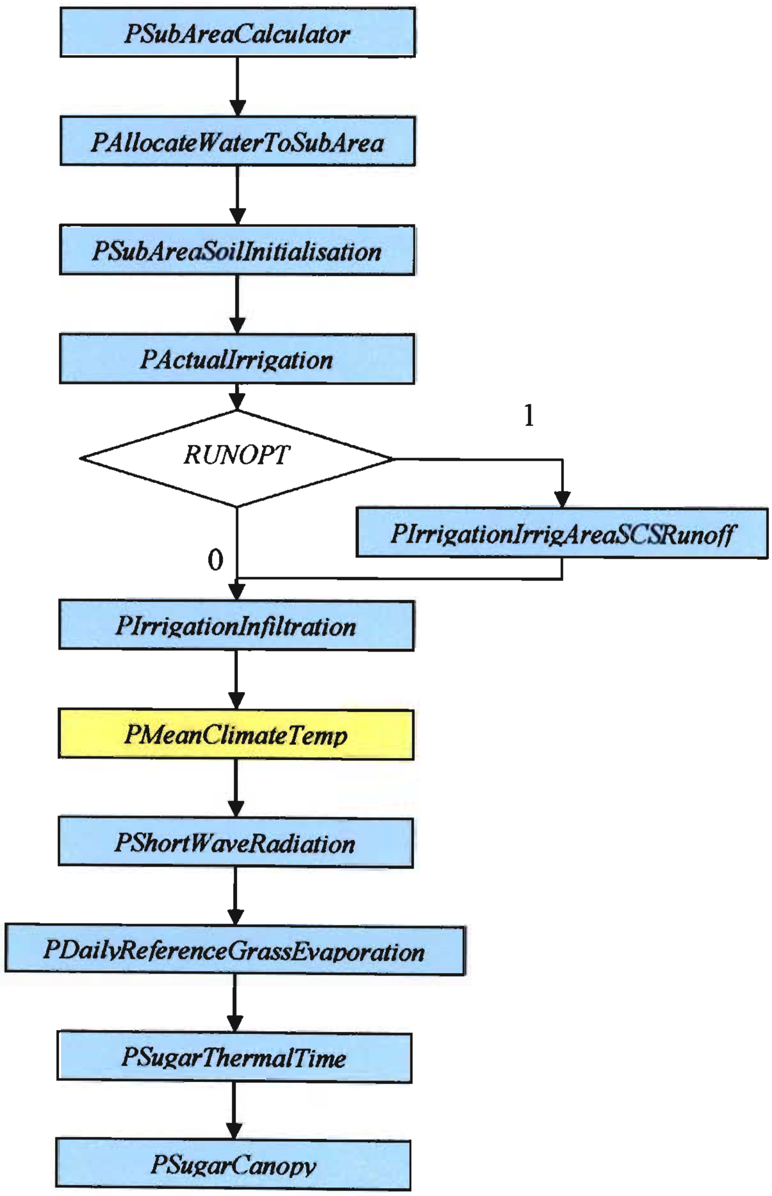
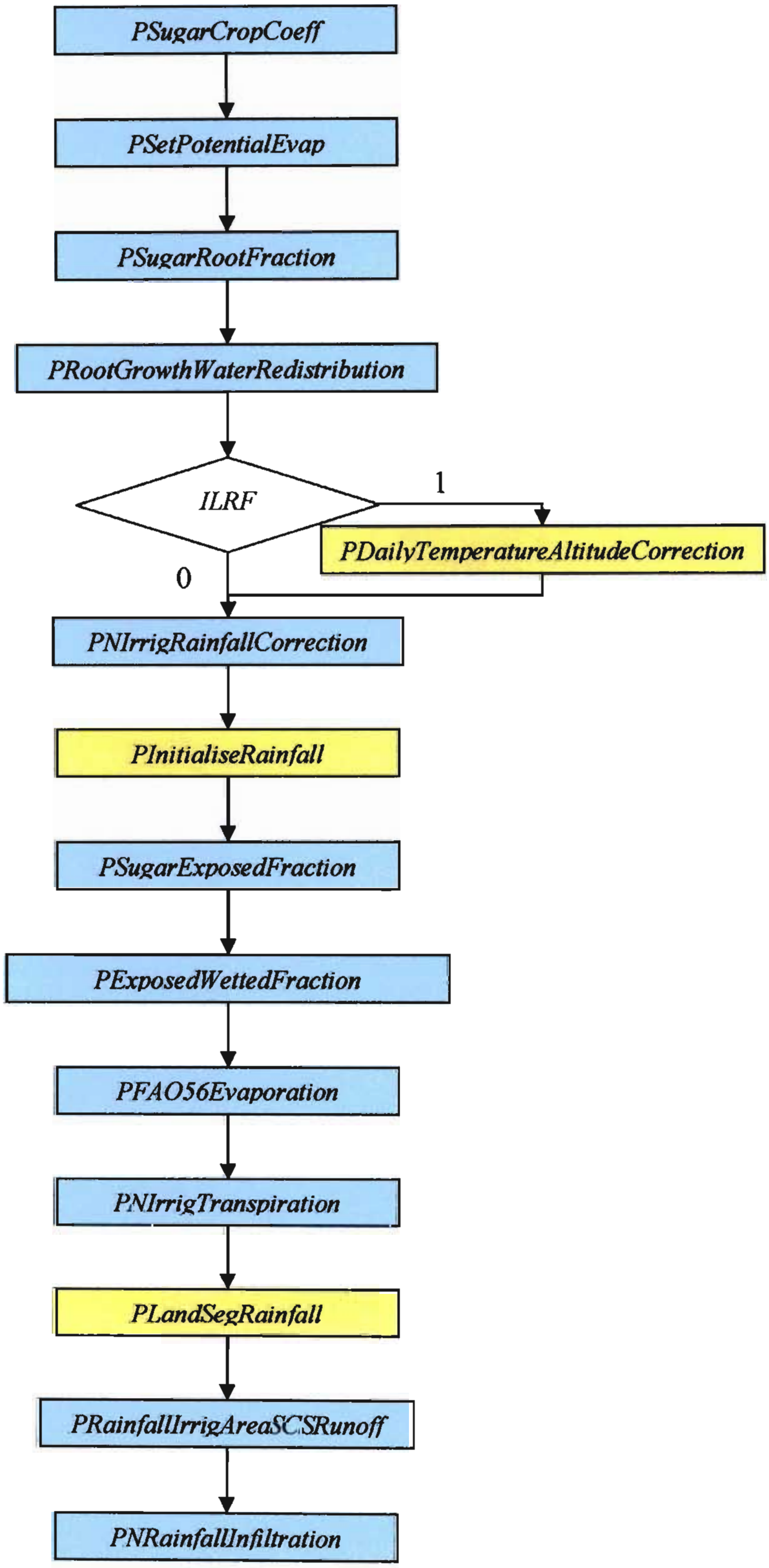
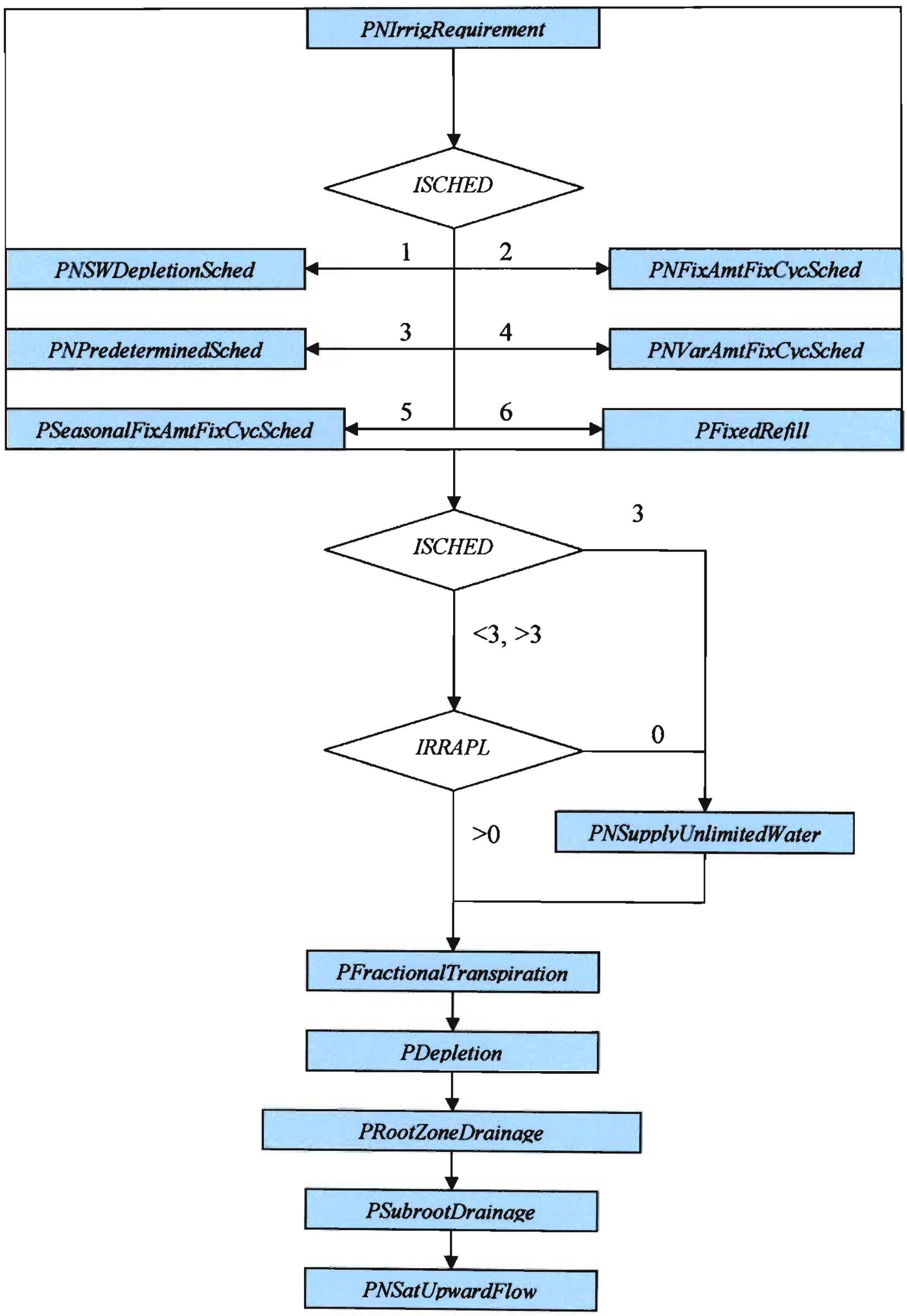
9. APPENDIX A: PROCESS FLOWCHART AND DESCRIPTION

This appendix provides a flow chart of the processes simulated by *ACRUCane*, followed by a brief description of each process. The majority of the process objects listed were written by the author. However, some of processes used had already been created for the *ACRU2000* model and have been highlighted in yellow.





PSugarCropCoeff
PSetPotentialEvap
PSugarRootFraction
PRootGrowthWaterRedistribution
ILRF
1
PDailyTemperatureAltitudeCorrection
0
PNIrrigRainfallCorrection
PInitialiseRainfall
PSugarExposedFraction
PExposedWettedFraction
PFAO56Evaporation
PNIrrigTranspiration
PLandSegRainfall
PRainfallIrrigAreaSCSRunoff
PNRainfallInfiltration


PNIrrigRequirement
ISCHED
1
2
PNSWDepletionSched
PNFixAmtFixCycSched
3
4
PNPredeterminedSched
PNVarAmtFixCycSched
5
6
PSeasonalFixAmtFixCycSched
PFixedRefill
ISCHED
3
<3, >3
IRRAPL
0
>0
PNSupplyUnlimitedWater
PFractionalTranspiration
PDepletion
PRootZoneDrainage
PSubrootDrainage
PNSatUpwardFlow

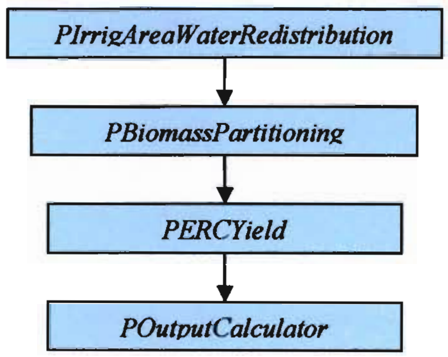


Figure A1 Flow chart of Process objects used in *ACRUCane*

Table A1 Descriptive list of process objects used in *ACRUCane*

Process Name	**Process description**
PSubAreaCalculator	Determines the size of the irrigated sub-areas.
PAllocateWaterToSubArea	Takes all the water allocated to the irrigated area and re-allocates it to the different sub-areas according to the specified uniformity. Any uniformity parameter that is input is internally converted to *CV*.
PSubAreaSoilInitialisation	Sets many initial attributes of soil for irrigated sub-areas such as initial soil water content, TAM, *REW* etc. This process is only run once at the beginning of the simulation.
PActualIrrigation	Determines the actual irrigation applied based on the total volume supplied and the losses incurred.
PIrrigationIrrigAreaSCSRunoff	Determines stormflow as a result of irrigation via the SCS equation.
PIrrigationInfiltration	Infiltrates irrigation applied. If application exceeds saturation then the remainder of applied irrigation contributes to stormflow.
PMeanClimateTemp	Determines mean air temperature from maximum and minimum temperatures to avoid repetition of this calculation.
PShortWaveRadiation	Determines shortwave solar radiation using FAO56 methodology and is used in sucrose yield estimation.
PDailyReferenceGrassEvaporation	Determines reference grass evaporation on a daily basis using FAO56 methodology.
PSugarThermalTime	Accumulates thermal time over the course of the growing season, a driver of several physiological processes. Also calculates the growing season flag, an integer indicating the current position in the growing season.

PSugarCanopy	Determines canopy cover using the Hill model
PSetPotentialEvap	Determines K_{cmax} in order to determine maximum potential evapotranspiration from sugarcane each day.
PSugarRootFraction	Determines R_{frac}, the portion of the effective rooting depth occupied by the roots. Also determines the depth of the root and sub-root soil layers.
PRootGrowthWaterRedistribution	Redistributes water in the soil profile as a result of daily root growth.
PDailyTemperatureAltitudeCorrection	Adjusts the observed daily temperature values for altitude differences between the point where the values were observed and the point where the simulation is taking place.
PNIrrigRainfallCorrection	Adjusts the rainfall for the irrigated area using a correction factor to account for the fact that the irrigated area and remainder of the catchment may experience different daily rainfall amounts.
PInitialiseRainfall	Takes the corrected rainfall and adds it to a *CRainfallStore* object.
PSugarExposedFraction	Determines the fraction of soil exposed/not shaded.
PExposedWettedFraction	Determines the fraction of the soil both exposed and wetted by irrigation.
PFAO56Evaporation	Evaporates water from the soil using FAO56 methodology.
PNIrrigTranspiration	Transpires water from soil layer occupied by roots.
PLandSegmentRainfall	Transfers water from *CRainfallStore* to the portion of land on which precipitation is occurring.
PRainfallIrrigAreaSCSRunoff	Determines stormflow as a result of rainfall via the modified SCS equation.

PNRainfallInfiltration	Infiltrates remaining rainfall (after runoff) into soil profile.
PNIrrigRequirement	Determines the total irrigation requirement (including losses) based on one of six available scheduling options. A water "request" is then sent to the appropriate water source indicating the volume of water required. This process is only run for the median sub-area.
PNSWDepletion	Determines irrigation requirement based on user specified fraction of soil water depletion.
PNFixAmtFixCycSched	Applies a fixed amount of irrigation at a fixed cycle. This cycle can be interrupted by rainfall, if the user specified threshold is exceeded.
PNPredeterminedSched	Applies irrigation by duplicating a known regime of specified amounts on specified days.
PNVarAmtFixCycSched	A variable amount is applied at a fixed cycle depending on soil water depletion levels and soil water holding capacity.
PSeasonalFixAmtFixCycSched	Applies a fixed amount of irrigation using different cycles for summer and winter.
PFixedRefill	Determines irrigation requirement based on user specified depletion of soil water below FC.
PNSupplyUnlimitedWater	Supplies any amount of water requested by an irrigated sub-area.
PFractionalTranspiration	Determines the fraction of transpiration that leaves the top 100 mm of soil.
PDepletion	Determines the depletion of water from the top 100 mm of soil.
PRootZoneDrainage	Transfers water from root soil layer to sub-root layer is water content is above FC.
PSub-rootDrainage	Transfers water from sub-root layer to groundwater storage if water content is above FC.

PNSatUpwardFlow	Starting with deepest soil layer, this process works upwards moving water to the next soil layer if it the soil water content is above porosity.
PIrrigAreaWaterRedistribution	Distributes runoff and baseflow from the irrigated sub-area to the appropriate outflow components.
PBiomassPartitioning	Accumulates biomass and partitions it to different parts of plant primarily to determine sucrose mass.
PERCYield	Estimates *ERC* yield. Also estimates cane yield via Thompson equation and CANESIM polynomial.
POutputCalculator	Determines averaged values of important outputs for the entire irrigated area using the individual values determined for each irrigated sub-area.