IMPROVING THE BASIS FOR PREDICTING TOTAL EVAPORATION FROM NATURAL VELD TYPES IN SOUTH AFRICA

A focus on Moist Upland Grassland, Valley Thicket and Coastal Bushveld/Grassland

Report to the
Water Research Commission

by

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Report to the Water Research Commission on the project "Improving The Basis For Predicting Total Evaporation From Natural Veld Types In South Africa"

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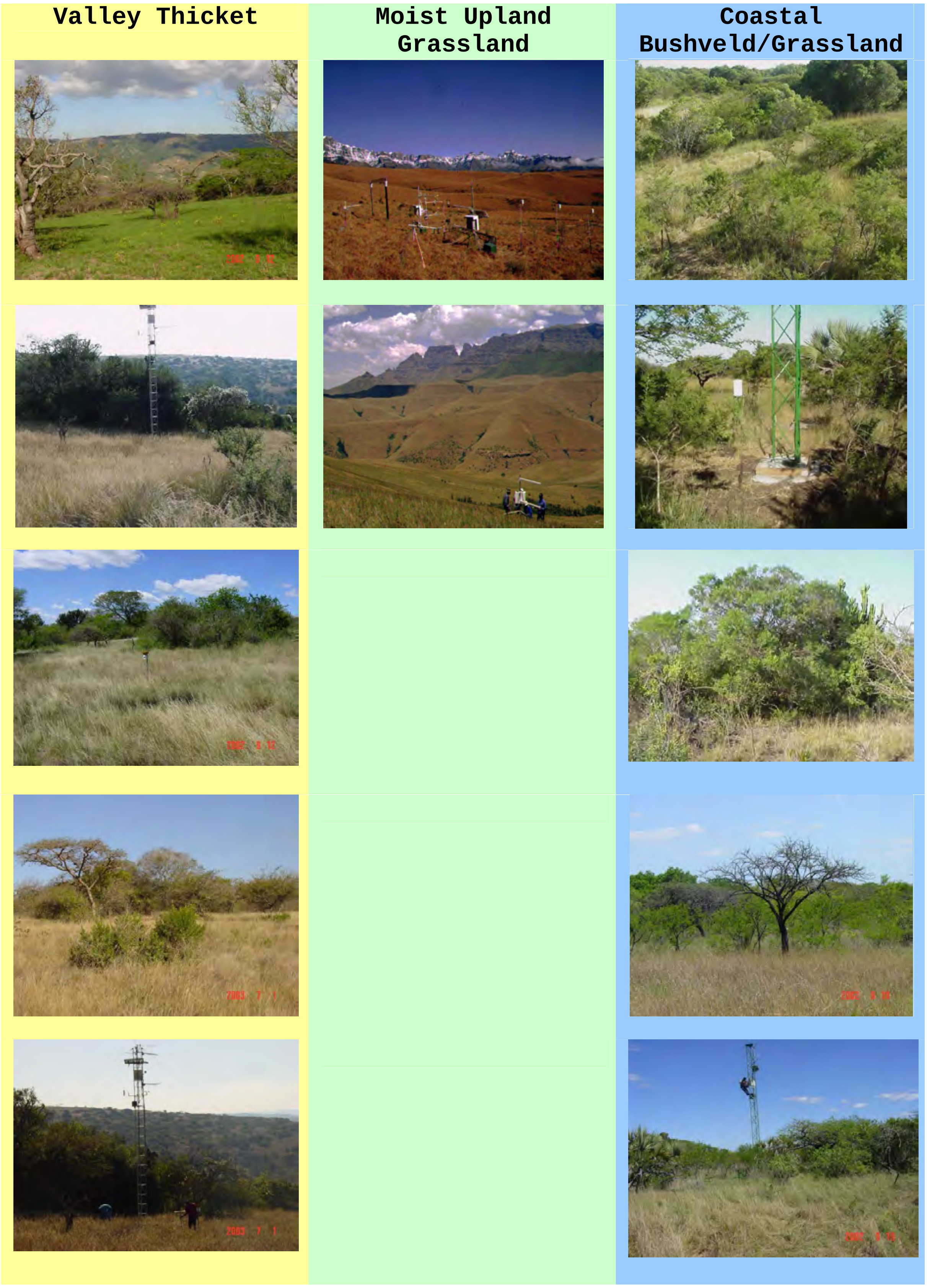

Frontispiece: Images of sites and instrumentation used in the study of the water use by natural vegetation

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NOTATION LIST

Lower case

a	Empirical coefficient used in *SWAP*	Unitless
*acru*_et	Total evaporation simulated with *ACRU*	mm d^{-1}
*acru*_dS	Soil water storage change simulated with *ACRU*	mm d^{-1}
*acru*_S	Soil water storage simulated with *ACRU*	mm
bet	Bowen ratio total evaporation	mm d^{-1}
e_a	Saturated vapour pressure at mean air temperature	kPa
e_d	Actual vapour pressure at mean air temperature	kPa
e_{sat}	Saturated water vapour pressure	kPa
h_o	Net radiation	MJ m^{-2}
kc	Crop coefficient	mm mm^{-1}
prof. swc	Profile soil water content	mm
rain	Rainfall	mm d^{-1}
r_{air}	Aeodynamic resistance	s m^{-1}
*swap*_et	Total evaporation simulated with *SWAP*	mm d^{-1}
*swap*_dS	Soil water storage change simulated with *SWAP*	mm d^{-1}
*swap*_S	Soil water storage simulated with *SWAP*	mm
*swat*_et	Total evaporation simulated with *SWAT*	mm d^{-1}
*swat*_dS	Soil water storage change simulated with *SWAT*	mm d^{-1}
*swat*_S	Soil water storage simulated with *SWAT*	mm
z	Soil depth	cm

Upper case

ACRU 7-day ave	Seven-day average total evaporation simulated with the *ACRU* model	mm d^{-1}
AD	Air density	g m^{-3}
A-pan	Reference evaporation estimated with the A-pan	mm d^{-1}
AR	Aerodynamic resistance for heat and vapour transfer	s m^{-1}
BET 7-day ave	Seven-day average total evaporation estimated with the Bowen Ratio Energy Balance technique	mm d^{-1}
C_{air}	Specific heat capacity of moist air	J kg^{-1} K^{-1}
EC	Electrical conductivity	S m^{-1}
E_a	Actual soil evaporation calculated using an empirical function	mm d^{-1}
E_{max}	Maximum evaporation according to Darcy's Equation	mm d^{-1}
E_p	Potential evaporation	mm d^{-1}
E_{p0}	Potential evaporation of a wet bare soil	mm d^{-1}
ET_0	Potential evapotranspiration according to Penman-Monteith	mm d^{-1}
ET_{ref}	Reference potential evapotranspiration	mm d^{-1}
ET_p	Reference potential evapotranspiration simulated in *SWAP*	mm d^{-1}
ET_{p0}	Potential evapotranspiration of a dry canopy completely covering the soil	mm d^{-1}
ET_{w0}	Potential evapotranspiration of a wet canopy	

	completely covering the soil	mm d^{-1}
G	Soil heat flux density	W m^{-2}
G	Soil heat flux used in *SWAT* and *SWAP*	J m^{-2} d^{-1}
H	Sensible heat flux density	W m^{-2}
HV	Latent heat of vaporization	MJ kg^{-1}
K_d	Daily crop coefficient	mm mm^{-1}
LAI	Leaf area index	m^2 m^{-2}
LE	Latent heat flux density	W m^{-2}
PAW	Plant available water	mm
P_{gross}	Gross precipitation	mm d^{-1}
P_i	Intercepted precipitation	mm d^{-1}
R_n	Net irradiance	W m^{-2}
Rn	Net irradiance	W m^{-2}
R_n	Net irradiance used in *SWAP*	J m^{-2} d^{-1}
Rs	Solar radiant density	MJ m^{-2}
S_p	Potential root water extraction rate	mm d^{-1}
SC	Soil cover fraction	cm^2 cm^{-2}
SWAP 7-day ave	Seven-day average total evaporation simulated with the *SWAP* model	mm d^{-1}
SWAT 7-day ave	Seven-day average total evaporation simulated with the *SWAT* model	mm d^{-1}
Ta	Air temperature	°C
T_p	Potential transpiration	mm d^{-1}

Others

δ	Slope of vapour pressure curve	kPa $°C^{-1}$
Δ	Slope of vapour pressure curve	kPa K^{-1}
Δ_v	Slope of vapour pressure curve	kPa K^{-1}
γ	Psychrometric constant	kPa $°C^{-1}$
λE	Latent heat flux density	W m^{-2}
λ_w	Latent heat of vaporization	J kg^{-1}
ρ_{air}	Density of air	kg m^{-3}

Model abbreviations

ACRU	Agro-hydrological modelling system
ACRUVELD	Agro-hydrological modelling system for natural veld
BEWAB	BEsproeiings WAter Bestuursprogram
CERES-MAIZE	Crop Environment REsource Synthesis adjusted for maize
SAPWAT	A computer program for establishing irrigation requirements and scheduling strategies in South Africa
SWAMP	Soil Water Management Program
SWAP	Soil Water Atmosphere Plant model
SWAT	Soil and Water Assessment Tool
SWB	Soil Water Balance model

EXECUTIVE SUMMARY

1. MOTIVATION

1.1 National Water Act and potential Stream Flow Reduction Activities

The National Water Act (NWA) (1998) provides guidelines to the National Government to regulate water use within South Africa. In terms of the National Water Act, any land-based activity which reduces streamflow, may be declared a Stream Flow Reduction Activity (SFRA). Declaration of such Stream Flow Reduction Activities depends on "*the extent of stream flow reduction, its duration, and its impact on relevant water resources and on other water users* (Warren, 2003)."

The magnitude of the impact of a potential Stream Flow Reduction Activity is usually measured against baseline vegetation[i]. A first estimate of the impact of a land-based activity compared to baseline vegetation on the availability of water, is through the reduction in the mean annual runoff (MAR) within a catchment due to a change in the total evaporation. This estimated change in total evaporation may be an indication of the reduction in the available water. Therefore, any land-based activity that is likely to increase total evaporation (relative to the baseline vegetation) can be identified as a potential Stream Flow Reduction Activity.

1.2 Assessment of the impact of potential Stream Flow Reduction Activities

1.2.1 Introduction

Accurate total evaporation estimates of natural (baseline) vegetation types are required when assessing the impact of a potential Stream Flow Reduction Activity, or a change thereof on the water balance and the availability of water in streams (Dye and Bosch, 2000). Within the context of the current National Water Act (1998), water resource managers will increasingly need to assess whether proposed changes in land-use within catchments are likely to reduce the quantity and temporal availability of water to downstream users. Such decisions need to be based on relative annual (and seasonal) water use of the existing and proposed crops or vegetation.

The implementation of the National Water Act (1998) is forcing consideration of a far wider range of crops and baseline vegetation than in the past. However, our knowledge of the water use (total evaporation) from dryland crops and natural veld types is in most cases quite inadequate.

1.2.2 Measuring the total evaporation of baseline vegetation

In previous years, the emphasis on streamflow research was focussed in areas where fynbos and grassland were converted to plantations of pine and eucalypt, whereas today the need for information on the total evaporation and streamflow is much wider (Dye and Bosch, 2000). The total evaporation of only a few of the seventy Acocks (1988) or sixty eight Low and Rebello (1996) natural vegetation classes occurring within South Africa have been measured directly (Jarmain, et al. 2003). However, the total evaporation of these natural veld types or changes in the total evaporation between baseline vegetation and agricultural crops, are frequently simulated with hydrological models.

Historically, land-use change/streamflow studies have mainly involved paired catchment experiments where Grassland or Fynbos were converted into plantations (Dye and Bosch, 2000). Versfeld (1993) describes these experiments. However, differences in the degree of streamflow reduction and the period of streamflow reduction occurrence in the studies were not explained satisfactorily by analysis of the streamflow data only. Therefore, hydrological process studies similar to those in the Cathedral Peak (Everson et al., 1998) and Weatherley catchments (Lorentz, 1999), followed. These hydrological process studies also involved measurements of rainfall, interception, total evaporation and soil water storage changes. These studies have confirmed that streamflow is sensitive to changes in total evaporation.

Several examples exist where the total evaporation of natural vegetation were measured with the Bowen Ratio Energy Balance system as part of hydrological processes or other studies. These include total evaporation measurements for Moist Upland Grassland within the Cathedral Peak (Everson, 2001) and Weatherley catchments (Everson and Jarmain, unpublished), riparian Fynbos and riparian Mistbelt Grassland (Dye et al., 2001) and riparian forest and reeds within the Kruger National Park (Everson et al., 2001).

1.2.3 Modelling the potential impact of a change in vegetation on the availability of water in the streams

Currently, the most comprehensive land-use sensitive hydrological model in South Africa is the Agrohydrological modelling system or *ACRU* (Schulze, 1995). This model allows simulation of the water balance components for a wide range of crops and natural veld types. *ACRU* has been employed widely, e.g. to:

- Argue the possible declaration of rain-fed sugarcane as a Stream Flow Reduction Activity (Schulze et al., 2000);
- Establish compensatory forestry approaches to clearing alien invasive vegetation from riparian zones (Jewitt et al., 2002);

- Establish approaches to modelling streamflow reductions resulting from commercial afforestation (Gush et al., 2003) and verify the *ACRU* model for e.g. forest hydrology application (Jewitt and Schulze, 1999);
- Determine the sensitivity of hydrological responses to different land uses (Shulze et al., 1998; Everson, 2001; Kienzle and Schulze, 1995; Tarboton and Cluer, 1993; Schulze, 1987); and
- Study not only the hydrology, but also the water quality of a catchment (Kienzle et al., 1997).

ACRU simulates the catchment water balance on a daily time step and uses daily and monthly data inputs. Where monthly input data are used, these are disaggregated into daily values using Fourier analysis. *ACRU* has the ability to use different crop growth models for different crops and natural veld types found in South Africa. The growth approach depends on the availability of data or input parameters. The most widely used approach within *ACRU* is the use of daily climatic data together with monthly crop/vegetation parameters (i.e. crop coefficients). Alternatively a dynamic vegetation parameter file is used. Here, measured leaf area indices may be specified on a daily time step.

Initial crop coefficients are specified for various vegetation types and crops within *ACRU*. Although initial crop coefficients are fixed for a monthly time step, these crop coefficients are modified by stress factors, which depend on the soil water availability. Crop coefficients are one of the factors influencing the simulations of total evaporation. However, few of the crop coefficients for natural veld types were determined through field experiments. Therefore, in order to improve the accuracy of the total evaporation for natural veld types based on models applying crop coefficients, these coefficients need to be verified *via* field experiments, and reassessed if necessary.

1.2.4 Alternative modelling approaches to determine the effect of a change in vegetation on the available water in a catchment

Calder (1986) lists determining factors (limits) for transpiration of *Eucalyptus* spp. and most other vegetation types as atmospheric demand, physiological mechanisms, canopy structure and the availability of soil water to roots. More specifically, the total evaporation of vegetation and differences in total evaporation between vegetation types can be attributed to leaf area index (Greenwood et al., 1985; Dunin, 2002), canopy height (Greenwood et al., 1985; Dunin, 2002; Le Maitre and Scott, 1997), length of growing season or seasonality (Greenwood et al., 1985; Dunin, 2002), soil water availability (Silberstein et al., 2001; Dunin, 2002; Calder, 1998; Sharma, 1984; Olbrich et al., 1994) and rooting depth and depth of soil water extraction (Greenwood et al., 1985; Dunin, 2002). Models estimating the differences in total evaporation between baseline vegetation and potential Stream Flow Reduction Activities therefore need to take these factors into account. A total evaporation or water balance model, growing a crop or vegetation over a season, and which is based on principle processes, may therefore possibly simulate the total evaporation more accurately than a model parameterised initially with ‘fixed’ monthly (or growth stage define) growth parameters.

Several water balance models, applying ‘flexible’ growth routines, are described in the literature. However, the inputs required by these models could potentially limit their applications for complex, species-diverse vegetation types.

2. OBJECTIVES

2.1 Initial objectives

The initial objectives of this project were to:

a. Investigate available generic crop growth models and recommend one that simulates crop growth and canopy conditions with sufficient accuracy for plant water use predictions, and
b. Improve the accuracy of crop coefficients, as used in South African models, for the most important crops and veld types (from a Stream Flow Reduction Activity perspective).

These objectives were revised to fit within the proposed time frame of the project, and to focus the research.

2.2 Revised objectives

Therefore, this project aimed to:

a. Investigate available generic plant growth models and recommend one that simulates plant growth and canopy conditions with sufficient accuracy, for plant water use predictions, and
b. Improve the evaporation simulations, as used in South African models, for the natural veld types Moist Upland Grassland, Valley Thicket (Valley Bushveld) and Coastal Bushveld-Grassland (Coastal Forest and Thornveld) from a potential Stream Flow Reduction Activity (SFRA) perspective.

3. MATERIALS AND METHODS

3.1 Introduction

This project ***estimated the total evaporation*** of Valley Thicket and Coastal Bushveld/Grassland, not previously estimated in South Africa. The Bowen ratio energy balance technique was used to determine the total evaporation. The project further ***suggested improvements for the prediction of total evaporation*** of Valley Thicket, Coastal Bushveld/Grassland and Moist Upland Grassland with different models. The vegetation types selected commonly occur in areas among potential Stream Flow Reduction Activities.

3.2 Sites

3.2.1 Moist Upland Grassland

The soil water balance of a Moist Upland Grassland site was studied in the northern part of the Natal Drakensberg Park (29° 00'S, 29° 15'E). Cathedral Peak Catchment VI is a natural grassland catchment receiving a biennial spring burning treatment. It has a catchment area of 0.68 km^2 (Everson, 2001).

Total evaporation and climatic conditions were measured and simulated from October 1990 to September 1994. The results for the period 1 January to 31 December 1992 are presented in this report.

3.2.2 Valley Thicket

The total evaporation of Valley Thicket was studied on a private farm located near Noodsberg (29° 19'S, 30° 49'E; 838 m a.m.s.l). The Valley Thicket vegetation on this farm covers an area of approximately 0.25 km^2.

The total evaporation of Valley Thicket and climatic conditions at the Noodsberg site were measured from May 2002 to September 2003. The profile soil water content was measured to a depth of 3 m for the period August 2002 to September 2003. All measurements were stopped following vandalism to the equipment on the site during September 2003. The components of the soil water balance were simulated from 1 May 2002 to 15 February 2003. The models were configured for a Valley Thicket area of approximately 0.25 km^2.

3.2.3 Coastal Bushveld/Grassland

The Coastal Bushveld/Grassland experimental site was located in the Bonamanzi Nature Reserve (29° 01'S, 32° 16'E; 57.4 m a.m.s.l). The Coastal Bushveld/Grassland vegetation within this reserve covers an area of approximately 0.47 km^2.

The total evaporation of Coastal Bushveld/Grassland was measured from April 2002 to August 2003. The soil water contents to a depth of 2 m were measured from August 2002 to August 2003. All measurements were stopped following vandalism to and theft of the equipment at the site during August and September 2003. The components of the soil water balance were simulated from 11 June 2002 to

24 March 2003. The models were configured for a Coastal Bushveld/Grassland area of approximately 0.47 km^2.

3.3 Equipment to measure total evaporation

The Bowen Ratio Energy Balance technique was used to estimate the total evaporation of moist upland grassland, valley thicket and coastal bushveld/grassland. This technique estimates the components of the energy balance and therefore the total evaporation above the vegetation. The technique requires measurement of the available energy flux density and the air temperature and water vapour pressure profile differences above a surface.

3.4 Models to simulate total evaporation

Many soil water balance and catchment soil water balance models are available which operate on different scales (time and spatial) and have varying levels of complexity. A few have been reviewed in this research project to identify different mechanisms operating in various models. This model review identified the extensive data requirements of these models, data which are not always readily available or do not exist for selected research sites or vegetation types. The models were reviewed in terms of the type of model (soil water balance, catchment water balance or other), the time and scale the model is operating in, the models' spatial capabilities, the type of growth model employed (mechanistic or empirical), the method of crop/vegetation growth, the method of reference and total evaporation estimation, and the availability of data required in parameterisation of model.

Three models, representing different approaches to estimating total evaporation and modelling plant growth, were subsequently selected. Although not generic, all these models were supply/demand limited models. The three models selected were the (1) Agrohydrological modelling system (*ACRU*), (2) Soil and Water Assessment Tool (*SWAT*) and (3) Soil Water Atmosphere Plant (*SWAP*) model. The three selected models were parameterised for the three natural veld types, for the period overlapping with the Bowen ratio total evaporation measurements.

4. MODELLING RESULTS

4.1 Moist Upland Grassland

ACRU tended to simulate the total evaporation accurately during summer, but slightly underestimated (< 1 mm d^{-1}) the total evaporation during autumn, when compared to the actual total evaporation. In contrast, *SWAT* tended to overestimate total evaporation by up to 2.5 mm d^{-1} during summer, but simulated the total evaporation accurately during most of autumn. Towards the end of autumn (May) *SWAT* overestimated total evaporation by up to 1.5 mm d^{-1}, compared to the actual total evaporation. For the remainder of the year (winter and spring), both *ACRU* and *SWAT* underestimated the total evaporation when compared to the actual total evaporation. Underestimations of total evaporation were less than 1 mm d^{-1} during winter, and up to 2.5 mm d^{-1} during spring. In contrast to these simulations, the total evaporation simulated with *SWAP* did not follow the trend of the actual total evaporation and was characterised by periodic under- and overestimations throughout the season.

4.2 Valley Thicket

The *ACRU*, *SWAT* and *SWAP* models generally underestimated the total evaporation at the Valley Thicket site, when compared to the actual total evaporation measured at this site. Occasionally, the simulated and actual total evaporation rates were similar (e.g. winter 2002, autumn 2002, spring 2002 and summer 2002/2003). All the models simulated the total evaporation more accurately during late winter and spring, compared to autumn and summer.

Generally, the *SWAT* model simulated the total evaporation at the Valley Thicket site better than *ACRU* and *SWAP*. This was the case for periods in July/August 2002 and December 2002 to February 2003. During these periods, *SWAT* maintained high total evaporation rates more similar to that measured. In contrast, the total evaporation simulated with *ACRU* and *SWAP* during these periods, decreased to less than 1 mm d^{-1}, which was up to 5.6 mm d^{-1} lower than the actual total evaporation.

All three models, responded to rainfall events and the associated availability of soil water through increased total evaporation. Total evaporation rates generally decreased as the soil water became limiting over time. When rainfall ceased to occur, e.g. over extended periods in January and February 2003, the total evaporation simulated with *ACRU* and *SWAP* were significantly reduced compared to the actual total evaporation. This was possibly due to soil water stress which limited the total evaporation rates to less than 1 mm d^{-1}.

4.3 Coastal Bushveld/Grassland

All three models underestimated the total evaporation at the Coastal Bushveld/Grassland site throughout the simulation period, when compared to the actual total evaporation. The trends simulated with the three models were similar. Occasional dissimilarities occurred within these trends in September and November 2002 and at the end of February 2003.

5. CONCLUSIONS

5.1 Investigate and suggest an available generic plant growth model

One of the aims of this project was to investigate available generic plant growth models and to recommend a model that simulates the plant growth, canopy conditions and total evaporation from natural veld types accurately. This study demonstrated that no single model can be recommended for accurate plant water use predictions of all natural veld types. This was concluded from the irregular model performances at each research site. Therefore, to improve future total evaporation simulations for Moist Upland grassland, Valley Thicket and Coastal Bushveld/Grassland found in South Africa, it is suggested that model developments address the limitations highlighted for each model and vegetation type.

5.2 Improve the total evaporation simulations

Firstly, within *ACRU*, the following need to be addressed to improve the total evaporation simulations for natural veld types:

- Initial crop coefficients (Moist Upland Grassland, Valley Thicket), and the effect that soil water has on the final crop coefficients (all vegetation types); and
- Current growth routines need to be replaced by a more mechanistic growth model (Valley Thicket and Coastal Bushveld/Grassland).

Secondly, for improved total evaporation simulations for natural veld types with *SWAT*, the following needs to be improved:

- Reference evaporation routine (Moist Upland Grassland and Coastal Bushveld/Grassland);
- Current growth routine need to be replaced by a more mechanistic growth model (all vegetation types); and
- Soil water storage component (Coastal Bushveld/Grassland).

Thirdly, the crop growth routines within *SWAP* need to be replaced by a more mechanistic crop growth model to improve the accuracy of the total evaporation simulations for complex vegetation types as Valley Thicket and Coastal Bushveld/Grassland.

Therefore, a comparison of the three models showed that improved estimation of total evaporation from natural veld types is dependent upon accurate representation of the reference evaporation, crop growth routines, and soil water storage. Complex natural veld types like Valley Thicket and Coastal Bushveld/Grassland, with different vegetation compositions and stages of succession, are not easily characterised by average vegetation parameters and cannot be adequately represented by simple systems.

6. STORAGE OF DATA

The data (raw and processed) collected during the course of this project will be presented to the Water Research Commission (WRC) on a CD at the completion of the project. The data will be stored at the WRC offices in Pretoria.

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The Water Research Commission is gratefully acknowledged for financing the project entitled: "Improving the basis for predicting total evaporation from natural veld types in South Africa".

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Mr R Dube (Chairman)	Water Research Commission
Dr GPW Jewitt/ Prof RE Schulze	University of Natal (BEEH)
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Mr CT Crosby	Inst of Agric Eng / Agricultural Research Council
Mr JM Bosch	CSIR
Mrs L McKune (Committee Secretary)	Water Research Commission

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CHAPTER 1

INTRODUCTION

1.1 National Water Act and potential Stream Flow Reduction Activities

The National Water Act (NWA) (1998) provides guidelines to the National Government to regulate water use within South Africa. In terms of the National Water Act, any land-based activity which reduces streamflow may be declared a Stream Flow Reduction Activity (SFRA). Declaration of such Stream Flow Reduction Activities depends on *"the extent of stream flow reduction, its duration, and its impact on relevant water resources and on other water users* (Warren, 2003)*."*

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The implementation of the National Water Act (1998) is forcing consideration of a far wider range of crops and baseline vegetation than in the past. However, our knowledge of the water use (total evaporation) from dryland crops and natural veld types is in most cases quite inadequate.

1.2.2 Measuring the total evaporation of baseline vegetation

In previous years, the emphasis on streamflow research was focussed in areas where fynbos and grassland were converted to plantations of pine and eucalypt, whereas today the need for information on the total evaporation and streamflow is much wider (Dye and Bosch, 2000). The total evaporation of only a few of the seventy Acocks (1988) or sixty eight Low and Rebelo (1996) natural vegetation classes occurring within South Africa have been measured directly. However, the total evaporation of these natural veld types or changes in the total evaporation between baseline vegetation and agricultural crops, are frequently simulated with hydrological models.

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1.2.3 Modelling the potential impact of a change in vegetation on the availability of water in the streams

Currently, the most comprehensive land-use sensitive hydrological model in South Africa is the Agrohydrological modelling system, generally referred to as *ACRU* (Schulze, 1995). This model allows simulation of the water balance components for a wide range of crops and natural veld types. *ACRU* has been employed widely, e.g. to:

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- Study not only the hydrology, but also the water quality of a catchment (Kienzle et al., 1997).

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Several water balance models, applying ‘flexible’ growth routines, are described in the literature. However, the inputs required by these models could potentially limit their applications for complex, species-diverse vegetation types.

1.3 Project aims

This project *initially* aimed to:

a. Investigate available generic crop growth models and recommend one that simulates crop growth and canopy conditions with sufficient accuracy for plant water use predictions, and
b. Improve the accuracy of crop coefficients, as used in South African models, for the most important crops and veld types (from a potential Stream Flow Reduction Activity perspective).

However, these objectives were revised to fit within the proposed time frame of the project, and to focus the research. The *revised* objectives were to:

a. Investigate available *generic plant growth models* and recommend one that simulates plant growth and canopy conditions with sufficient accuracy, for plant water use predictions, and
b. Improve the *evaporation simulations*, as used in South African models, for the natural veld types: Moist Upland Grassland, Valley Thicket (Valley Bushveld) and Coastal Bushveld/Grassland (Coastal Forest and Thornveld) from a potential Stream Flow Reduction Activity (SFRA) perspective.

1.4 Methods

In order to add to the existing database of total evaporation measurements, and to determine the accuracy of model simulations of total evaporation from these vegetation types, this study focussed on the:

a. Measurement of total evaporation, climatic conditions and plant growth parameters at a Valley Thicket site and a Coastal Bushveld/Grassland site, and
b. Modelling of the soil water balance components at a Valley Thicket, a Coastal Bushveld/Grassland and a Moist Upland Grassland site.

The total evaporation was measured with Bowen Ratio Energy Balance systems, and the climatic conditions with automatic weather stations. The measured climatic, plant growth and soils data were used together with long-term climatic data to simulate the soil water balances at a Valley Thicket, Coastal Bushveld/Grassland and Moist Upland Grassland site. Three models, using different crop growth approaches, were used in these simulations. These were the Agrohydrological (*ACRU*) model, the Soil and Water Assessment Tool (*SWAT*), and the Soil Water Atmosphere Plant (*SWAP*) model.

1.5 Report structure

The layout of the field experiment, installation of equipment, selection of models and their underlying theories, are discussed in *Chapter 2*.

The results from the field measurements at the Valley Thicket and Coastal Bushveld/Grassland sites are presented and discussed in *Chapter 3*.

The results from the soil water balance modelling of Moist Upland Grassland, Valley Thicket and Coastal Bushveld/Grassland are presented, compared and discussed in *Chapter 4*.

The report is concluded in *Chapter 5*, which includes recommendations relating to the research.

CHAPTER 2

MATERIALS AND METHODS

2.1 Introduction

The total evaporation of only a few of the seventy Acocks (1988) or sixty eight Low and Rebelo (1996) natural vegetation classes occurring within South Africa were estimated since the start of hydrological research in South Africa in 1915. Total evaporation of most of these vegetation types were estimated with the Bowen Ratio Energy Balance technique. These vegetation types include (Figure 1):

- Moist Upland Grassland within the Cathedral Peak (Everson, 2001) and Weatherley catchments (Everson and Jarmain, unpublished),
- Valley Thicket (Jarmain et al., 2003),
- Coastal Bushveld/Grassland (Jarmain et al., 2003).
- riparian Fynbos (Dye et al., 2001),
- riparian Mistbelt Grassland (Dye et al., 2001) and
- riparian forest and reeds within the Kruger National Park (Everson et al., 2001).

This report provides information on the total evaporation of Valley Thicket and Coastal Bushveld/Grassland. It also suggests improvements for the prediction of the total evaporation of Valley Thicket, Coastal Bushveld/Grassland and Moist Upland Grassland frequently found in areas where potential Stream Flow Reduction Activities are considered.

2.2 Site descriptions

2.2.1 Moist Upland Grassland

The soil water balance of a Moist Upland Grassland site was measured at the Cathedral Peak Forestry Research Station which lies in the northern part of the uKhahlamba-Drakensberg Park World Heritage Site (29° 00'S, 29° 15'E). Cathedral Peak Catchment VI is a natural grassland catchment receiving a biennial spring burning treatment. It has a catchment area of 0.68 km^2 and is moderately dissected by streams. Elevations range from 1860 m a.m.s.l. at the basin outlet to 2070 m a.m.s.l. at the highest point. The Bowen ratio energy balance system was installed at an altitude of 1953 m. The terrain has an average slope of 19 % (Everson, 2001).

Winters at Cathedral Peak are cold and dry, while summers are hot and wet (Scott et al. 2000). Bosch (1979) provides a detailed description of the weather in these catchments. The mean annual precipitation is 1299 mm. Catchment VI falls within the summer rainfall region, with 85 % of the rain falling in the months October to March. Occasional snowfall occurs in winter, mostly on the upper parts of the catchments (Scott et al. 2000).

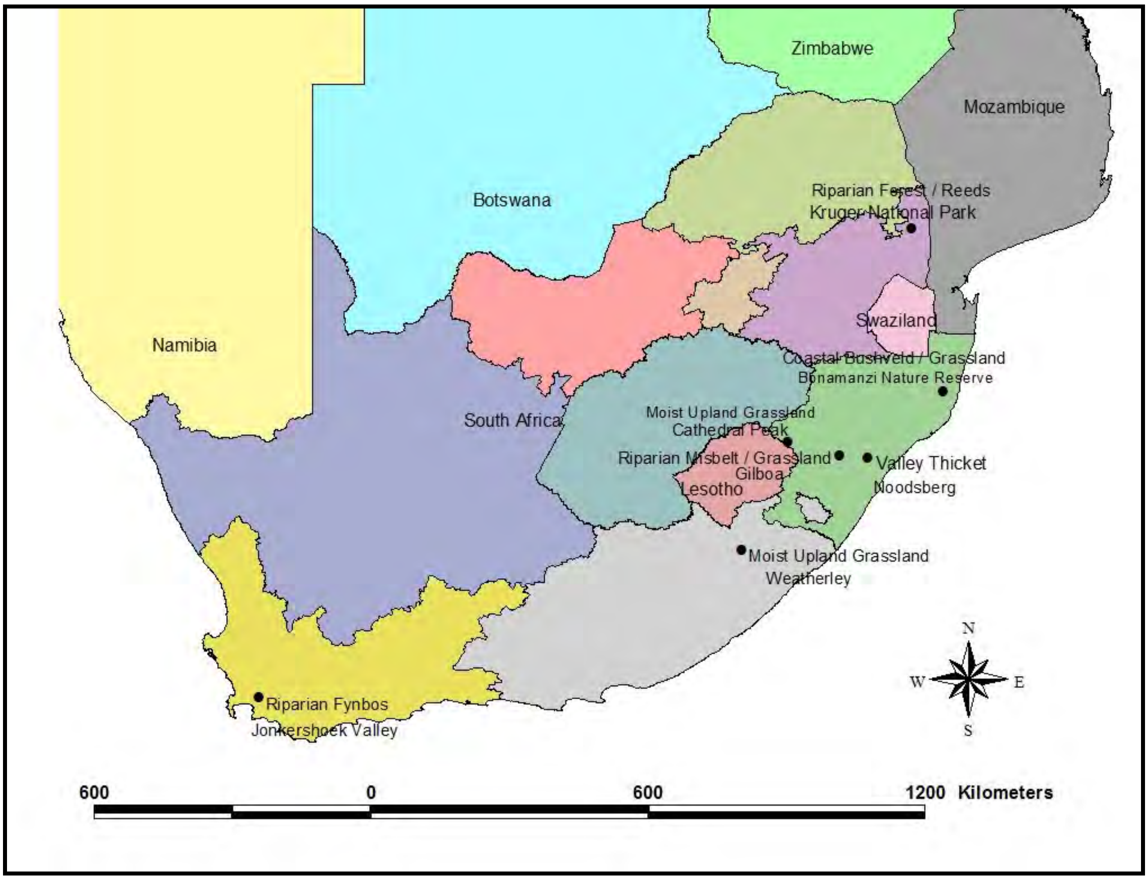


Figure 1 Distribution of natural veld types studied in terms of their total evaporation and found within South Africa

The soils of the catchment are classified as Lateritic Red and Yellow earths, grading into heavy black soils (Katspruit and Champagne) in saturated zones and along the stream banks (Granger, 1976). They are of residual and colluvial origin and derived from basalt. Characteristically these soils are acidic, highly leached and structureless.

The top soils are of friable consistence and are well suited for rapid infiltration and storage of water. The organic content of the top soil is high (6 to 10 %), resulting in a high water holding capacity of the soils. In contrast, the sub-soils have a very high clay content and low hydraulic conductivity (Everson, 2001).

The total evaporation of this Moist Upland Grassland vegetation and the climatic conditions at the experimental site were measured from October 1990 until September 1994.

2.2.2 Valley Thicket

The total evaporation of Valley Thicket was studied on a private farm located near Noodsberg (29° 19'S, 30° 49'E; 838 m a.m.s.l).

Winters at Noodsberg are cold and dry, while summers are hot and wet. Schulze (1997) gives a general description of the general climatic conditions in this area. The mean annual precipitation is 843 mm. Noodsberg falls within the summer rainfall region, with the highest monthly rainfall occurring during mid-summer (January). The lowest average minimum temperature occurs in June and July (7.5 °C) and the highest average maximum temperature in February (26.7 °C). The average annual air temperature is 22 °C.

According to aerial photographs, the Valley Thicket vegetation at the Noodsberg site consists of approximately 62 % of various tree species clusters and 38 % of grass patches. Granger (unpublished) gives a description of the various species found at this site.

The soil at the Valley Thicket site was classified as of the Cartref soil form. This soil form is characterised by being very sandy. At the research site, the fraction of sand within the different layers range between 69 and 88 %. The saturated hydraulic conductivities of the different soil layers within the upper 3 m ranged between 1895 and 102 mm d^{-1}, and decrease with depth. The upper soil layer (0 to 200 mm) has a very good infiltration, whereas the hydraulic conductivities of the sub-soil layers are much lower (577, 277 and 102 mm d^{-1} for the 0.50 m, 2 m and 3 m soil layers).

The total evaporation and climatic conditions at this Valley Thicket site at Noodsberg were measured from May 2002 to September 2003. The soil water contents were measured at different depths below the soil surface, to a maximum depth of 3 m. Measurements were made from August 2002 to September 2003. Leaf area indices and canopy heights were measured during field visits. All measurements were discontinued during September 2003 following vandalism to and theft of the equipment on the site.

The models were configured for a Valley Thicket area of approximately 0.25 km^2.

2.2.3 Coastal Bushveld/Grassland

The Coastal Bushveld/Grassland experimental site was located in the Bonamanzi Nature Reserve (29° 01’S, 32° 16’E; 57.4 m a.m.s.l).

Winters at this site are mild, while summers are hot and wet. Schulze (1997) provides a description of the general climatic conditions in this area. The mean annual precipitation is 758 mm. Bonamanzi falls within the summer rainfall region of South Africa, with the highest monthly rainfall occurring during late summer (February). The lowest average minimum temperature occurs in June and July (11°C), while the highest average maximum temperature occurs in January (30.7°C). The average annual air temperature is 21 °C.

The soil at the Coastal Bushveld/Grassland site was a clay loam soil of the Willowbrook soil form. The saturated hydraulic conductivities over the upper 2 m soil depth, ranged between 44 and 52 mm d^{-1}, increasing slightly with depth. All the soil layers have low hydraulic conductivities, but high soil water holding capacities.

According to aerial photographs, the Coastal Bushveld/Grassland vegetation studied consisted of approximately 41 % bush (tree) clumps of various species and 59 % grass patches. Granger (unpublished) gives a description of the various species found at this site.

The total evaporation of Coastal Bushveld/Grassland was measured from April 2002 to August 2003. The soil water contents of different soil layers to a depth of 2 m were measured from August 2002 to August 2003. Leaf area indices and canopy heights were measured during field visits. All measurements were stopped following vandalism to the equipment at the site during August and September 2003.

The models were configured for a Coastal Bushveld/Grassland area of approximately 0.47 km^2.

2.3 Field instrumentation

2.3.1 Bowen Ratio Energy Balance technique

2.3.1.1 Theory

The Bowen Ratio Energy Balance technique estimates the components of the energy balance and therefore the total evaporation above a surface.

The simplified energy balance (Eq. 1) above a surface is given by :

$$R_n - G = \lambda E + H \qquad 1$$

where R_n is the net irradiance, G soil heat flux density, λE latent heat flux density and H sensible heat flux density, all in Wm^{-2}. Solution of equation 1, requires the measurement of the available energy flux density (R_n - G) and the air temperature and water vapour pressure profile differences above a surface. The available energy flux density at a surface is partitioned into latent heat flux density (energy driving evaporation), and sensible heat flux density (energy heating the air). The latent heat flux density is a function of the water vapour pressure profile difference and the sensible heat flux density a function of the air temperature profile difference.

2.3.1.2 Instrumentation

The components of the energy balance system were measured with a Bowen ratio 023 A system (Campbell Scientific, Inc.). The net irradiance is measured with a net radiometer, installed above the vegetation (Figure 2). The soil heat flux density over the upper 80 mm depth of soil is calculated from the average soil temperature and soil water content over 80 mm, and the average soil heat flux at 80 mm. Two Bowen ratio arms with air temperature sensors and air intakes for water vapour pressure measurements are installed above the plant canopy. The lower arm is installed at least 0.5 to 1 m above the vegetation surface with the separation distance between the arms, approximately 1 m. The air temperature profile difference is calculated from the air temperatures measured with fine wire, type-E thermocouples (resolution 0.006°C) located at the end of each Bowen ratio arm. The water vapour pressure difference between the arms is calculated from water vapour pressure measured with a dew-10 hygrometer (resolution 0.01 kPa), *via* air intakes situated at the end of each Bowen ratio arm.

The required measurements were performed with CR23X dataloggers installed at the Valley Thicket and Coastal Bushveld/Grassland sites, and a CR21X datalogger at the Moist Upland Grassland site. Measurement intervals were 1 s for the air temperature and water vapour pressure profile differences, and 10 s for the net irradiance, soil heat flux and temperature and soil water content. These frequent measurements are subsequently average or totalled over a period of 20 minutes and output to a storage module.

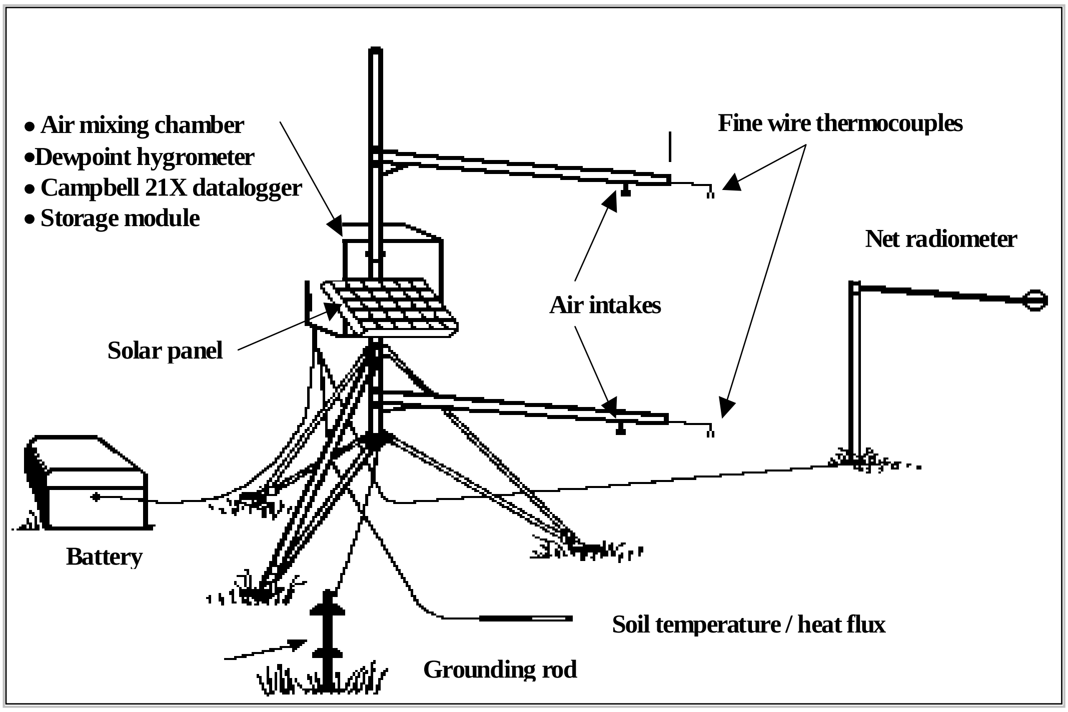


Figure 2 A diagrammatic representation of a Bowen ratio system

2.3.1.3 Installation of Bowen Ratio Energy Balance equipment

The Bowen ratio sampling arms and net radiometer were mounted onto 9 m masts at the Coastal Bushveld/Grassland and Valley Thicket sites, and a 3 m tripod at the Moist Upland Grassland site. The sampling arms of the Bowen Ratio Energy Balance system were orientated due north/south to avoid partial shading of the thermocouples on the arms, while the net radiometers were positioned north/south to prevent sensor shading. The air sensed by sensors mounted on these arms was representative of the surface studied. The lower arm was installed low enough that the bulk vegetation surface environment was not sensed, whereas the upper arms were installed low enough not to sense a different environment upwind. In order to ensure that the air temperature and water vapour profile differences measured were within the resolution of the sensors, a separation distance of at least 0.5 to 1 m between the Bowen ratio sampling arms was maintained, with the height of the lower Bowen ratio arms at approximately 1 m above the vegetation.

As the moist upland grassland surface was uniform, the surface soil heat flux density was estimated using only one pair of heat flux plates and two pairs of averaging thermocouples. The soil heat flux plates were installed at 80 mm below the soil surface, the averaging thermocouples at 20 mm and 60 mm below the surface, and the soil water content reflectometer within the upper 80 mm of soil. Soil sensors were installed similarly at the Coastal Bushveld/Grassland and Valley Thicket sites.

2.3.2 Automatic weather station

Complete automatic weather stations were used to monitor the rainfall, solar irradiance, air temperature, relative humidity, windspeed and wind direction at the sites studied. Climatic conditions were continuously measured during the field experiments. However, gaps in the data sets occurred and were the result of power problems at the research sites.

The rainfall was measured with a tipping bucket raingauge (MCS) with a 0.2 mm resolution. The irradiance was measured with a quantum sensor (Li-Cor) and a solarimeter (Kipp & Zonen) at the Coastal Bushveld/Grassland site, and a solarimeter (Kipp & Zonen) at the Valley Thicket site. Air temperature and relative humidity were measured with Vaisala model CS500 temperature and humidity probes. The windspeed and the winddirection were measured with MCS three cup anemometers (model 177) and MCS windvanes (model 176). All the automatic weather station sensors used at the Valley Thicket and Coastal Bushveld/Grassland sites were mounted onto the 9 m masts. The automatic weather station sensors installed at the Moist Upland Grassland site were mounted onto a 3 m tripod at a height of 2 m above ground, as described by Everson et al. (1998).

2.3.3 Water content reflectometers

2.3.3.1 Theory

The Campbell Scientific models CS615 and CS616[ii] water content reflectometers provide a measure of volumetric soil water content. The technique relies on the fact that each material has a unique dielectric constant. Different dielectric constants result in different propagation times of an electromagnetic wave from a sensing rod, or different oscillation frequencies of a sensor (Campbell Scientific, Inc., 1996). The dielectric constant of soil is the weighted sum of the dielectric constants of the soil constituents. The water content reflectometer therefore relates the dielectric constant to the volumetric soil water content (Campbell Scientific, Inc., 1996).

When this sensor is used under standard conditions (electrical conductivity *EC* less than 1 dS m^{-1} and clay content less than 30 %), the volumetric soil water content can be calculated directly using the manufacturers' calibration polynomials (Campbell Scientific, Inc., 1996). However, if used under non-standard conditions, e.g. in soils with clay contents greater than 30 %, this sensor needs to be calibrated individually for the field conditions.

2.3.3.2 Instrumentation

The CS615 water content reflectometer consists of two stainless steel rods of fixed length (300 mm), a built-in circuit board and a coaxial four core insulated cable. This circuit board controls the power supply, enables the measurements, and outputs the measuring period (propagation time). The circuit board is configured as a multi-vibrator and the outputs of this multi-vibrator are connected to the sensing rods and acts as a wave-guide. This multi-vibrator oscillates at a frequency dependent on the dielectric constant of the soil. Therefore, any change in the volumetric soil water content or the associated dielectric constant, will translate into a change or shift in the oscillation frequency.

2.3.3.3 Installation of water content reflectometers

The Campbell Scientific model CS615 and CS616 water content reflectometers were installed at different depths below the soil surface at the Valley Thicket and the Coastal Bushveld/Grassland sites. The installation depths were chosen to represent the soil water content within different soil layers. At the Valley Thicket site, the water content reflectometers were installed at depths 0.1, 0.5, 1.0, 1.5, 2.0 and 3.0 m below the soil surface (Figure 3: left). The soil water contents measured with these sensors are representative of the following layers: 0 to 0.1 m, 0.1 to 0.5 m, 0.5 to 1.0 m, 1.0 to 1.5 m, 1.5 to 2.0 m, and 2.0 to 3.0 m. At the Coastal Bushveld/Grassland site, water content reflectometers were installed at 0.08, 0.5, 1.0, 2.0 and 3.0 m below the soil surface (Figure 3: right). The soil water contents measured with these sensors are representative of the following layers: 0 to 0.08 m, 0.08 to 0.5 m, 0.5 to 1.0 m, 1.0 to 2.0 m and 2.0 to 3.0 m.

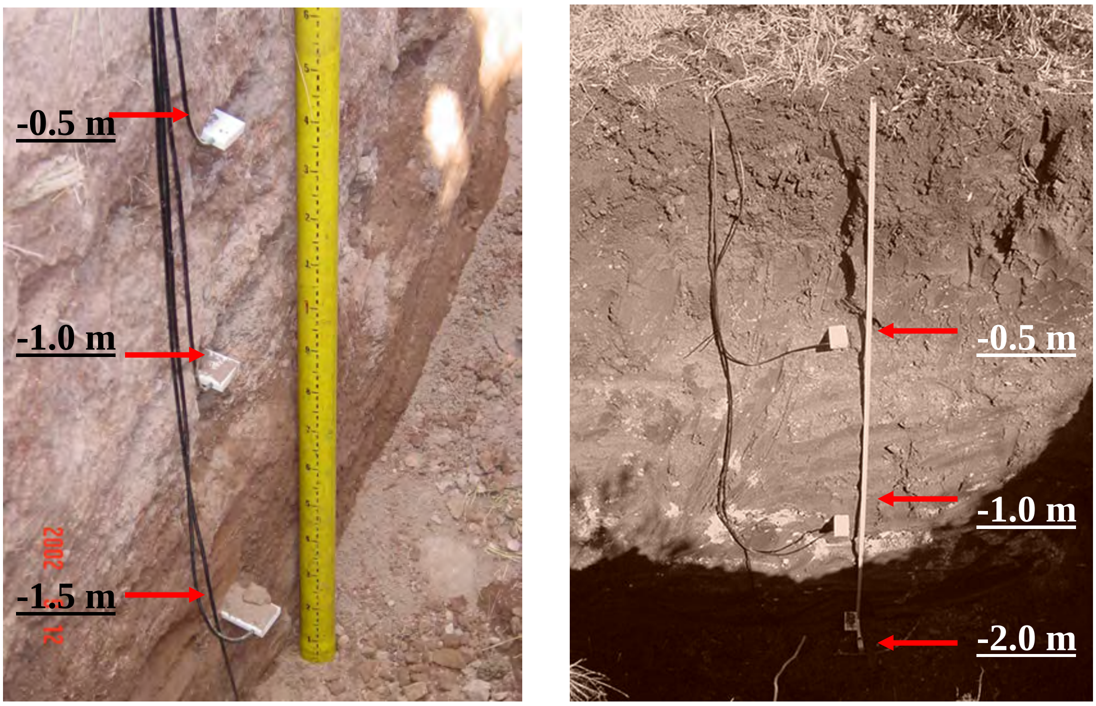


Figure 3 Water content reflectometer installation at the Valley Thicket (left) and Coastal Bushveld/Grassland sites (right)

2.4 Leaf area index and height

Leaf area indices (LAI's) of the Moist Upland Grassland, Coastal Bushveld/Grassland and Valley Thicket vegetation were measured with a Li-Cor LAI 2000 plant canopy analyzer. The leaf area indices measured during field visits represent the *total* (yellow and green) leaf area covering the soil surface. Canopy height was measured with a height rod.

2.5 Modelling

2.5.1 Model selection

Many soil water balance and catchment water balance models are available. The models operate on different time and spatial scales and have varying levels of complexity. A few have been reviewed in this research project, to identify the different mechanisms operating in the various models (Table 1). This model review identified the extensive data requirements of some models, data which are not always readily available or do not exist for selected vegetation types or research sites. The soil water balance and catchment water models were reviewed in terms of the:

- Type of model (soil water balance, catchment water balance or other),
- Time and scale the model is operating in,
- Models' GIS capabilities,
- Type of growth model employed (mechanistic or empirical),
- Method of crop/vegetation growth,
- Method of reference and total evaporation estimation, and
- Availability of data required in parameterisation of model.

Following the model review, three models were selected. These models represent different approaches to estimating total evaporation and modelling plant growth. The three models selected were the (1) Agrohydrological modelling system (*ACRU*), (2) Soil and Water Assessment Tool (*SWAT*) and (3) Soil Water Atmosphere Plant (*SWAP*) model. The three selected models are discussed in more detail below.

Table 1 A review of soil and catchment water balance models investigated in terms of crop growth and total evaporation estimation. The models review include the models *ACRU, ACRUVELD, BEWAB, CERES-MAIZE, Putu, SAPWAT, SWAMP, SWAP, SWAT* and *SWB*.

Components	***ACRU***	***ACRUVELD***	***BEWAB***	***CERES-MAIZE***	***Putu***	***SAPWAT***	***SWAMP***	***SWAP***	***SWAT***	***SWB***
Type of Model	Hydrological	Simple ecosystem model	Soil water balance	Crop Environment Resources Synthesis Model	Crop growth simulation model .	Planning and Management Tool - irrigation requirements; scheduling strategies	Soil water balance	Site soil water balance	Soil and Water Assessment Tool	Soil water balance model – Irrigation Scheduling,
Mechanistic[iii] or Empirical[iv] Growth Model	Empirical	Empirical	Empirical	Empirical	Empirical	Empirical	Empirical	Mechanistic and Empirical	Empirical	Mechanistic and Empirical
Reference potential evapotranspira tion	A-pan, or Daily A-pan equivalent;. Determined from variety of methods: Penman (1948), Linarce (1977, 1984, 1991), Hargreaves and Samani (1982, 1985), Blaney and Criddle (1950), Thornthwaite (1948), or actual A-pan.	A-pan, or Daily A-pan equivalent;. Determined from variety of methods: Penman (1948), Linarce (1977, 1984, 1991), Hargreaves and Samani (1982, 1985), Blaney and Criddle (1950), Thornthwaite (1948), or actual A-pan.	Potential total evaporation from historical crop water requirement curve or atmospheric evaporative demand and crop coefficient		Penman-Monteith	Monthly average Penman-Monteith	Atmospheric evaporative demand according to Penman-Monteith	Potential Evaporation according to Penman-Monteith	Penman-Monteith, Priestley Taylor, Hargreaves Method	Penman-Monteith Grass Reference Daily Total evaporation
Timestep	Daily using daily and monthly averages	Daily	Daily and seasonal for total crop water requirements	Daily	Daily	Daily – using monthly data	Daily and seasonal for total crop water requirements	Daily	Daily – using daily and monthly averages	Real Time or daily
Scale	Catchment – Pseudo Sub-catchment	Catchment	Field scale	Field scale	Field Scale	Catchment Scale	Field scale and ecotope level	Field Scale	Hydrological Response Unit	Field Scale
GIS Capabilities	Non-spatial	Non-spatial	Non-spatial	Non-spatial	Non-spatial	Non- spatial	Non-spatial	Non-spatial; can be run with GIS	Arcview Extension	Non-spatial; can be run with GIS
Crop models	“Yield” models and not “growth” models		Yield model for annual crop water requirement	Growth & yield model	Crop simulation model	Not a crop growth model - relies heavily on SA climate and crop database	Yield models	Crop growth model WOFOST (Hijmans et al., 1994),	Yield and growth models	Crop Growth, Irrigation Scheduling & Soil water balance model

Table 1 (continue….)

Components	***ACRU***	***ACRUVELD***	***BEWAB***	***CERES-MAIZE***	***Putu***	***SAPWAT***	***SWAMP***	***SWAP***	***SWAT***	***SWB***
Growth	Monthly Crop Coefficients & LAI	LAI and crop coefficients	Predetermined water extraction pattern	Primarily Degree days – crop genetic constants	Uses heat units, planting dates and densities crop information according to different growth stages.	Crop coefficients	Crop type, fractional cover parameters, root coefficients, stress factor, max biomass index and related parameters, critical plant water potential, coefficient, yield index parameter	According to WOfFOST growth model (rate of phenological development, interception of radiation, CO_2 assimilation, biomass accumulation, leaf decay and root extension. OR inputs LAI, crop heights, rooting depth as function of development	Generic crop growth, crop development simulated by thermal time or by specified dates	Generic crop growth, crop development simulated by thermal time 2 types of models: mechanistic crop growth model, FAO crop factor/coefficien t approach
Evapotranspir ation	Atmospheric Demand , plant transpiration through Ritchie (1972)	Plant transpiration through Ritchie (1972)	Evapotranspirati on calculated from relative crop water requirement (historical) *vs* days after planting polynomial function **OR** relative crop water requirement *vs* days after planting linear functions for different stages of crop development		Ritchie (1972)	Evaluates Soil evaporation and plant transpiration based on De Jager and van Zyl (1989) and Stroosnijder (1987)	Seasonal crop water requirements: specific yield predictions – function of production, max. total ET, others. Daily crop water requirements: atmospheric evaporative demand and crop coefficient, or yield prediction		Max Transpiration & Max Soil Evaporation according Ritchie (1972)	Supply and demand limited
Simulation of Total Evaporation	Simulate transpiration and evaporation separately or as an entity	Simulate transpiration and evaporation separately or as an entity			Simulates transpiration and evaporation separately	Simulates transpiration and evaporation separately		Simulates transpiration and evaporation separately	Simulates transpiration and evaporation separately	Simulates transpiration and evaporation separately
Availability	Yes	Code not available	Yes	Yes	Older Versions	Yes	Contact Developer	Yes	Yes	Yes
References	Schulze (1995)	Kiker (1998)	Bennie *et al*. 1997 Bennie et al. (1998)	Domleo (1988) Walker (1994)	De Jager *et al*. 1983 Domleo (1988) Walker (1994)	Crosby and Crosby (1999)	Bennie *et al*. 1997 Bennie et al. (1998)	Van Dam et al., 1997	Neitsch *et al*. 2001	Annandale *et al*. 1999

2.5.2 Description of selected models

2.5.2.1 The Agrohydrological Modelling System (*ACRU*)

The *ACRU* agrohydrological model (Schulze, 1995) is a multi-purpose, daily time step, conceptual-physical model. It contains a multi-layer, daily soil water budgeting routine. *ACRU* outputs total evaporation, daily stormflow and baseflow contributions, sediment yield, reservoir yield, irrigation supply and demand. The *ACRU* model was originally developed in the early 1980s for studies of land-use change and water resource assessment, and has subsequently undergone continuous development and enhancement. It is well suited for use in southern Africa, with links to appropriate local land-use, soil and climate databases.

ACRU can operate in lumped mode for smaller catchments or as a distributed cell-type model for areas with more complex land uses or soils. Individually requested outputs for each sub-catchment (which may be different to those of other sub-catchments) or outputs with different levels of information, may be generated. A schematic of the manner in which multi-layer soil water budgeting occurs in *ACRU* is depicted in Figure 4 (Schulze, 1995).

ACRU also includes a dynamic input option to facilitate modelling of hydrological responses to climate or land-use changes in a time series. These may be long-term or gradual changes (e.g. forest growth, urbanisation or climatic trends) or abrupt changes (e.g. clear felling, fire impacts or construction of a dam). *ACRU* also operates in conjunction with interactive *ACRU* Utilities (Smithers and Schulze, 1995). These comprise a suite of software tools to aid in the preparation of input and output information. E.g. the *Menubuilder* compiles catchment menus for *ACRU* application, the program *CALC_PPTCOR* facilitates selection of appropriate rainfall stations, the decision support system *AUTOSOILS* (Pike and Schulze, 1995) extracts appropriate relevant soil characteristics and the *Outputbuilder* selects the relevant output variables for graphical or statistical analysis. The components of the *ACRU* system are displayed in Figure 5 (Schulze, 1995). The version of the model used in this study was *ACRU 331*.

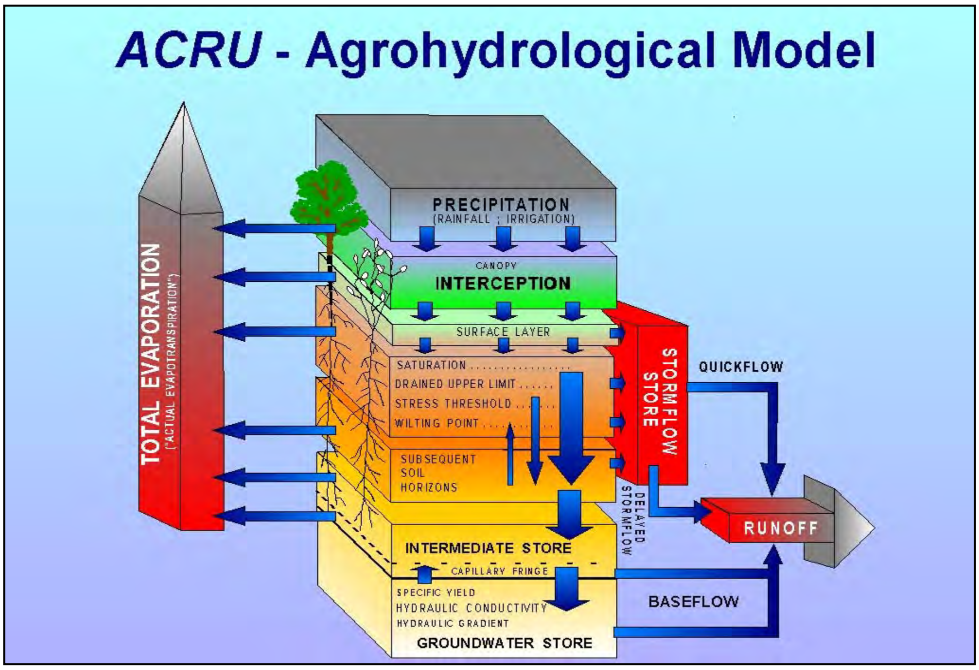


Figure 4 Structure of the multi-layered soil water budgeting system applied in *ACRU*, the agrohydrological modelling system (after Schulze, 1995)

Streamflow components generated by the *ACRU* model comprise of baseflow and stormflow, the latter from both pervious and impervious areas. Stormflow from pervious areas consists of a quickflow response that is released into the stream on the same day as the rainfall event, and a delayed stormflow response which represents a surrogate for post-storm interflow. Baseflow is derived from the groundwater store that is recharged by drainage out of the lower active soil horizon when its water content exceeds the drained upper limit. The estimation of stormflow depth is based on modifications to the equation derived by the Soil Conservation Services (United States Department of Agriculture, 1985) and Schmidt and Schulze (1987).

Evaporation takes place from previously intercepted water and simultaneously from the various soil horizons. It is either split into separate components of soil water evaporation (from the topsoil only) and plant transpiration (from all horizons in the root zone), or else combined as a total evaporation or actual evapotranspiration. Soil evaporation for a day can either occur at a maximum rate (if a minimum threshold of soil water content is exceeded), or below the maximum rate once the soil water content has dropped below this threshold. In the latter case, soil evaporation declines very rapidly over time. Plant roots absorb soil water in proportion to the distributions of root mass density in the respective horizons, except when conditions of low soil water content prevail. In such cases the relatively wetter soil horizons provide higher proportions of soil water to the plant in order to obviate plant stress as long as possible.

Vegetation or plant water use is estimated according to atmospheric demand (calculated from a reference potential evaporation), and crop coefficients representing the growth stage of the vegetation. The daily A-pan equivalent is the reference potential evaporation in *ACRU*. However, there are many options available in *ACRU* for estimating reference potential evaporation. These include daily A-pan evaporation, Symon's tank evaporation, gridded monthly A-pan equivalent evaporation, Penman's equation, and temperature based equations such as Linarce, Hargreaves and Samani, Blaney and Criddle, and Thornthwaite.

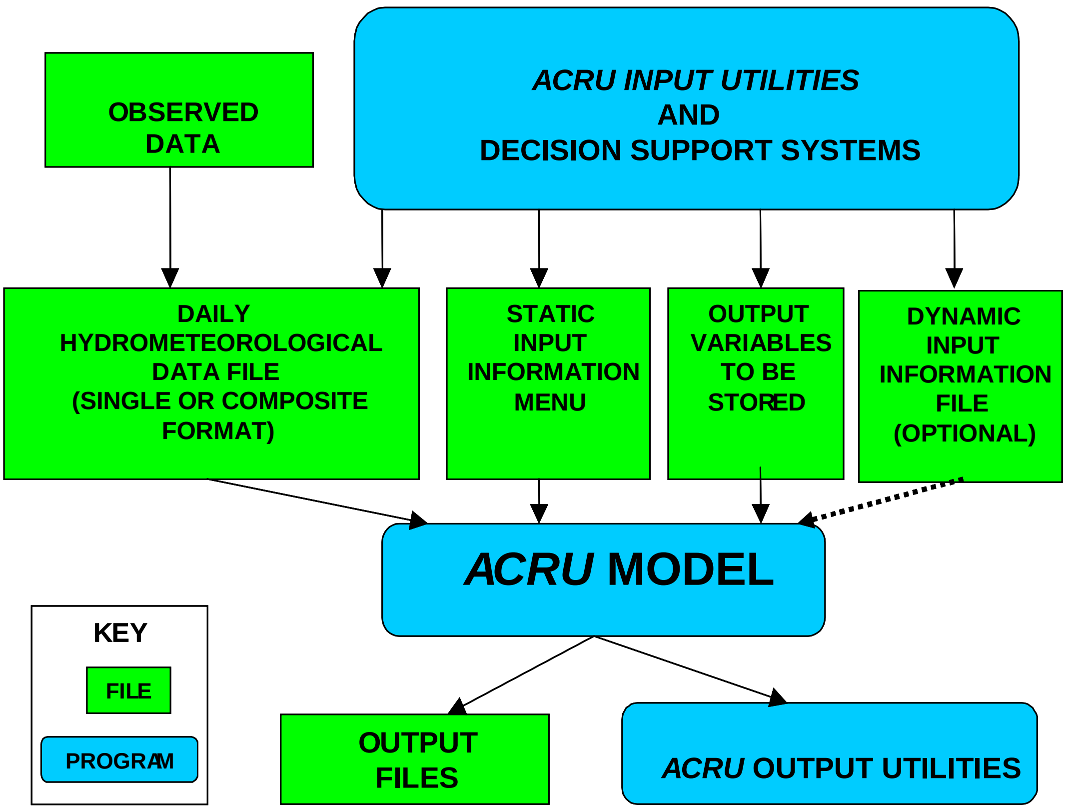


Figure 5 Relationship between the different inputs and outputs associated with the *ACRU* modelling system (after Schulze, 1995)

Crop coefficients are defined as the ratio of maximum evaporation from a plant at a given stage of plant growth to a reference potential evaporation. “Maximum” is used to describe the evaporation taking place under well-watered conditions when the effects of soil water shortages are negligible. Monthly crop coefficients are disaggregated into daily values according to Fourier analysis. Depending on the soil water content of each soil horizon, a stress index is applied to the crop coefficient. E.g. if the contents of both upper and lower soil horizons fall below 40 % of plant available water (PAW), plant stress is assumed to occur and the crop coefficient is reduced by a stress index. In *ACRU*, thermal time-crop coefficient relationships have been derived for maize and sugarcane (Schulze, 1995).

Two options are available for calculating maximum transpiration within *ACRU* and depend on whether leaf area index values or only crop coefficients are available. Maximum transpiration rates from crop coefficients are determined according to the following rules and assumptions:

1. When the plant surface has a complete canopy cover and maximum ground shading effects prevail, maximum evaporation comprises of 95 % transpiration and of 5 % soil water evaporation.
2. When no canopy cover exists, no transpiration takes place and maximum evaporation comprises entirely of soil water evaporation.
3. The daily crop coefficient (K_d) is used to determine the extent of canopy cover and full canopy is assumed when K_d is unity and no canopy cover when K_d is less than 0.2.

2.5.2.2 The Soil and Water Assessment Tool (*SWAT*)

The Soil and Water Assessment Tool (*SWAT*), developed at the Blackland Research Centre in Texas for the USDA Agricultural Research Service, is one of the few models which have been seamlessly integrated into the geographic information systems (GIS) environment. *SWAT* is also updated with recent advances in GIS. Some of its key strengths lie in the ability to predict the relative impacts of changes in management practices, climate and vegetation on water quantity and quality. Full details of the model are given in Arnold *et al*. (1999) and Neitsch et al. (2001). A brief outline of the concepts and general structure of *SWAT* are given below.

SWAT runs on a daily time step and was developed to simulate the long-term impacts of land and water management (e.g. reservoir sedimentation over several years) or agricultural practices (e.g. crop rotation, planting and harvesting dates and irrigation) on the water quantity and quality. *SWAT* is physically based and is computationally efficient to operate on catchments of varying sizes within reasonable time. Upland and channel processes simulated in a catchment include the hydrology, soil temperature, sedimentation, crop or plant growth, nutrient and pesticide loadings, and agricultural management. Figure 6 illustrates the hydrological balance applied in *SWAT*.

SWAT requires both spatial and non-spatial inputs. The model may simulate a catchment in lumped or distributed mode, by automatically delineating the catchment either into sub-catchments or hundreds of grid cells based on a Digital Elevation Model (DEM). The use of sub-catchments in a simulation is particularly beneficial to differentiate the impact of various land-uses and soils on the hydrology of a catchment.

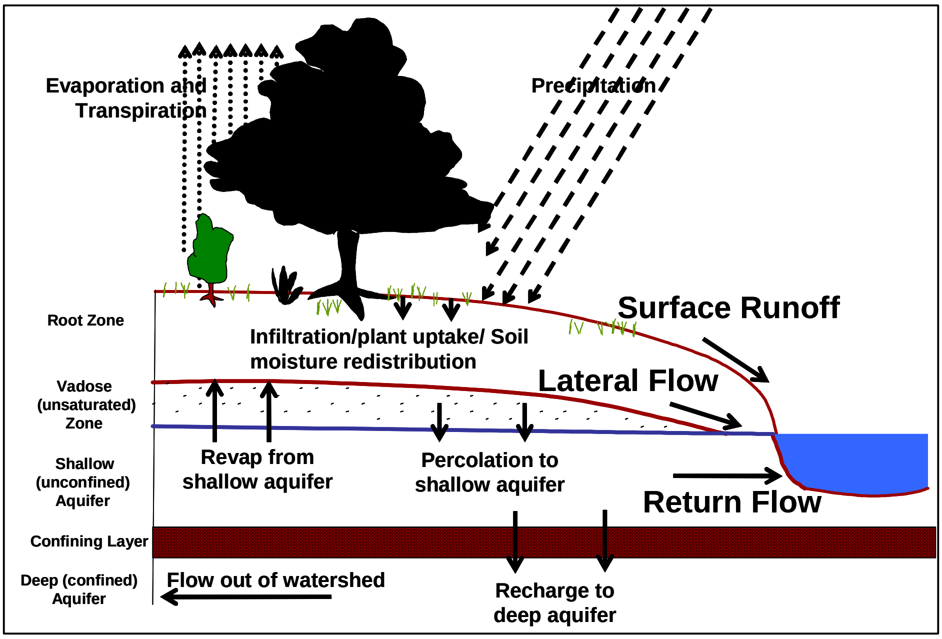


Figure 6 Schematic representation of the hydrological cycle considered in *SWAT*

The development of the model as an extension to Arcview has increased the flexibility of *SWAT*. Special features of Arcview are available to *SWAT* model users. The use of GIS minimizes the time involved to manually enter or manipulate the amount of input data required to describe the spatial detail of the watershed. It also minimizes human error and inconsistencies in distinguishing landscape characteristics across a watershed that would otherwise be collected by conventional methods.

Other basic data requirements include a spatial coverage for landcover and soil types, daily precipitation, and daily maximum and minimum air temperature. *SWAT 2000* has options to utilize measured solar irradiance, wind speed, relative humidity and evaporation data on a daily time step. Daily rainfall and air temperature data may be generated from statistical data in the weather generator file, if unavailable or missing for the simulation period. *SWAT* includes a number of storage databases, which may be customized for an individual catchment. These include databases for soils, landcover or plant growth, weather stations, pesticide applications, tillage practices, fertilization and urbanization.

SWAT applies three methods of estimating potential evapotranspiration (PET): the Penman-Monteith method (Monteith, 1965; Allen, 1986; Allen *et al*., 1989), the Priestley-Taylor method (Priestley and Taylor, 1972) and the Hargreaves method (Hargreaves and Samani, 1985). The potential evapotranspiration (Eq. 2) is calculated as:

$$E_o = \frac{\dfrac{\delta\ (h_o - G) + 86.7\ AD\ (e_a - e_d)}{AR}}{(HV)(\delta + \gamma)} \qquad 2$$

where δ is slope of the saturation vapour pressure curve (kPa °C^{-1}), h_o net radiation (MJ m^{-2}), G is the soil heat flux (MJ m^{-2}), AD the air density in g m^{-3}, e_a saturated vapour pressure at mean air temperature (kPa), e_d actual vapour pressure at mean air temperature (kPa), AR aerodynamic resistance for heat and vapour transfer in s m^{-1}, HV the latent heat of vaporization in MJ kg^{-1} and γ the psychrometer constant (kPa °C^{-1}).

SWAT also allows inputs of daily PET, calculated from a different potential evapotranspiration method. The three PET methods included in *SWAT* vary in the amount of required inputs. The most accurate estimates of evapotranspiration are obtained with the Penman-Monteith equation when calculated on an hourly basis and summed to obtain daily values. However, mean daily climatic input data have been shown to provide reliable estimates of daily evapotranspiration and this is generally the approach used in *SWAT*. However, calculating evapotranspiration with the Penman-Monteith equation using mean daily values does not account for the diurnal distributions of wind speed, humidity and net irradiance. Evapotranspiration based on daily average climatic conditions do not replicate that based on a combination of hourly climatic data.

Once total potential evapotranspiration is determined, actual evaporation is calculated. *SWAT* first evaporates any rainfall intercepted by the plant canopy and thereafter the maximum amount of transpiration and soil evaporation using an approach similar to that of Ritchie (1972). The actual amount of sublimation and evaporation from the soil is then calculated. Any free water present in the canopy is readily available for removal by evapotranspiration. The amount of actual evapotranspiration contributed by intercepted rainfall is especially significant in forests where in some instances evaporation of intercepted rainfall is greater than transpiration. *SWAT* removes as much water as possible from canopy storage when calculating actual evapotranspiration.

SWAT uses a single growth model for simulating growth of all crops. This growth model is based on a simplification of the EPIC crop growth model (Williams et al., 1984). Phenological development of the crop is based on daily heat unit accumulation, with the growing seasons being defined by date or accumulated heat units. Each degree of the daily mean temperature above the base temperature is one heat unit. This method assumes that the rate of growth is directly proportional to the increase in temperature. *SWAT* assumes that all heat above the base temperature accelerates crop growth and development. *SWAT* allows management operations to be scheduled by day or by fraction of potential heat units. Plant growth is modelled by simulating leaf area development, light interception and conversion of intercepted light into biomass, assuming a plant species-specific radiation use efficiency.

2.5.2.3 The Soil Water Atmosphere and Plant Model (*SWAP*)

SWAP, the Soil Water Atmosphere Plant model, simulates the hydrological processes at a field scale on a daily time step (Figure 7). The water flow and solute transport processes in the vadoze zone, are influenced by plant growth during the season. Van Dam *et al*. (1997) and Van Dam (2000) describe the processes applied in *SWAP* in detail. These processes include: soil water flow, solute transport, soil heat flow, daily evapotranspiration, crop growth, field irrigation and drainage, surface water and multi-level drainage at a sub-regional scale and discharge in a regional system.

SWAP uses a two-step approach to estimate potential evapotranspiraiton. Firstly, the potential evapotranspiration[v] is estimated with the Penman-Monteith equation on a daily time step. Secondly, the actual evapotranspiration is calculated and includes the reduction of the rootwater uptake due to water and salt stress. The Penman-Monteith equation is used to calculate the:

- potential evapotranspiration of a wet canopy completely covering the soil (ET_{w0});
- potential evapotranspiration of a dry canopy completely covering the soil (ET_{p0}); and
- potential evaporation of a wet bare soil (E_{p0}).

SWAP also allows for the calculation of reference potential evapotranspiration (ET_{ref}) using methods other than the Penman-Monteith method. This reference evapotranspiration is converted into potential evapotranspiration for a dry canopy using a canopy factor (k_c). Here, however, *SWAP* equates the potential evapotranspiration for a dry crop, wet crop or wet soil. *SWAP* assumes that the potential evapotranspiration of a wet (ET_{w0}) and a dry (ET_{p0}) canopy completely covering the soil is equal, and that the potential evaporation of a wet, bare soil (E_{p0}) is equal to the potential evapotranspiration of a dry canopy completely covering the soil.

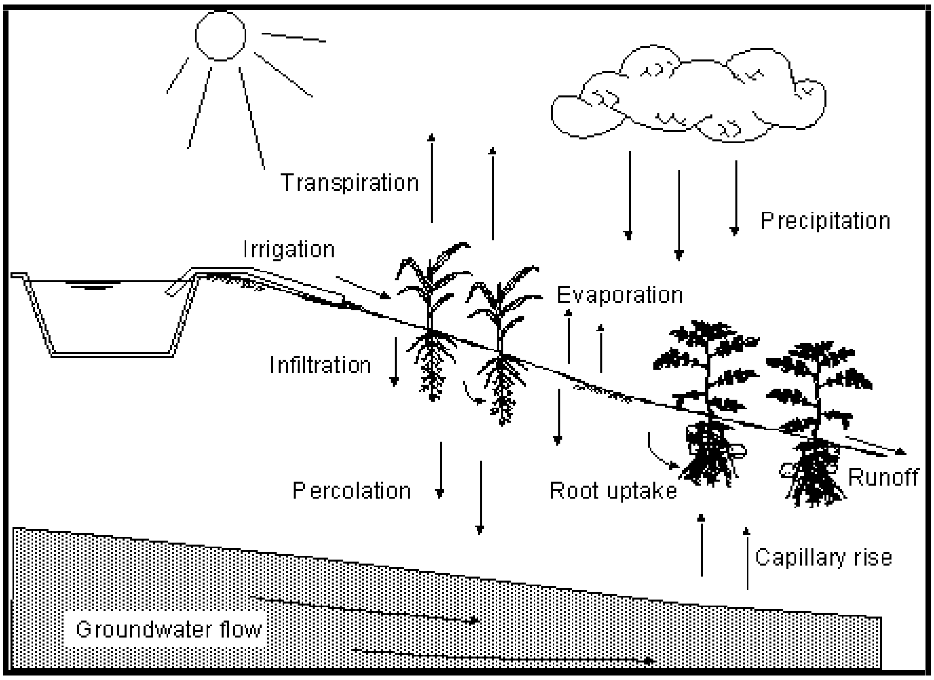


Figure 7 Processes considered in the *SWAP* model (*SWAP*, undated)

SWAP separates potential evapotranspiration into evaporation and transpiration, and uses a physically-based approach to estimate the reduction in the potential transpiration and the potential evaporation. The daily total potential evapotranspiration (ET_p) (Eq. 3) is given by:

$$ET_p = \frac{\frac{\Delta_v}{\lambda_w}(R_n - G) + \frac{p_1\,\rho_{air}\,C_{air}\,(e_{sat} - e_a)}{\lambda_w\,r_{air}}}{\Delta_v + \gamma_{air}\left(1 + \frac{r_{crop}}{r_{air}}\right)} \qquad 3$$

where Δ_v is the slope of the vapour pressure curve (kPa K^{-1}), λ_w is the latent heat of vaporization in J kg^{-1}, R_n is the net irradiance in J m^{-2} d^{-1}, G is the soil heat flux in J m^{-2} d^{-1}, p_1 accounts for unit conversion (86400 s d^{-1}), ρ_{air} is the density of air in kg m^{-3}, C_{air} is the specific heat capacity of moist air (J kg^{-1} K^{-1}), e_{sat} and e_a the saturated and actual vapour pressures respectively in kPa, r_{air} is the aerodynamic resistance in s m^{-1}, γ_{air} is the psychrometric constant in kPa K^{-1} and r_{crop} is the canopy resistance in s m^{-1}.

The potential evapotranspiration is partitioned into evaporation and transpiration using either the leaf area index or the soil cover fraction as a function of the crop development stage.

The potential soil evaporation under a crop is calculated using the Penman-Monteith equation, neglecting the aerodynamic term. Neglecting the soil heat flux density, and assuming an exponential decrease in net irradiance below the crop, this potential evaporation (E_p) is given as a function of the leaf area index (*LAI*) as given by Ritchie (1972).

The soil evaporation of a wet soil equals the potential soil evaporation (E_p) and is determined by the atmospheric demand. For a drying soil, with a decreasing hydraulic conductivity, the potential soil evaporation is reduced to actual soil evaporation. The actual soil evaporation is determined as the minimum of the potential soil evaporation (E_p), the maximum evaporation according to Darcy's equation (E_{max}), or the actual soil evaporation calculated using an empirical function (E_a) of Black (1969) or Boesten and Stroosnijder (1986) (cited by Van Dam et al., 1997).

The maximum root water extraction rate over the rooting depth is equal to the potential transpiration rate (T_p). The potential root water extraction rate (S_p) at a certain soil depth (z) is calculated as a function of root length density, rooting depth, and water or salinity stresses.

SWAP contains three crop growth routines: a detailed crop growth model (WOFOST), a detailed grass growth model (modified WOFOST) and a simple crop growth model. The simple crop growth model is applied when crop growth simulations are not required, or when insufficient data exists. The simple model is based on a big leaf (green canopy) that intercepts rainfall, transpires and covers the ground. Inputs to this model include leaf area index or soil cover fraction, crop height, and rooting depth as a function of development stage. The development stage can be linear or a function of the air temperature sum. This simple crop growth model can simulate up to three crops per year, and does not calculate the crop potential or actual yield.

SWAP utilizes a general formula for canopy interception proposed by Von Hoyningen-Hüne (1983) and Braden (1985) (cited by Van Dam *et al*., 1997 and Van Dam, 2000). This equation relates the intercepted precipitation (P_i), the leaf area index (*LAI*), the gross precipitation (P_{gross}), an empirical coefficient (*a*), and the soil cover fraction (*SC*).

2.5.3 Parameterisation of models

The three selected models, *ACRU*, *SWAT* and *SWAP*, were parameterised for the three natural veld types: Moist Upland Grassland, Valley Thicket and Coastal Bushveld/Grassland sites. Each model was parameterised for all three sites (veld types) for a period which overlapped with the Bowen ratio total evaporation measurements (See Section 2.2). A description of the parameters used in *ACRU*, *SWAT* and *SWAP* are given in Appendix I, II and III respectively.

CHAPTER 3

RESULTS AND DISCUSSION: FIELD MEASUREMENTS OF TOTAL EVAPORATION AND OTHER PARAMETERS

3.1 Introduction

In this study the seasonal changes in the climatic conditions, reference evaporation, leaf area index, canopy height and profile soil water content were measured to complement the total evaporation measured at the Valley Thicket and a Coastal Bushveld/Grassland sites. This additional information aided our interpretation of the total evaporation measured.

3.2 Total evaporation of a Valley Thicket site

The total evaporation, climatic and growth data collected at the Valley Thicket site during the field experiment are presented below. This includes data for the period April 2002 to February 2003 for which total evaporation data was available. The seasonal changes in the total evaporation (Figure 8) of the Valley Thicket site were related to (a) seasonal changes in the climatic conditions (Figure 9) and reference evaporation (Figure 8), (b) seasonal changes in the profile soil water content and the soil water content of the individual soil layers (Figure 10) and the (c) seasonal changes in the leaf area index and canopy height (Figure 11).

Minimum total evaporation rates at the Valley Thicket site were measured during autumn and winter (May to July 2002) (Figure 8). During autumn and winter 2002, the total evaporation ranged between 1.2 and 2.1 mm d^{-1} on sunny days. The minimum total evaporation rates coincided with minimum daily air temperatures (12.1 to 13.3 °C), minimum daily solar radiant densities (14.1 to 16.5 MJ m^{-2}), minimum monthly total rainfall (0.2 to 29.4 mm) and minimum canopy height and leaf area index (0.88) (Figures 8, 11 and 12). These minimum total evaporation rates were also similar to the reference evaporation rates (Figure 8).

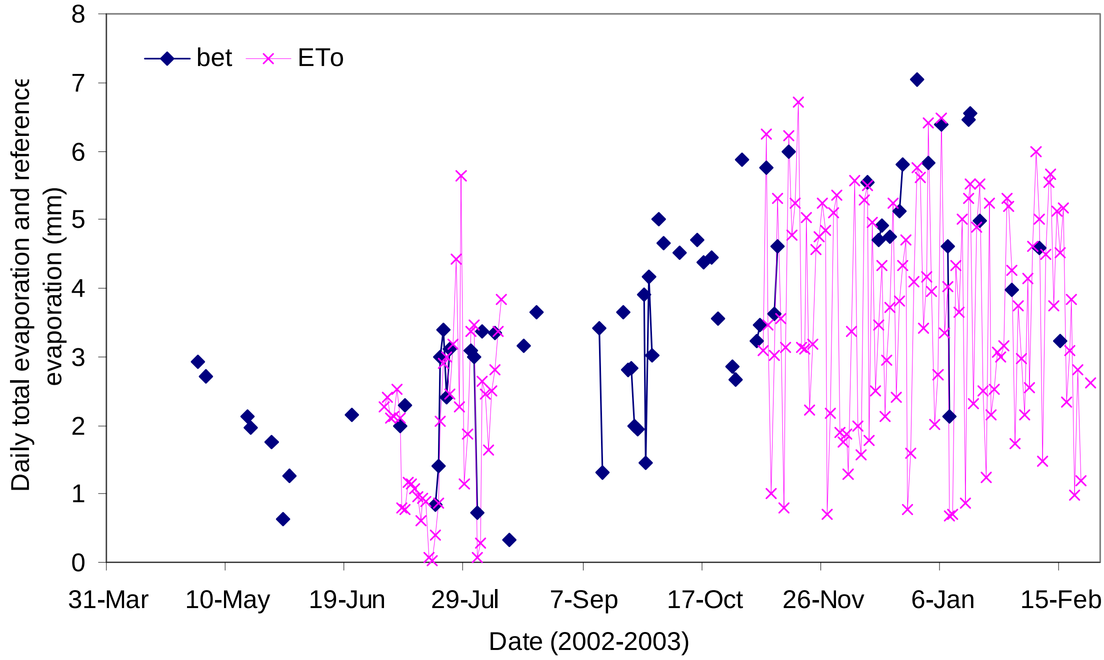


Figure 8 Daily total evaporation (bet) for a Valley Thicket site compared to reference evaporation (ETo) for the period April 2002 to February 2003

During autumn and winter, the daily energy fluxes (Figure 13) at the Valley Thicket site showed that most of the net irradiance (and available energy) was partitioned into the latent heat flux density, i.e. most of the net irradiance was used to drive evaporation. The similarity in the total evaporation and reference evaporation rates suggests that the Valley Thicket vegetation at this site was not experiencing any significant soil water stress during winter 2002, and that the Valley Thicket vegetation had access to soil water to drive evaporation. It further suggests that the total evaporation of the Valley Thicket during winter 2002 was possibly governed mainly by the dominant tree clusters, as most of the grass species have reached senescence. The winter 2002 total evaporation therefore represents mainly transpiration from the tree (bush) component of this vegetation type.

Following the rainfall events from June to August 2002 (101.7 mm in total), the total evaporation increased from ± 2.1 mm d^{-1} (June 2002) to 3.6 mm d^{-1} (August 2002) (Figures 8 and 12). The increase in total evaporation was the result of the increased availability of soil water following the rainfall, and the slight increase in daily average air temperature (14.1 to 16.5 °C) (Figure 9 and 12). The daily total reference evaporation during this period ranged between 2.1 and 3.8 mm d^{-1} and was still very similar to the actual total evaporation (Figures 8). The similar evaporation rates suggest little or no soil water stress experienced by the Valley Thicket vegetation, even towards the end of winter 2002.

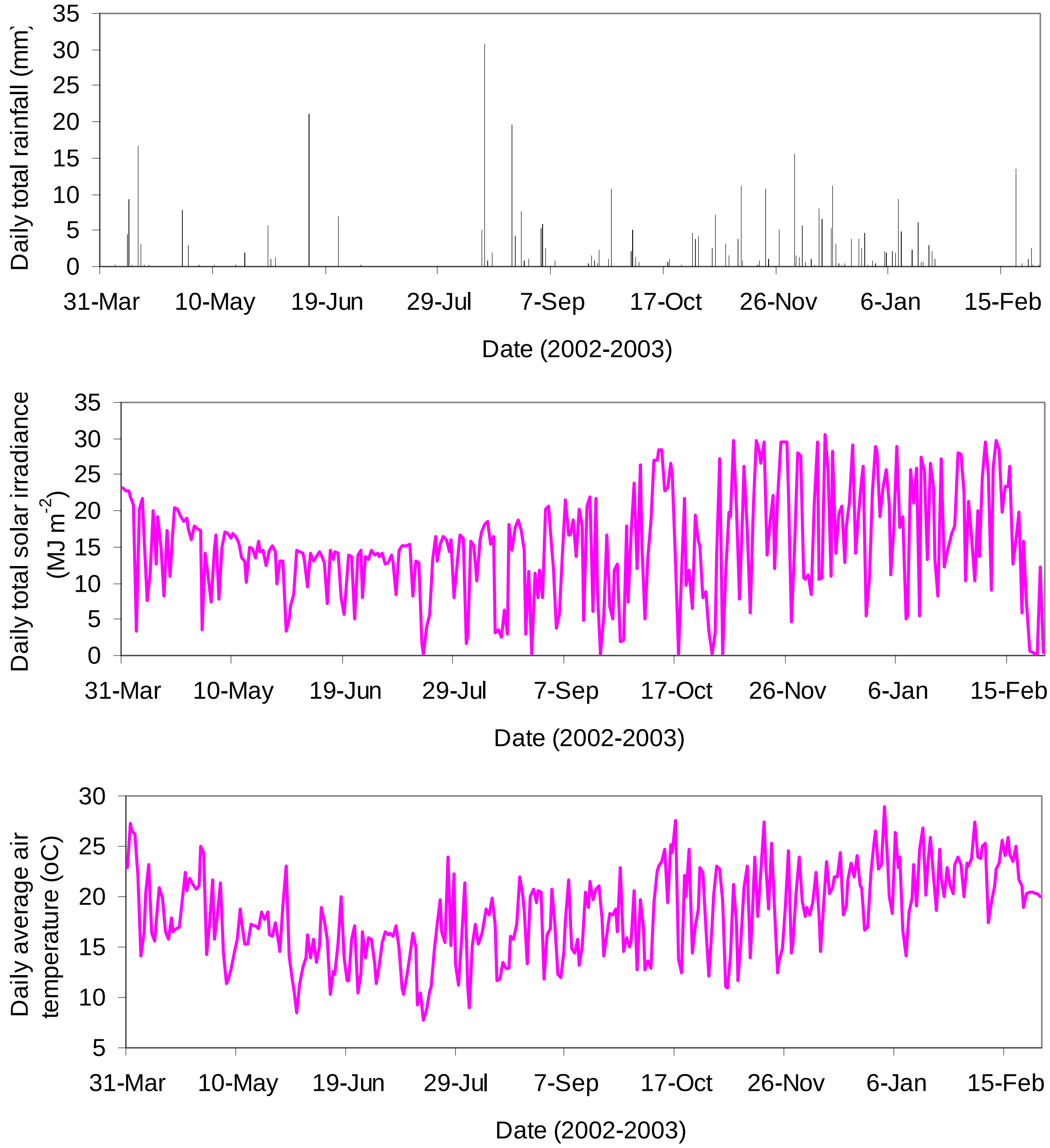
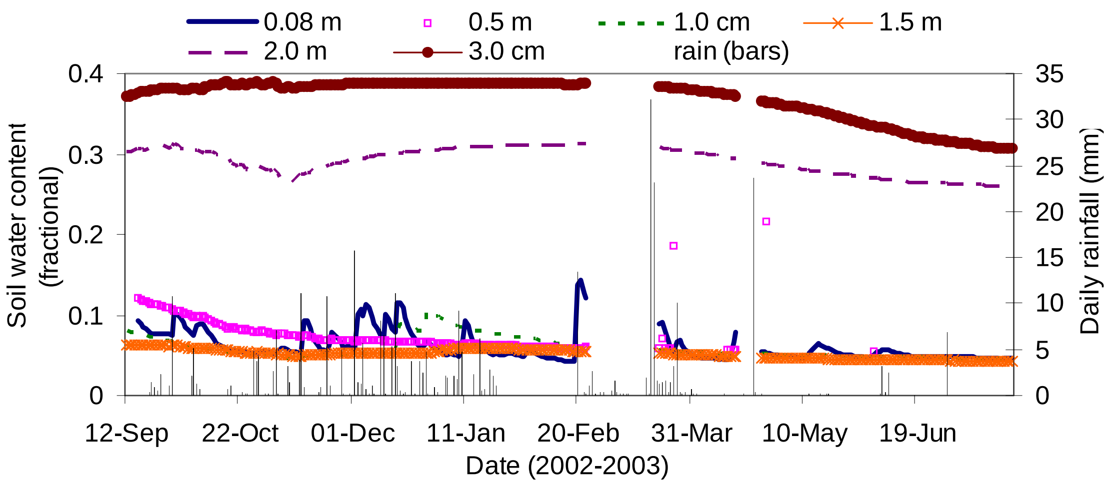


Figure 9 Seasonal changes in the climatic conditions monitored at the Valley Thicket site for the period April 2002 to February 2003. From top to bottom: Daily total rainfall, daily total solar radiant density and daily average air temperature

The increasing trend in the total evaporation continued from winter 2002 to summer 2002/2003. Towards summer 2002/2003, maximum and similar total evaporation and reference evaporation rates, exceeding 6 mm d^{-1}, were reached (December 2002 and January 2003). The Valley Thicket vegetation was possibly transpiring at potential rates. The maximum total evaporation rates during this period again coincided with maximum monthly rainfall (89.2 mm mth^{-1}), maximum monthly average daily total solar radiant density (19.3 MJ m^{-2}), maximum profile soil water content (652 mm), maximum leaf area index (2.19) and canopy height (1.6 and 6.8 m for the grass and tree clusters respectively) (Figures 8 to 12). At this time (summer 2002/2003), the energy balance of the Valley Thicket vegetation reflected the high total evaporation rates. Most of the net irradiance was partitioned into latent heat flux density (Figure 14).



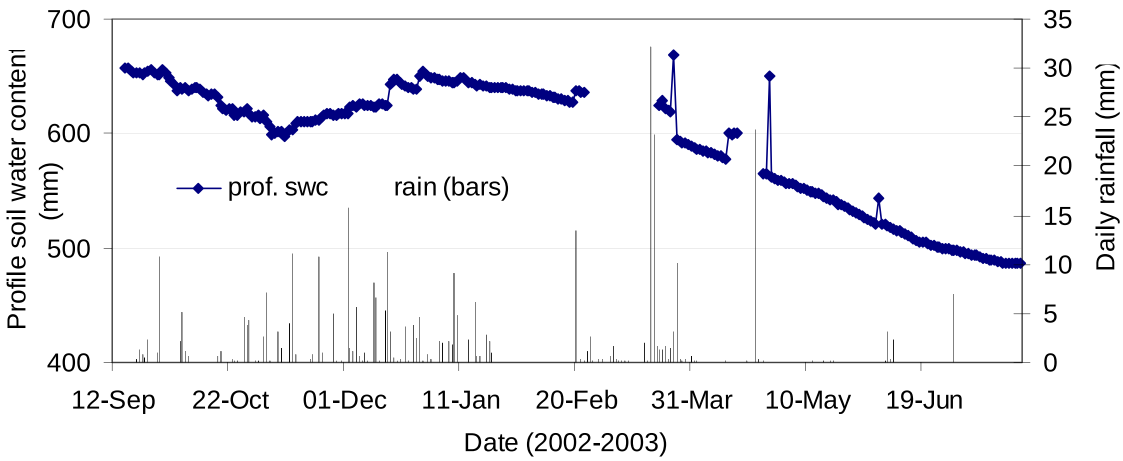


Figure 10 Top: Seasonal changes in the soil water content (expressed as a fraction) of the individual soil layers (0.08, 0.5, 1.0, 1.5, 2.0 and 3.0 m below the soil surface) at the Valley Thicket site, and Bottom: Seasonal changes in the profile soil water content for the period September 2002 to July 2003. Gaps in the data set present data lost due to power problems

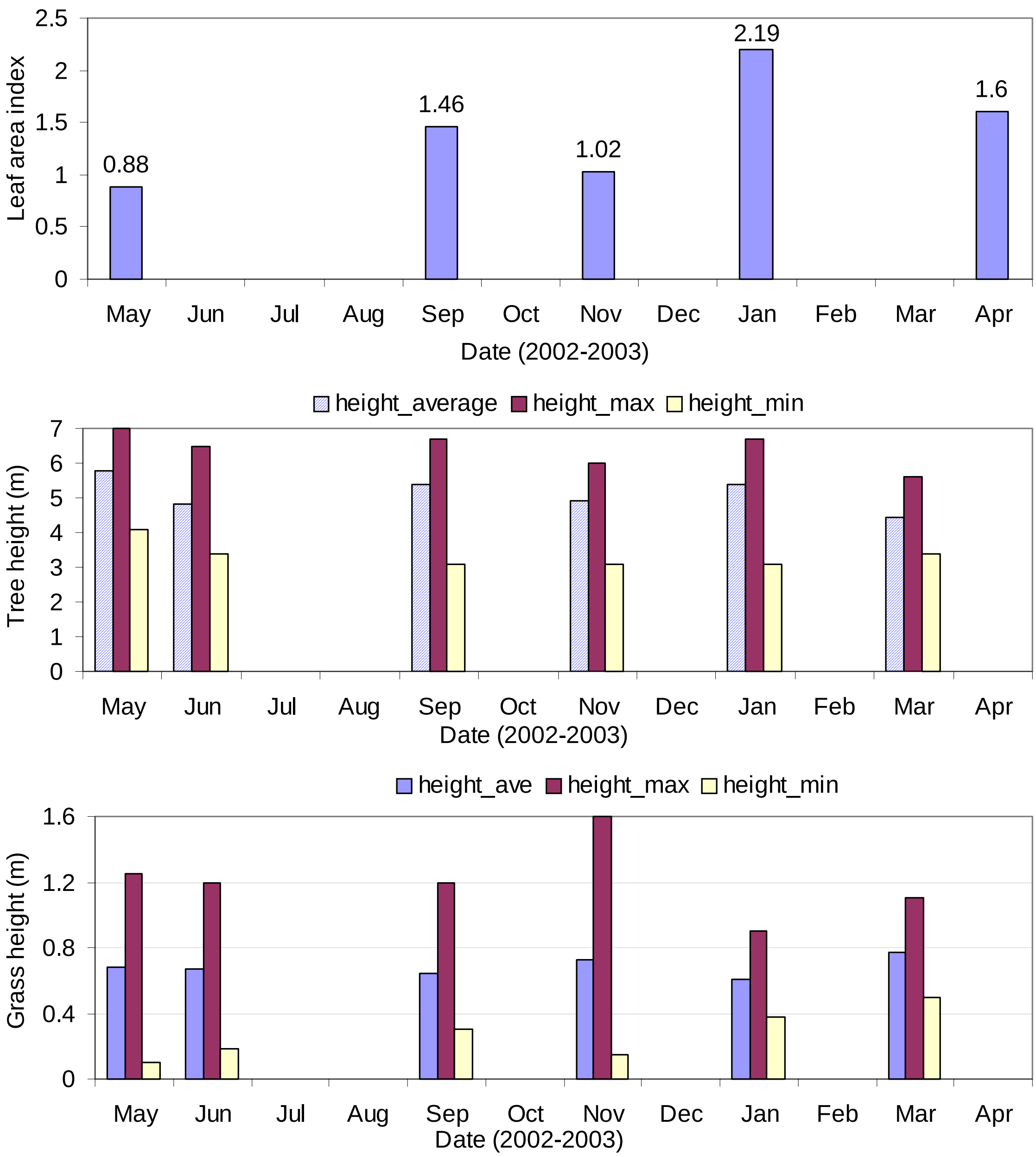


Figure 11 From top to bottom: Seasonal changes in the leaf area index and canopy height (grass and tree clusters shown separately) at the Valley Thicket site for the period May 2002 to March 2003. height_ave, height_max and height_min refer to the average, maximum and minimum height

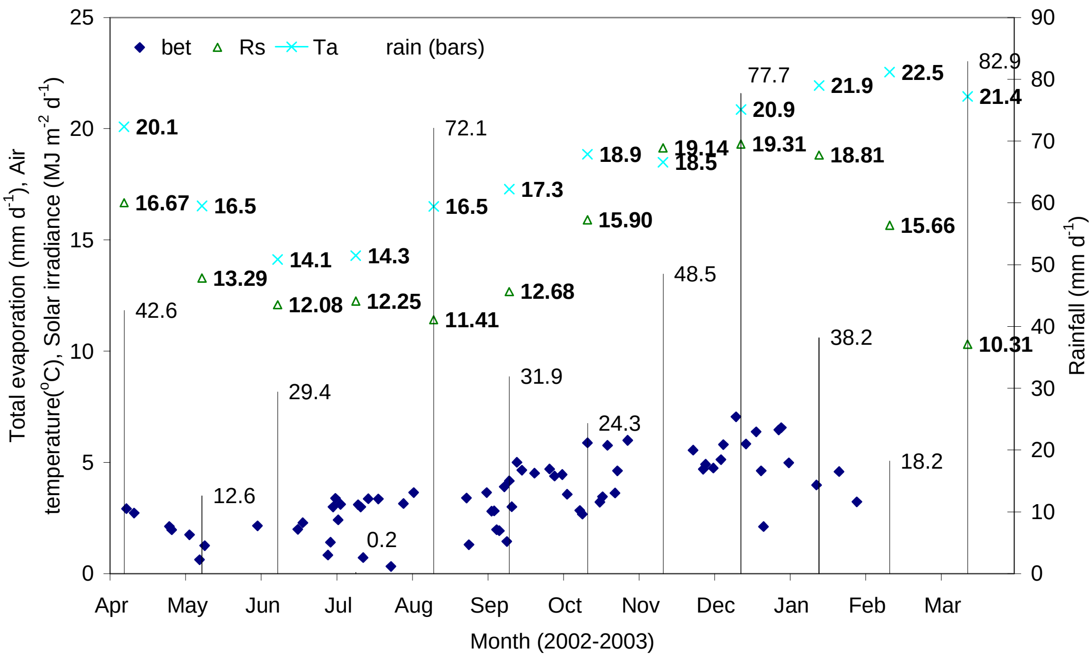


Figure 12 Daily total evaporation (bet), and monthly average solar radiant density (Rs), monthly average air temperature (Ta) and monthly total rainfall (bars) for the period April 2002 to March 2003

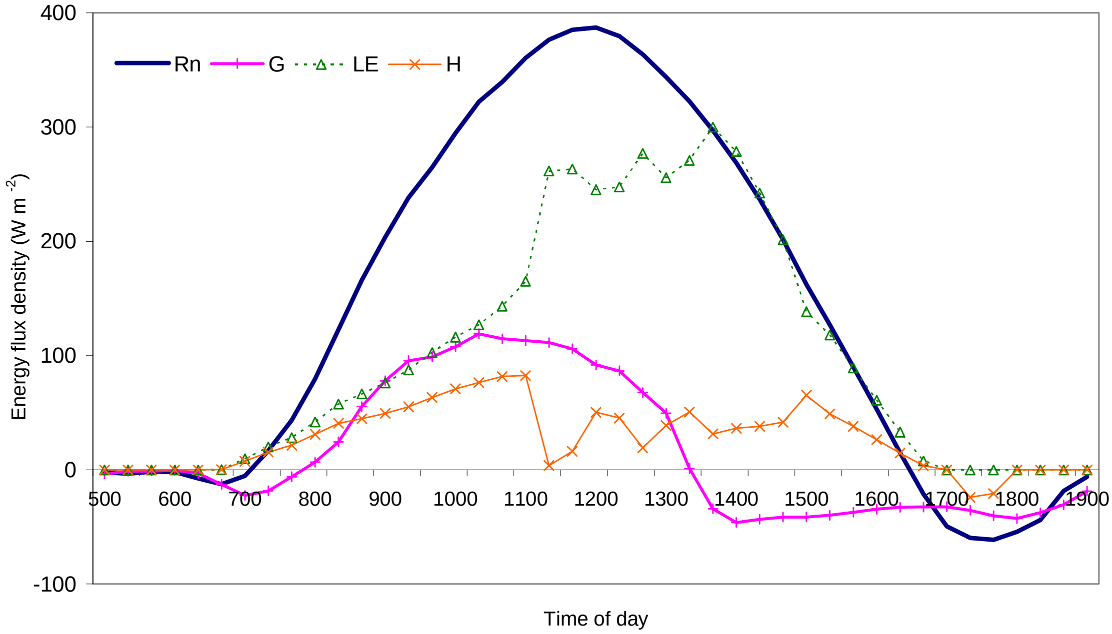


Figure 13 Energy flux densities at a Valley Thicket site as measured with the Bowen Ratio Energy Balance system on 18 May 2002, where Rn is the net irradiance, G the soil heat flux density, LE the latent heat flux density and H the sensible heat flux density

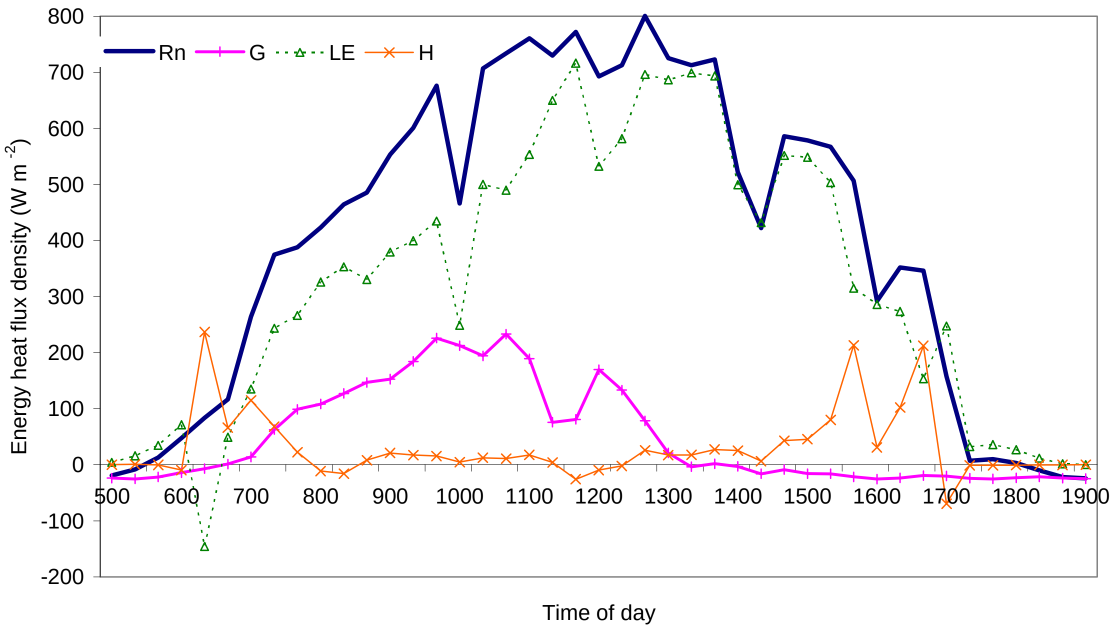


Figure 14 Energy flux densities at a Valley Thicket site as measured with the Bowen Ratio Energy Balance system on 29 December 2002, where Rn is the net irradiance, G the soil heat flux density, LE the latent heat flux density and H the sensible heat flux density

As no rainfall occurred between 21 January and 18 February 2003, the total evaporation decreased from maximum summer rates (> 6 mm d^{-1}) to total evaporation rates of ± 3.2 mm d^{-1} (Figures 8 and 12). This decrease in total evaporation suggests that the Valley Thicket was experiencing some level of soil water stress. This was further supported by the total evaporation rates being less than potential (reference evaporation) rates (Figure 8). During this 28-day period, the profile soil water content (over a 3 m soil depth) also showed a continual decrease, but by only 12 mm (or 0.4 mm d^{-1}) (Figure 10). Although no total evaporation data are available for the period following 18 February 2003, it is expected that the rainfall towards the end of February and during March 2003, would result in autumn 2003 evaporation rates similar to or lower than that measured at the end of summer 2003 (± 3.2 mm day^{-1}). The daily changes in the profile soil water contents over the upper 3 m, however, suggest lower total evaporation rates (if equivalent to profile soil water content changes) (Figure 10). The profile soil water content at the beginning of autumn 2003 (27 March to 13 April 2003) decreased by 16 mm or 0.9 mm d^{-1}. However, following a 24 mm rainfall event at the end of April 2003, the profile soil water depletion, increased to 1.2 mm d^{-1} (or 41 mm over 36 days).

3.3 Total evaporation of a Coastal Bushveld/Grassland site

The total evaporation and growth of the Coastal Bushveld/Grassland studied, and the climatic conditions experienced at the research site for the period June 2002 to May 2003, are presented below.

The limited total evaporation data set (Figure 15) for the Coastal Bushveld/Grassland site, shows that the total evaporation ranged between minimum rates of 2.6 and 3.6 mm d^{-1} during winter 2002 (June and July 2002) and maximum rates of 5 and 8.7 mm d^{-1} during summer 2002/2003 (December 2002 to February 2003) (Figure 15). The seasonal changes in total evaporation of Coastal Bushveld/Grassland can be attributed to (a) seasonal changes in the climatic conditions (Figure 16) and reference evaporation (Figure 15), (b) leaf area index and canopy height (Figure 17) and (c) the fractional soil water content of the individual soil layers (Figure 18) at the Coastal Bushveld/Grassland site.

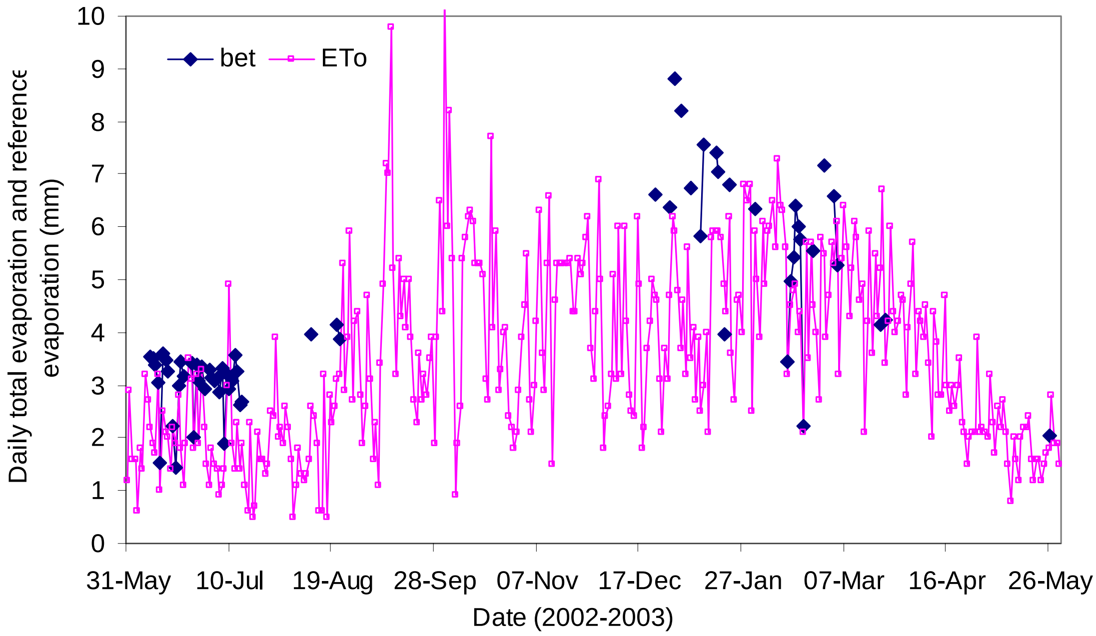


Figure 15 Total evaporation (bet) of a Coastal Bushveld/Grassland site and reference evaporation (ETo) for the period May 2002 to May 2003

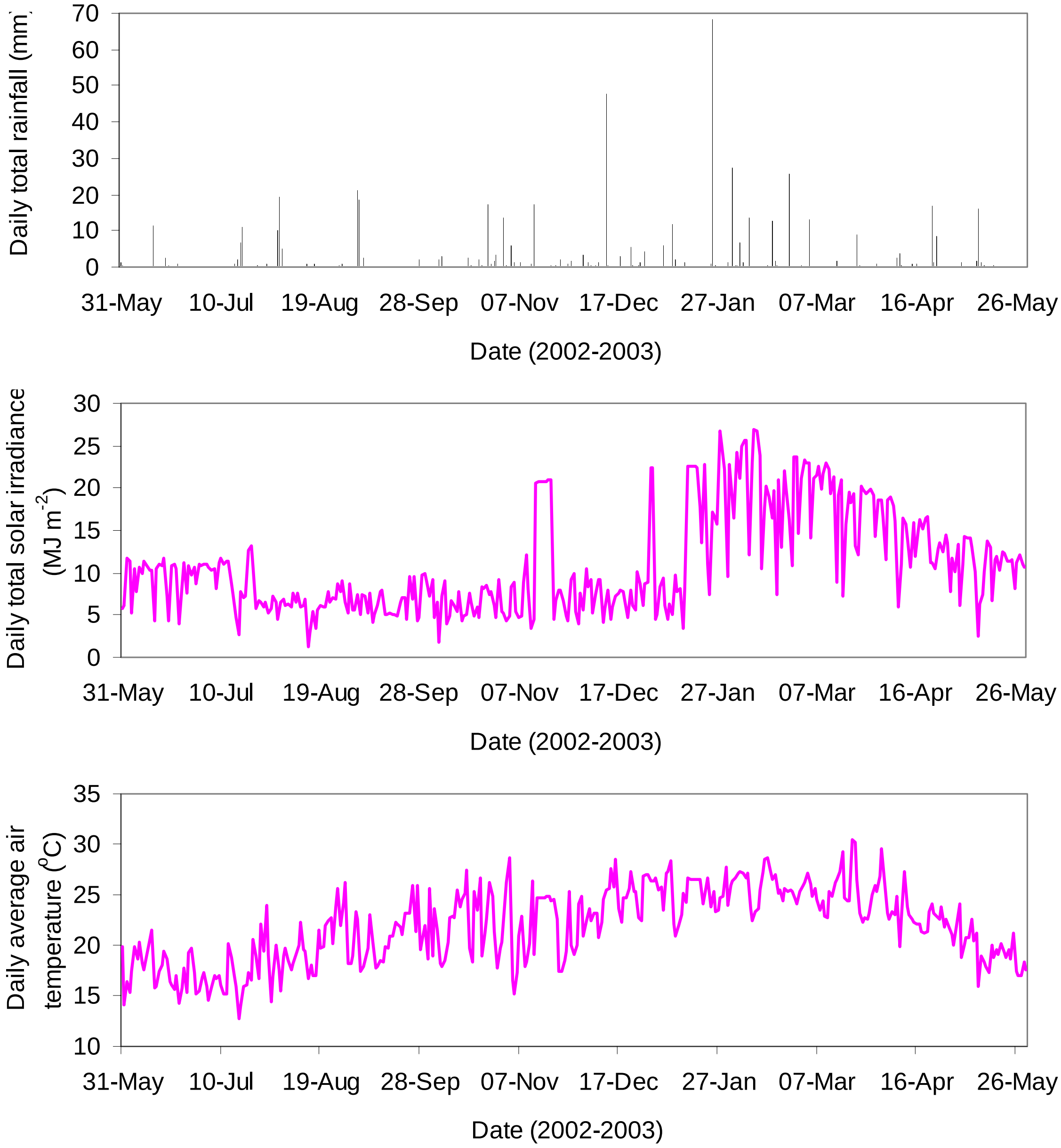


Figure 16 From top to bottom: Daily total rainfall, daily total solar radiant density and daily average air temperature for the period May 2002 to May 2003

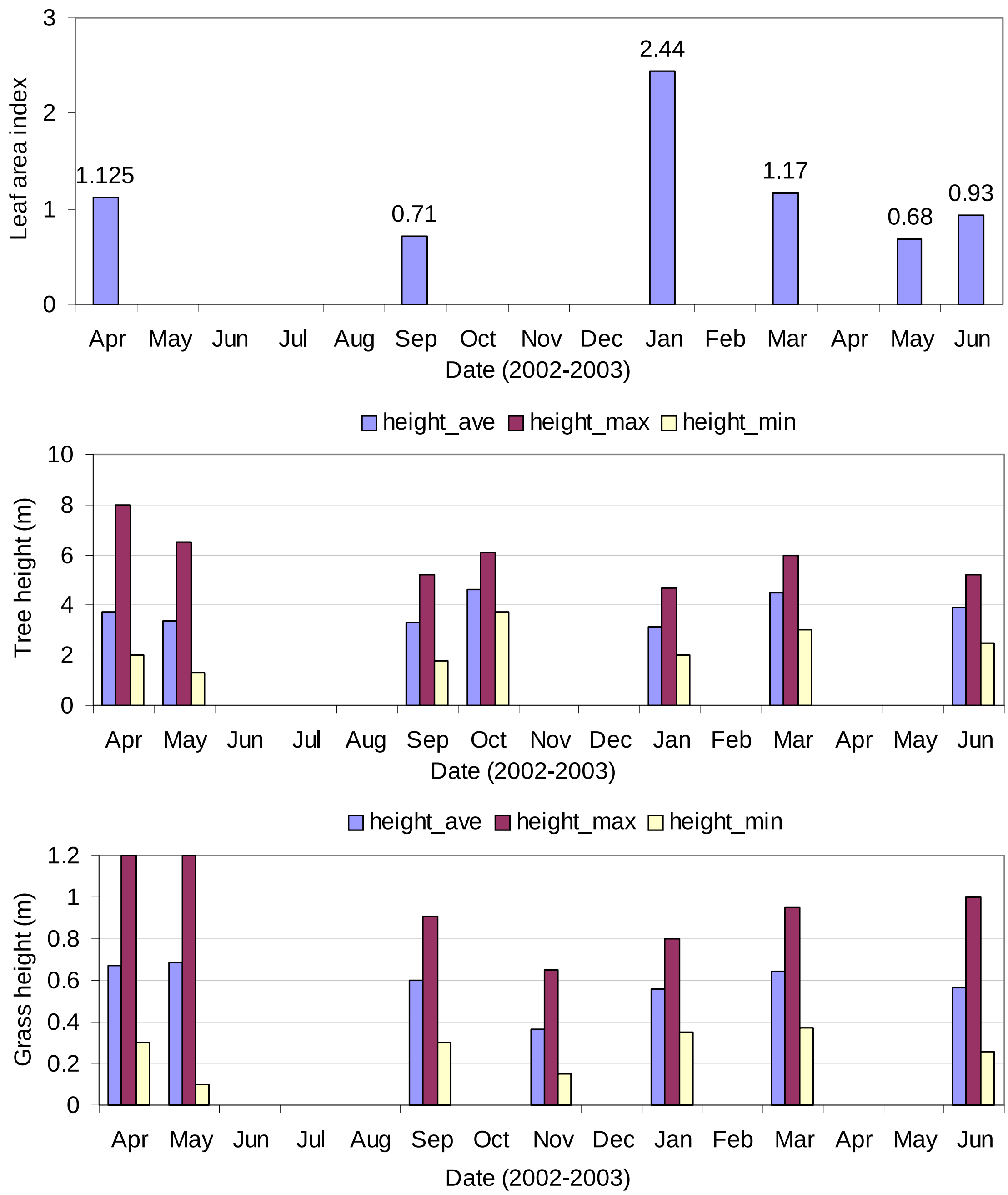


Figure 17 From the top to bottom: Leaf area index at a Coastal Bushveld/Grassland site, and canopy height of the grass and tree clusters – show separately – for the period May 2002 to June 2003. height_ave, height_max and height_min refer to the average, maximum and minimum heights

The minimum total evaporation rates at the Coastal Bushveld/Grassland site measured during winter 2002 (June and July 2002) reflect the low leaf area indices (0.71 to 1.25), monthly average air temperatures (17.0 to 17.6 °C), monthly average solar radiant density (8.8 to 9.2 MJ m^{-2}) and monthly total rainfall (16.7 and 22.1 mm respectively) (Figures 15, 17 and 19) measured during winter 2002. During winter 2002 (June and July 2002), the total evaporation at the Coastal Bushveld/Grassland site, was similar to or slightly exceeded the reference evaporation calculated with the Penman-Monteith equation (Figure 15). Also during winter 2002, almost all the net irradiance during a day, was partitioned into the latent heat flux density ($\lambda E \approx Rn$) (Figure 20). This is surprising, as one would expect lower evaporation rates during drier winter months (e.g. June to August 2002), when compared to summer 2002/2003. Further, during winter 2002, one would expect most of the net irradiance to be partitioned into sensible heat flux density. The high latent heat flux densities (and total evaporation) during winter 2002 therefore suggest that the Coastal Bushveld/Grassland was not experiencing significant water stress during winter 2002, that the vegetation possibly had access to an adequate soil water storage source, and that the vegetation type was actively transpiring. However, this could unfortunately not be verified from the soil water content data (Figure 18), as measurements had not commenced at that time. The high total evaporation rates measured during winter 2002 therefore reflects the ability of the tree clusters to transpire at high rates during winter 2002. It suggests that the total evaporation was not significantly influenced or reduced by the senescence of the grass component at this research site.

Although no total evaporation data is available for spring 2002 (September to November 2002), the total evaporation at the Coastal Bushveld/Grassland site increased by between 2.5 and 5 mm d^{-1}, to reach maximum total evaporation rates during summer 2002/2003 (December 2002 to February 2003) (Figures 15 and 19). Maximum evaporation rates ranged between 5 and 8 mm d^{-1} during summer 2002/2003 with values occasionally exceeding 8 mm d^{-1} (Figures 15 and 19). The maximum total evaporation rates measured during summer 2002/2003, followed air temperature and solar radiant density increases (8.2 to 8.8 °C and 5 to 10.9 MJ m^{-2} respectively), an increase in leaf area index (1.73) and grass and tree height, and 231 mm rainfall (Figures 15, 17 and 19). During summer 2002/2003, the total evaporation also exceeded the reference evaporation (Figure 15) and most of the net irradiance was partitioned into the latent heat flux density (Figure 21). The high latent heat flux density (and total evaporation), similar to or occasionally exceeding the net irradiance (or reference evaporation), suggests that the Coastal Bushveld/Grassland vegetation was not experiencing much soil water stress and that advective conditions might have occurred around mid-day.

Summer total evaporation rates decreased to ± 5 mm d^{-1} towards the end of summer 2003 (January 2003), and further to ± 2 mm d^{-1} at the end of autumn 2003 (April 2003). The decrease in total evaporation followed decreases in solar radiant density, air temperature, rainfall, leaf area index, canopy height and fractional soil water content (Figures 15 to 19).

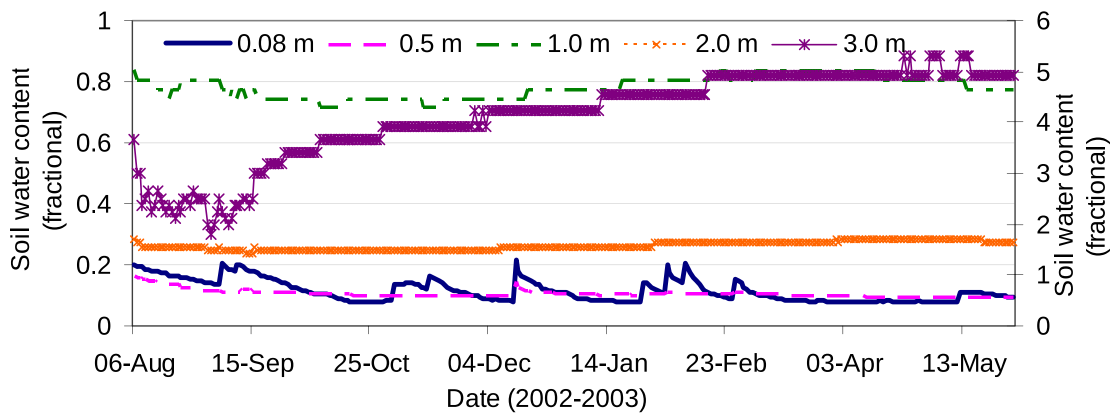


Figure 18 Fractional soil water content of the soil layers (0.08, 0.5, 1.0 and 2.0 m) at the Coastal Bushveld/Grassland site and rainfall (bars) for the period August 2002 to May 2003. Data for the depths of 2.0 and 3.0 m are shown on the 2nd axis

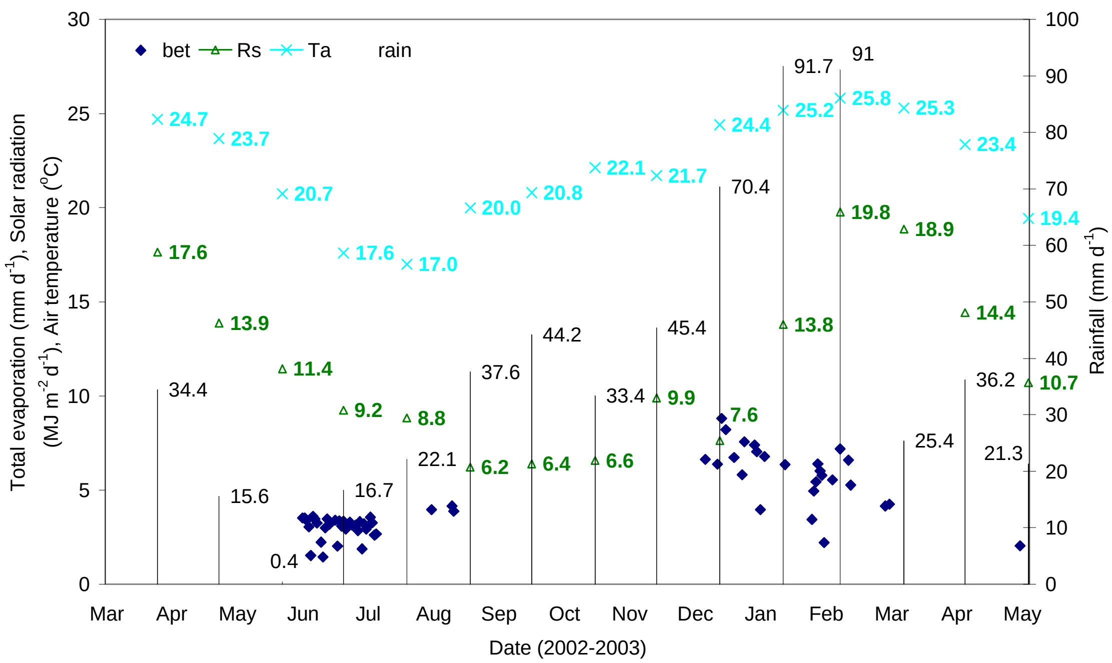


Figure 19 Daily total evaporation (bet) at the Coastal Bushveld/Grassland site, monthly total rainfall (rain), monthly average solar radiant density (Rs) and monthly average air temperature (Ta) for the period May 2002 to May 2003

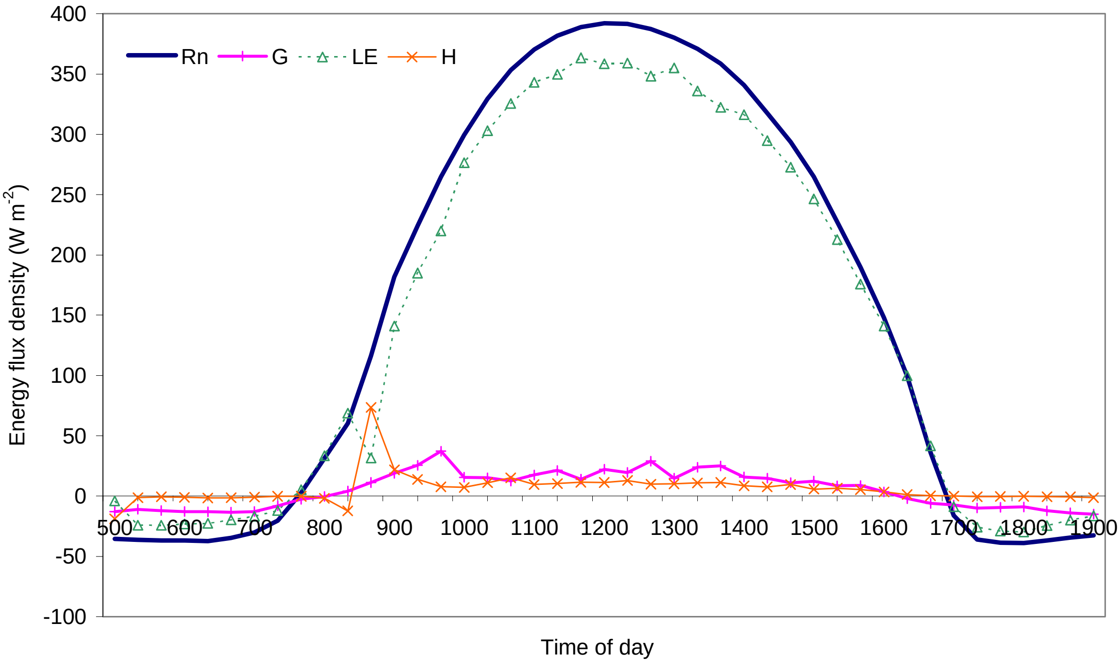


Figure 20 Energy flux densities at the Coastal Bushveld/Grassland site as measured with the Bowen Ratio Energy Balance system on 23 June 2002, where Rn is net irradiance, G is soil heat flux density, LE the latent heat flux density, and H the sensible heat flux density

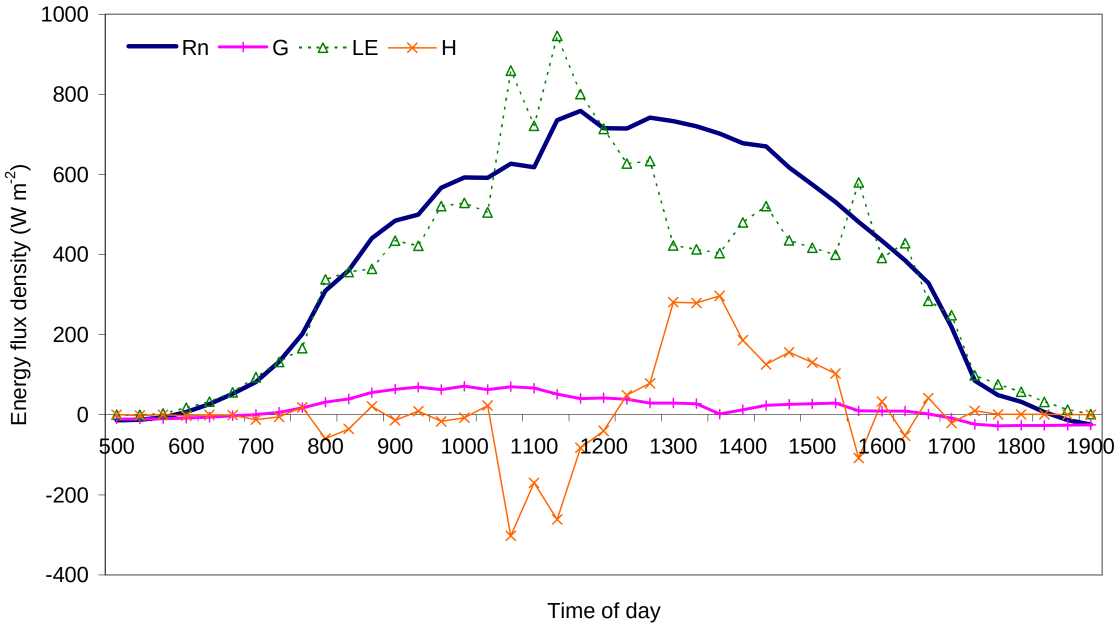


Figure 21 Energy flux densities at the Coastal Bushveld/Grassland site as measured with the Bowen Ratio Energy Balance system on 17 January 2003, where Rn is net irradiance, G is soil heat flux density, LE the latent heat flux density, and H the sensible heat flux density

3.4 Total evaporation of a Moist Upland Grassland site

The soil water balance of the Moist Upland Grassland at Cathedral Peak was measured during a previous project, funded by the Water Research Commission. The results from this study are discussed in detail by Everson et al. (1998), and will not be discussed in this report.

3.5 Conclusions

The high total evaporation rates measured for the Valley Thicket and Coastal Bushveld/Grassland sites during summer (up to 6 mm d^{-1} and 8.7 mm d^{-1} respectively), suggest that these vegetation types had access to a sufficient soil water store, which allowed continued high total evaporation rates. The evaporation rates sometimes exceeded the reference evaporation and the net irradiance the latent heat flux densities. These conditions suggest advective conditions.

During winter, both the Valley Thicket and Coastal Bushveld/Grassland vegetation maintained high evaporation rates (up to 2.1 mm d^{-1} and 3.6 mm d^{-1} at the respective sites). The total evaporation rates were, as during summer, similar to the reference evaporation and suggest no/little soil water stress experienced by the vegetation. The high rates during winter represent the total evaporation from the actively transpiring tree/shrub/thicket component of the vegetation, as most of the grasses at these sites were dormant during winter.

CHAPTER 4

RESULTS AND DISCUSSION: TOTAL EVAPORATION MODELLING

4.1 Introduction

The water balances of a Moist Upland Grassland, Valley Thicket and Coastal Bushveld/Grassland site were each simulated with the *ACRU*, *SWAT* and *SWAP* models. The actual and simulated total evaporation were compared for the same time period within the data sets for each vegetation type. Where ever possible, seven-day moving averages of the measured and simulated total evaporation were compared.

The simulated and measured total evaporation data for the respective natural veld types included the following periods:

- Moist Upland Grassland for the period 1 January 1992 to 31 December 1992,
- Valley Thicket for the period 1 May 2002 to 15 February 2003, and
- Coastal Bushveld/Grassland for the period 11 June 2002 to 24 March 2003.

The parameters used in the simulations are given in Appendices I to III.

4.2 Reference evaporation method used in the simulation of total evaporation

In the application of the *ACRU* model, monthly means of A-pan evaporation were used to calculate the reference evaporation at the Moist Upland Grassland site. The monthly values were disaggregated within *ACRU*, into daily reference evaporation values using Fourier analysis. Monthly means of A-pan evaporation were also disaggregated into daily data at the Valley Thicket and Coastal Bushveld/Grassland. However, the use of disaggregated data in the initial simulations at the Valley Thicket and Coastal Bushveld/Grassland sites did not yield a good relationship between the measured and modelled total evaporation. Therefore, the reference evaporation was subsequently calculated as a function of actual daily minimum and maximum air temperature within *ACRU*. This ensured a more realistic and representative reference evaporation data set, indicative of the daily atmospheric fluctuations.

In the *SWAT* and *SWAP* simulations the Penman-Monteith (1965) formulation, together with daily climatic data (rainfall, maximum and minimum air temperature, solar radiant density**,** relative humidity and windspeed), were used to calculate the daily potential evaporation or reference evaporation.

4.3 Total evaporation at a Moist Upland Grassland site

4.3.1 A comparison of the actual total evaporation and the total evaporation simulated with *ACRU*, *SWAT* and *SWAP* at a Moist Upland Grassland site

ACRU tended to simulate the total evaporation accurately during summer, but slightly underestimated (< 1 mm d^{-1}) the total evaporation during autumn, when compared to the actual total evaporation (Figures 22 and 23). In contrast, *SWAT* tended to overestimate total evaporation by up to 2.5 mm d^{-1} during summer, but simulated the total evaporation accurately during most of autumn (Figures 22 and 24). Towards the end of autumn (May) *SWAT* overestimated total evaporation by up to 1.5 mm d^{-1}, compared to the actual total evaporation (Figures 22 and 24). For the remainder of the year (winter and spring), both *ACRU* and *SWAT* underestimated the total evaporation when compared to the actual total evaporation (Figures 22 to 24). Underestimations of total evaporation were less than 1 mm d^{-1} during winter, and up to 2.5 mm d^{-1} during spring (Figures 22 to 24). In contrast to these simulations, the total evaporation simulated with *SWAP* did not follow the trend of the actual total evaporation and was characterised by periodic under- and overestimations throughout the season (Figure 25).

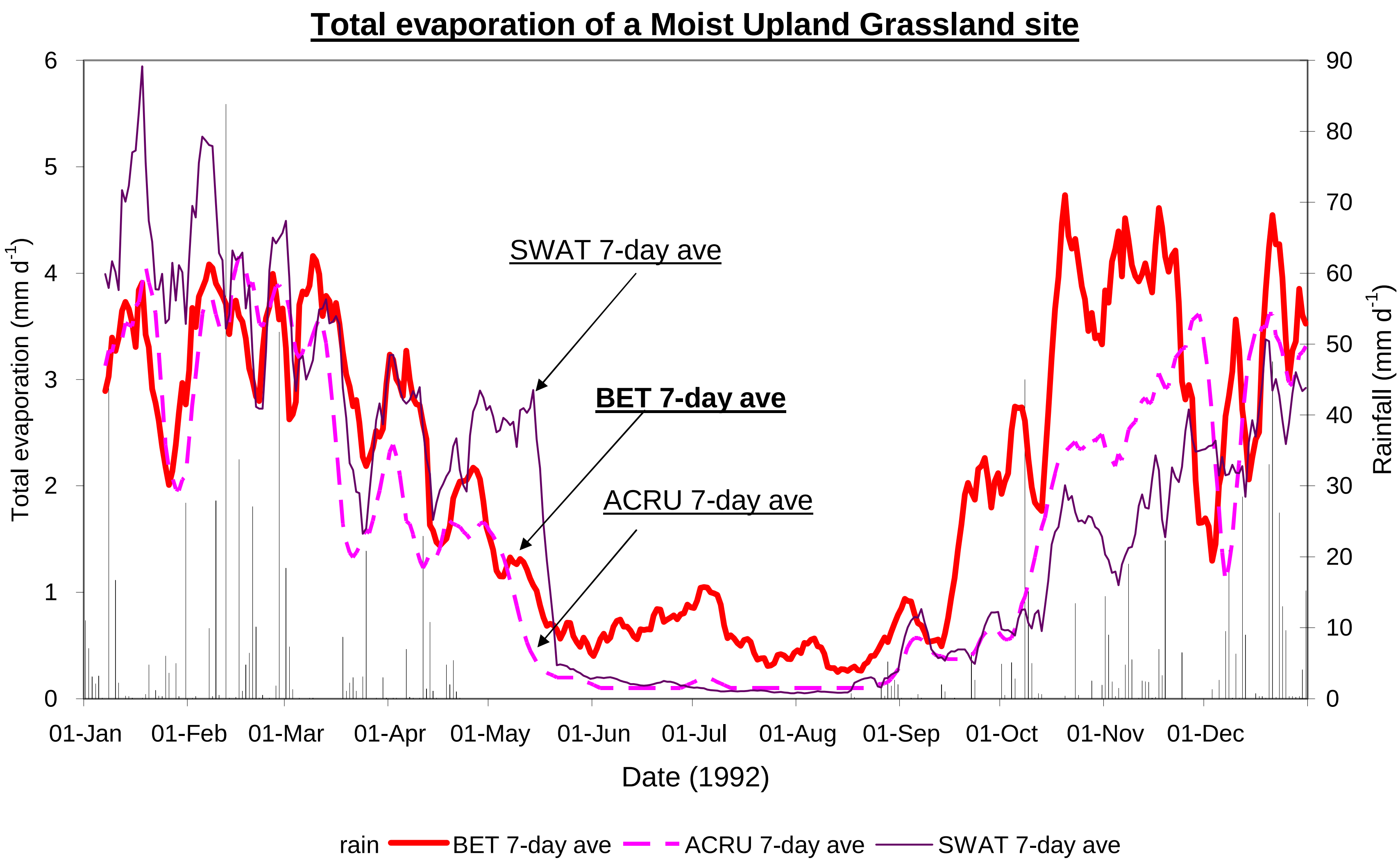


Figure 22 Seven-day averages of the actual total evaporation (BET 7-day ave) of a Moist Upland Grassland site and the total evaporation simulated with *ACRU* (*ACRU* 7-day ave) and *SWAT* (*SWAT* 7-day ave), for the period 1 January to 31 December 1992. Daily rainfall is represented by the bars

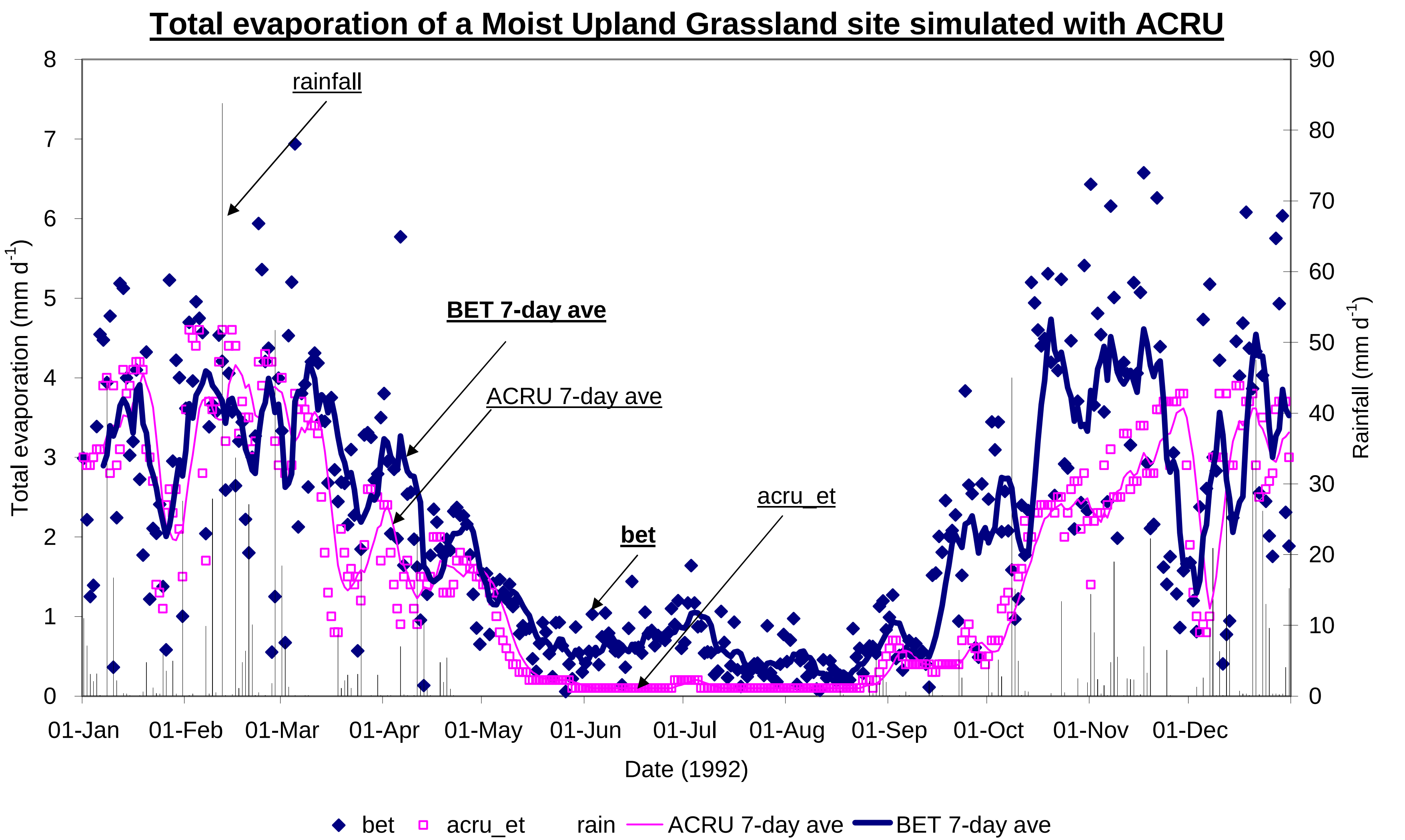


Figure 23 Seven-day averages of the actual total evaporation of Moist Upland Grassland (BET 7-day ave), the seven-day average total evaporation simulated with *ACRU* (*ACRU* 7-day ave), the actual daily total evaporation (bet) and the daily total evaporation simulated with *ACRU* (acru_et) for the period 1 January to 31 December 1992. Daily rainfall represented by bars

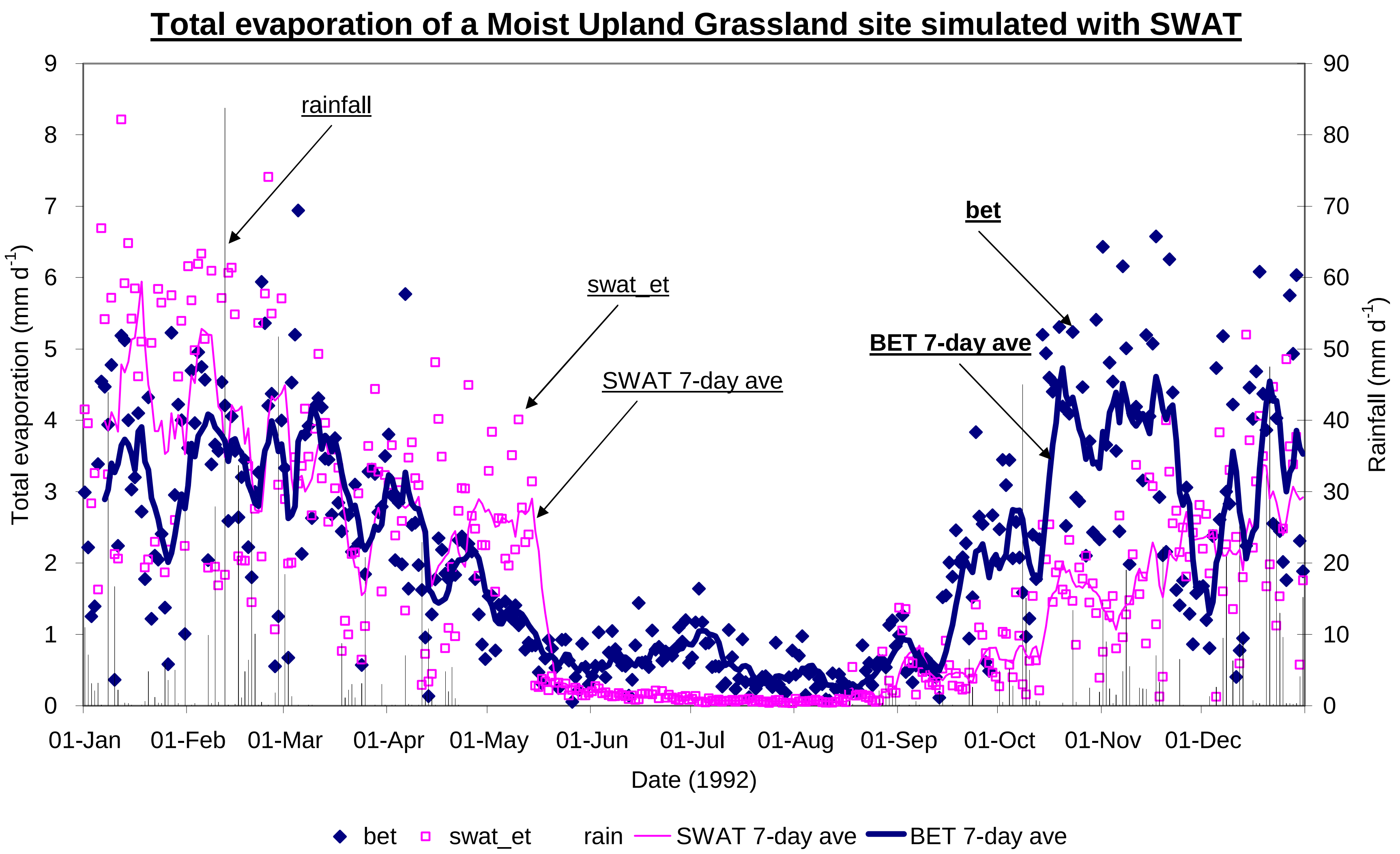


Figure 24 Seven-day averages of the actual total evaporation (BET 7-day ave) of a Moist Upland Grassland site, the seven-day average total evaporation simulated with *SWAT* (*SWAT* 7-day ave), the actual daily total evaporation (bet) and the daily total evaporation simulated with *SWAT* (swat_et) for the period 1 January to 31 December 1992. Rainfall represented with the bars

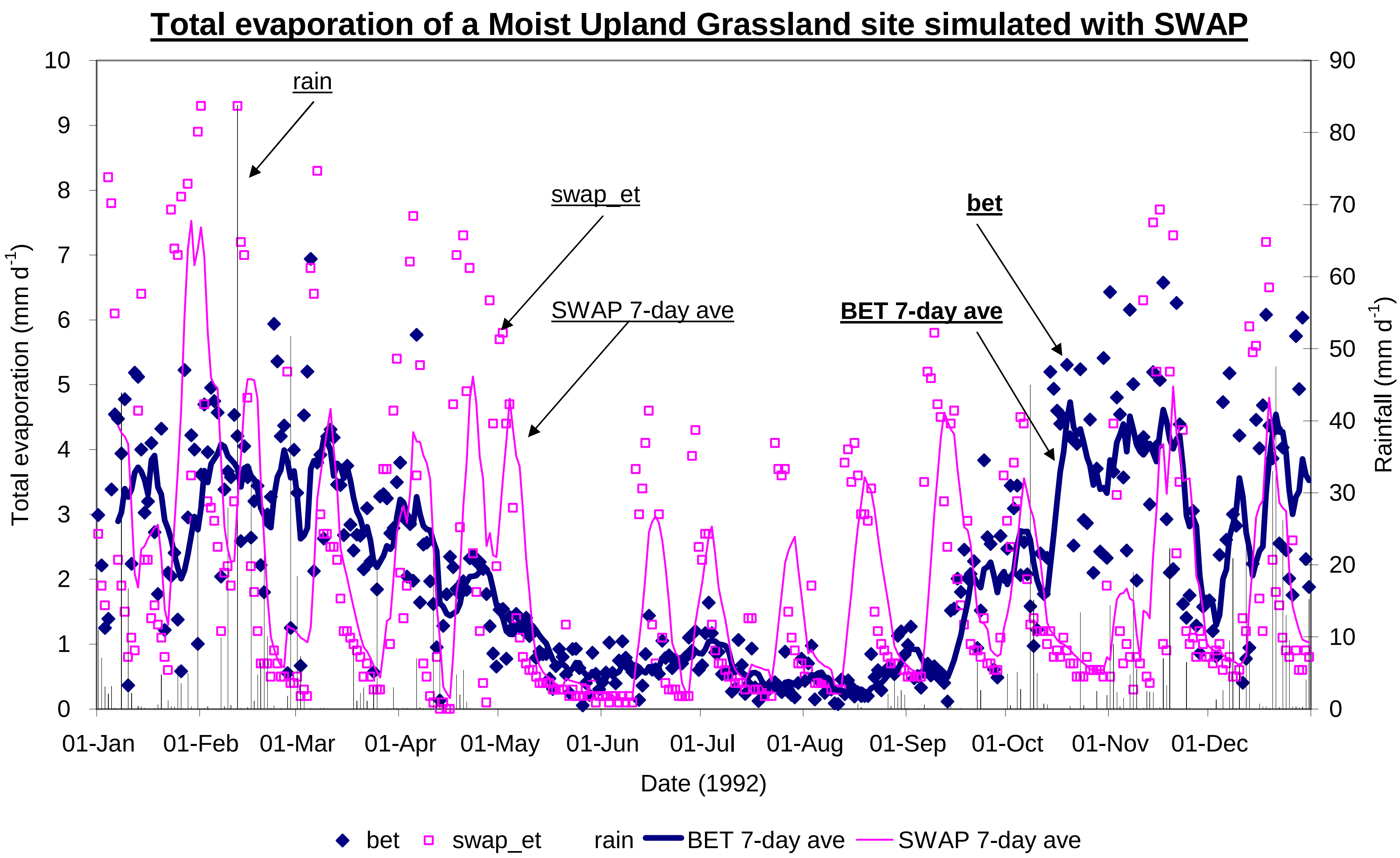


Figure 25 Seven-day averages of the actual total evaporation (BET 7-day ave) of a Moist Upland Grassland site, the seven-day average total evaporation simulated with *SWAP* (*SWAP* 7-day ave), the actual daily total evaporation (bet) and the daily total evaporation simulated with *SWAP* (swap_et) for the period 1 January to 31 December 1992. Rainfall represented by bars

4.3.2 Possible causes for differences in actual and simulated total evaporation at a Moist Upland Grassland site

A number of possible reasons can be given for the differences in the total evaporation simulated with *ACRU*, *SWAT*, *SWAP* and measured with the Bowen Ratio Energy Balance system (Figures 22 to 25). These include:

1. **<u>Differences in the level of detail required in model configurations</u>**
   SWAP and *SWAT* require daily climatic data inputs, whereas *ACRU* generally requires monthly data which are disaggregated according to Fourier analysis. Other parameters, e.g. plant growth parameters, are either specified according to growth stage (e.g. *SWAP*), accumulated heat units (*SWAT*) or different calendar months (*ACRU*) during the initial model set up.
2. **<u>Differences in the time step at which total evaporation is measured</u>**
   The *ACRU*, *SWAT* and *SWAP* models use daily climatic inputs e.g. daily rainfall, daily maximum and minimum temperature or, when daily data is not available, monthly average data (e.g. A-pan, maximum and minimum temperature, crop coefficients). In contrast, the Bowen Ratio Energy Balance system determines total evaporation on a 20 minute average time step. These 20 minute values are summed to obtain daily total evaporation rates. Therefore, the Bowen Ratio Energy Balance technique is much more sensitive to variations in climatic conditions, and will reflect these changes more accurately than the simulation results.
3. **<u>Fundamental limitations of models related to soil depth</u>**
   A fundamental limitation in the configuration of some models is the maximum thickness per soil layer and therefore the maximum depth of the soil profile. For example, the maximum thickness of the subsoil specified in *ACRU* is 1.5 m. In comparison, *SWAT* can use up to 10 soil layers, each with a maximum thickness of 3 m. Within *SWAP* there is no soil depth limitation specified. These differences result in different soil water stores within the profile, available for total evaporation.

4. **Differences in the methods calculating total evaporation and reference evaporation**

   ACRU generally uses an A-pan or an A-pan equivalent evaporation, whereas *SWAT* and *SWAP* generally use the Penman-Monteith equation to estimate reference evaporation. The latter two models use different formulations of the Penman-Monteith equation.

5. **Differences between the mechanisms applied by models to limit transpiration simulated**

   ACRU, *SWAT* and *SWAP* operate on different plant water uptake compensation mechanisms. For example, within the *ACRU* model, on a daily basis, the "potential" daily crop coefficient is determined through Fourier analysis from the average monthly crop coefficients input into the model. This daily crop coefficient is modified according to the soil water content of each soil horizon. If the soil water content of *both* the upper and lower soil horizons fall below 40 % of plant available water, the "potential" daily crop coefficient is reduced by a stress index. This in turn reduces the total evaporation.

   In the *SWAT* model if the upper layers in the soil profile do not contain enough water to meet the potential plant water uptake, a plant compensation factor is applied and allows the model to uptake water from the lower layers. However, as the soil dries out, the efficiency of the plant to extract water becomes increasingly difficult. The actual plant water uptake is calculated from the potential plant water uptake, modified either by the field capacity and wilting point, or the wilting point only.

   In *SWAP*, the actual soil evaporation and plant transpiration is determined separately. The potential soil evaporation is reduced by soil hydraulic functions (soil water content/soil water potential, and soil hydraulic conductivity/soil water content) when the soil becomes dry. The potential root water extraction rate integrated over the rooting depth (or potential transpiration) is reduced by reduction coefficients, due to soil water and/or salinity stress. The reduction coefficients are expressed as functions of soil water pressure head (after Feddes et al., 1978) and electrical conductivity (Maas and Hoffmann, 1977), derived for different crops.

6. **Other factors** also influence the estimation of total evaporation and are specific to soil water storage (Figure 26). These differ between the models and include:

- **<u>Initial soil water content and soil water potential for different soil layers within the profile</u>**

ACRU requires initial soil water contents for the top- and subsoil layers expressed as a percentage of the plant available water capacity, defaulted to 50 % of plant available soil water. *SWAP* requires initial soil water potentials (pressure heads) for each defined soil layer. In *SWAT* the initial soil water storage is expressed as a function of the water content at field capacity, or defaulted as a function of average annual rainfall.

- **<u>Bottom boundary conditions of soil profile</u>**

SWAP requires the bottom boundary conditions to be stipulated either as free drainage beyond the soil profile, no drainage, or drainage as a function of a reference (e.g. groundwater levels, pressure heads or bottom flux).

Within *ACRU* and *SWAT,* the soil water content of the subsoil layer is compared to the drained upper limit (field capacity) of this layer, and when the soil water content exceeds the drained upper limit, a fraction of the soil water contained in the subsoil will move into the intermediate zone[vi] (*ACRU*) and shallow aquiver (*SWAT*) below.

The factors mentioned above indicate that the differences in the total evaporation simulated with *ACRU*, *SWAT* and *SWAP* and the actual total evaporation measured with the Bowen Ratio Energy Balance system (Figures 22 to 25), can occur.

4.3.3 Possible reasons for the increased underestimation of total evaporation with *ACRU* and *SWAT* during spring 1992

Larger discrepancies between the total evaporation simulated with *ACRU* and *SWAT* and the actual evaporation measured during spring 1992, existed (Figures 22 to 24). Reference evaporation (Figure 27) calculated by *SWAT* limited the total evaporation rates achievable during spring 1992. The leaf area indices predicted with *SWAT* were lower than the measured leaf area indices (Figure 28) and could have contributed to the underestimation of total evaporation during this period.

Total evaporation within *ACRU* is calculated from the product of a crop coefficient and reference evaporation which can be further modified depending on the availability of soil water. The total evaporation of Moist Upland Grassland simulated with *ACRU* was limited to rates less than the actual total evaporation measured. This was possibly a result of the product of a low crop coefficient but likely reference evaporation. These crop coefficients were lower than the initial crop coefficients (Figure 28), and were therefore reduced due to soil water stress.

4.3.4 Possible causes of periodic overestimation of total evaporation with *SWAT* during autumn 1992

The total number of heat units (potential heat units) required to bring a plant to maturity, are specified within *SWAT*. The potential heat units specified in *SWAT* for Moist Upland Grassland during spring 1992 was possibly too high. This resulted in continued growth of the Moist Upland Grassland. However, this vegetation type typically shows a die-back during early autumn, which is translated into lower measured total evaporation rates. Therefore, *SWAT* overestimated the total evaporation during autumn 1992 when compared to the actual total evaporation (Figures 22 and 24).

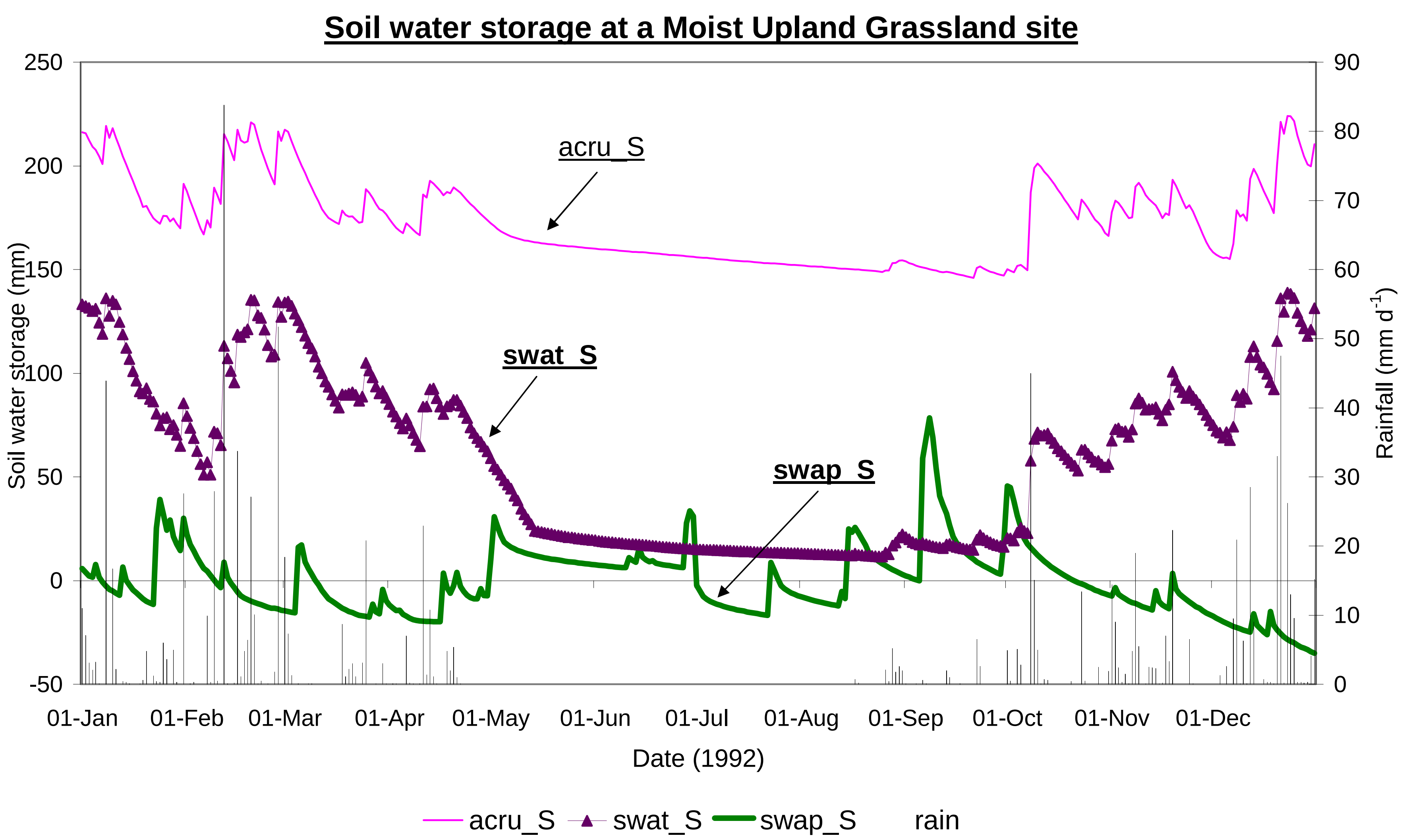


Figure 26 Soil water storage at a Moist Upland Grassland site, simulated with *ACRU* (acru_S), *SWAT* (swat_S) and *SWAP* (swap_S), and rainfall (bars) for the period 1 January to 31 December 1992. Bars represent daily rainfall

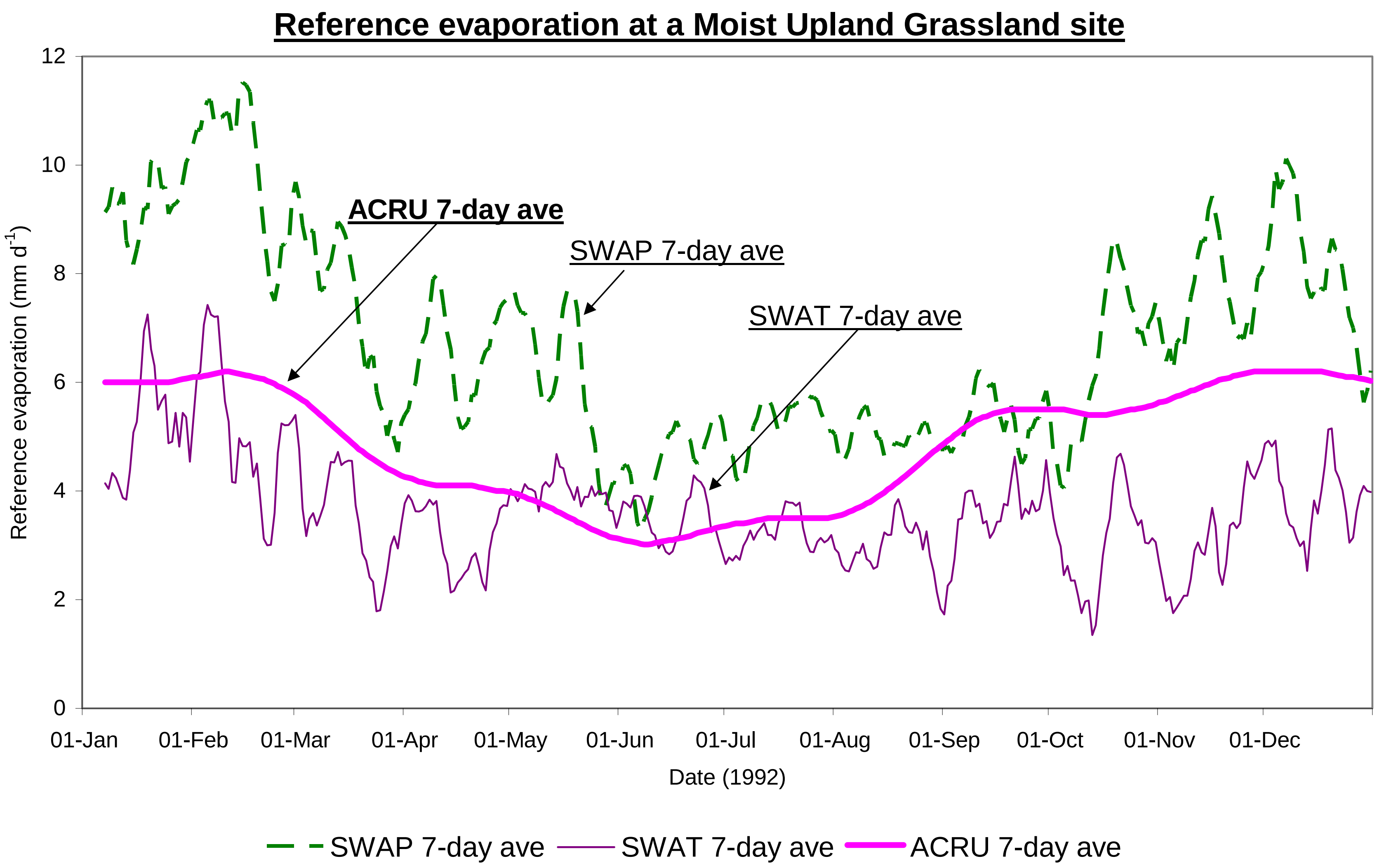


Figure 27 Seven-day average reference evaporation used in *ACRU* (ACRU 7-day ave), *SWAT* (SWAT 7-day ave) and *SWAP* (SWAP 7-day ave) at the Moist Upland Grassland site, for the period 1 January to 31 December 1992

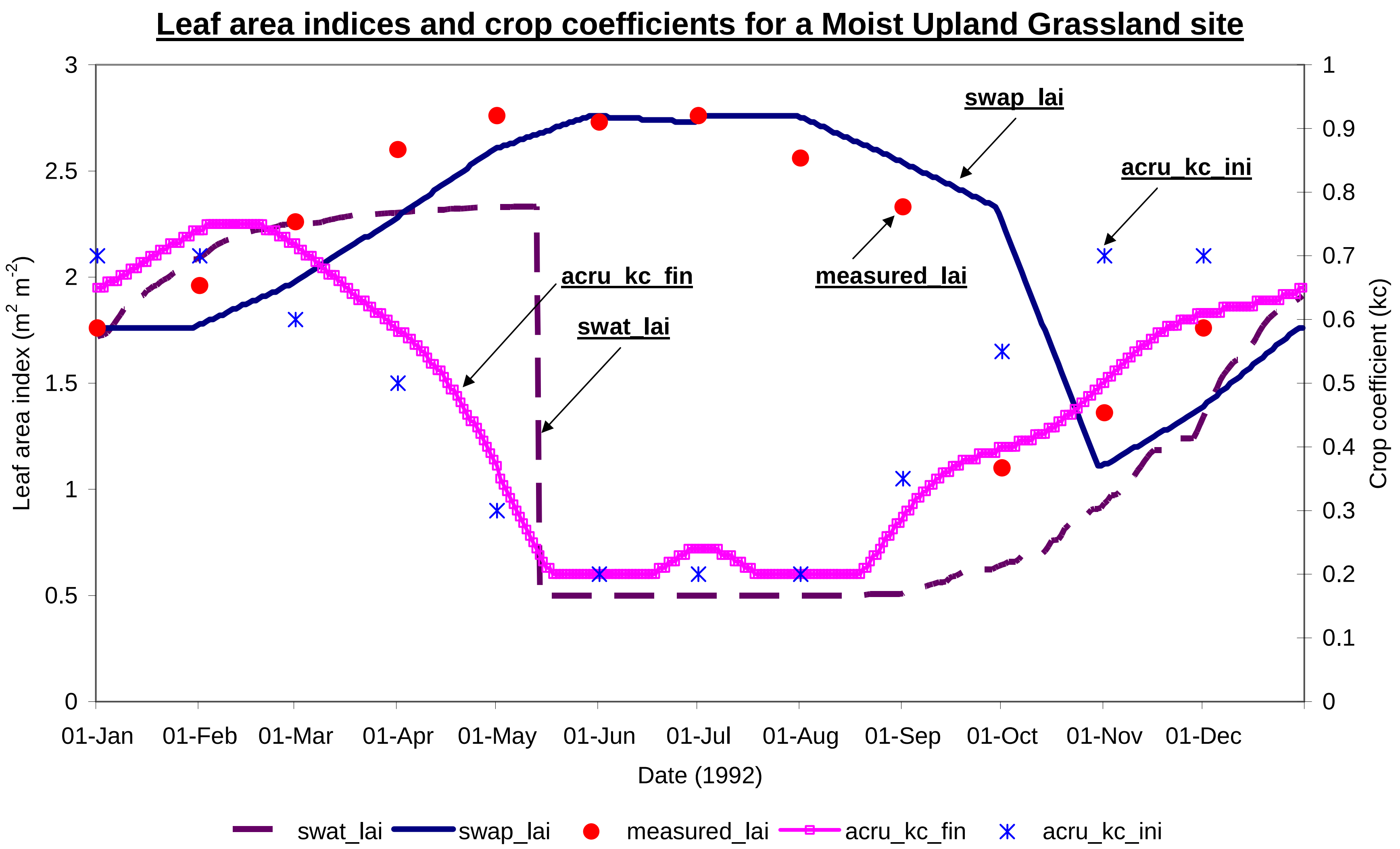


Figure 28 Measured leaf area indices (measured_lai) and input into *SWAP* (swap_lai), output by *SWAT* (swat_lai) and crop coefficients in (acru_kc_ini)- and output (acru_kc_fin) by *ACRU* in the simulation of the water balances of a Moist Upland Grassland site, for the period 1 January to 31 December 1992

4.3.5 Conclusions and Recommendations for improved simulation of total evaporation at a Moist Upland Grassland site

A number of factors have been identified that affect the accuracy of the simulation of total evaporation of Moist Upland Grassland. By addressing these factors during model configuration, or through modifications to the *ACRU* and *SWAT* models, the accuracy of total evaporation simulations of Moist Upland Grassland could be improved.

Within the ***ACRU*** model, the initial crop coefficients specified for Moist Upland Grassland are always less than one. These crop coefficients specified will inevitably limit the total evaporation rates to less than the potential. These initial crop coefficients potentially need to be reviewed. In addition, soil water availability following the dry season influences the growth and total evaporation. At the start of the new rainy season, the soil water content is often less than 40 % of the Plant Available water, and hence the crop coefficients are reduced. Such conditions further reduce the total evaporation below potential evaporation rates.

Within the ***SWAT*** model, the factors influencing accurate total evaporation simulations of Moist Upland Grassland were the growth and reference evaporation routines. The growth parameters specified within the model resulted in abrupt changes in the growth pattern. This does not mimic the gradual die-back of the grasses when plant maturity is reached or the renewed growth of the grasses at the start of a new rainy season. These parameters need to be re-evaluated, and adjusted in order to mimic the growth of grass better. The reference evaporation formulation applied in *SWAT* often limits the reference evaporation rates to rates lower than the total evaporation rates measured for Moist Upland Grassland. Therefore, it is expected that the total evaporation simulated with *SWAT* will often be lower than that measured at the Moist Upland Grassland site.

4.4 Total evaporation at a Valley Thicket site

4.4.1 A comparison of the actual total evaporation and the total evaporation simulated with *ACRU*, *SWAT* and *SWAP* at a Valley Thicket site

The *ACRU*, *SWAT* and *SWAP* models generally underestimated the total evaporation at the Valley Thicket site, when compared to the actual total evaporation measured at this site (Figures 29 to 32). Occasionally, the simulated and actual total evaporation rates were similar. These include periods during winter 2002, autumn 2002, spring 2002 and summer 2002/2003. All the models simulated the total evaporation more accurately during late winter and spring, compared to autumn and summer.

Generally, the *SWAT* model simulated the total evaporation at the Valley Thicket site better than *ACRU* and *SWAP* (Figures 29 to 32). This was the case for periods in July/August 2002 and December 2002 to February 2003. During these periods, *SWAT* maintained high total evaporation rates more similar to that measured (Figures 29 and 31). In contrast, the total evaporation simulated with *ACRU* (Figures 29 and 30) and *SWAP* (Figures 29 and 32) during these periods, decreased to less than 1 mm d^{-1}, which was up to 5.6 mm d^{-1} lower than the actual total evaporation.

All three models, responded to rainfall events and the associated availability of soil water through increased total evaporation (Figure 29 to 32). Total evaporation rates generally decreased as the soil water became limiting over time. When rainfall ceased to occur, e.g. over extended periods in January and February 2003, the total evaporation simulated with *ACRU* and *SWAP* were significantly reduced compared to the actual total evaporation. This was possibly due to soil water stress which limited the total evaporation rates to less than 1 mm d^{-1}.

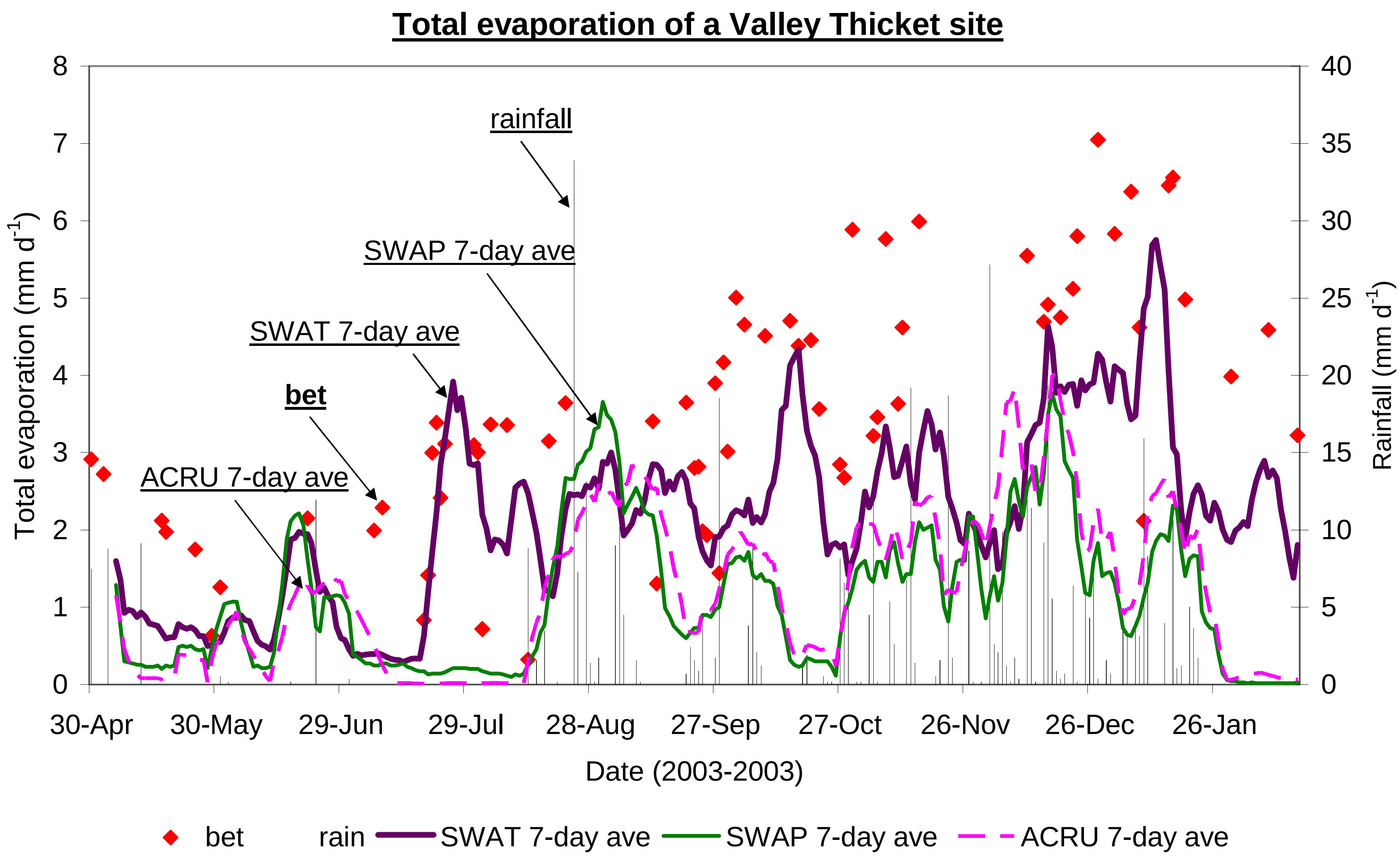


Figure 29 Daily actual total evaporation (bet) and seven-day averages of the total evaporation of a Valley thicket site simulated with *ACRU* (ACRU 7-day ave), *SWAT* (SWAT 7-day ave) and *SWAP* (SWAP 7-day ave) respectively for the period 1 May 2002 to 15 February 2003. Bars represent daily rainfall

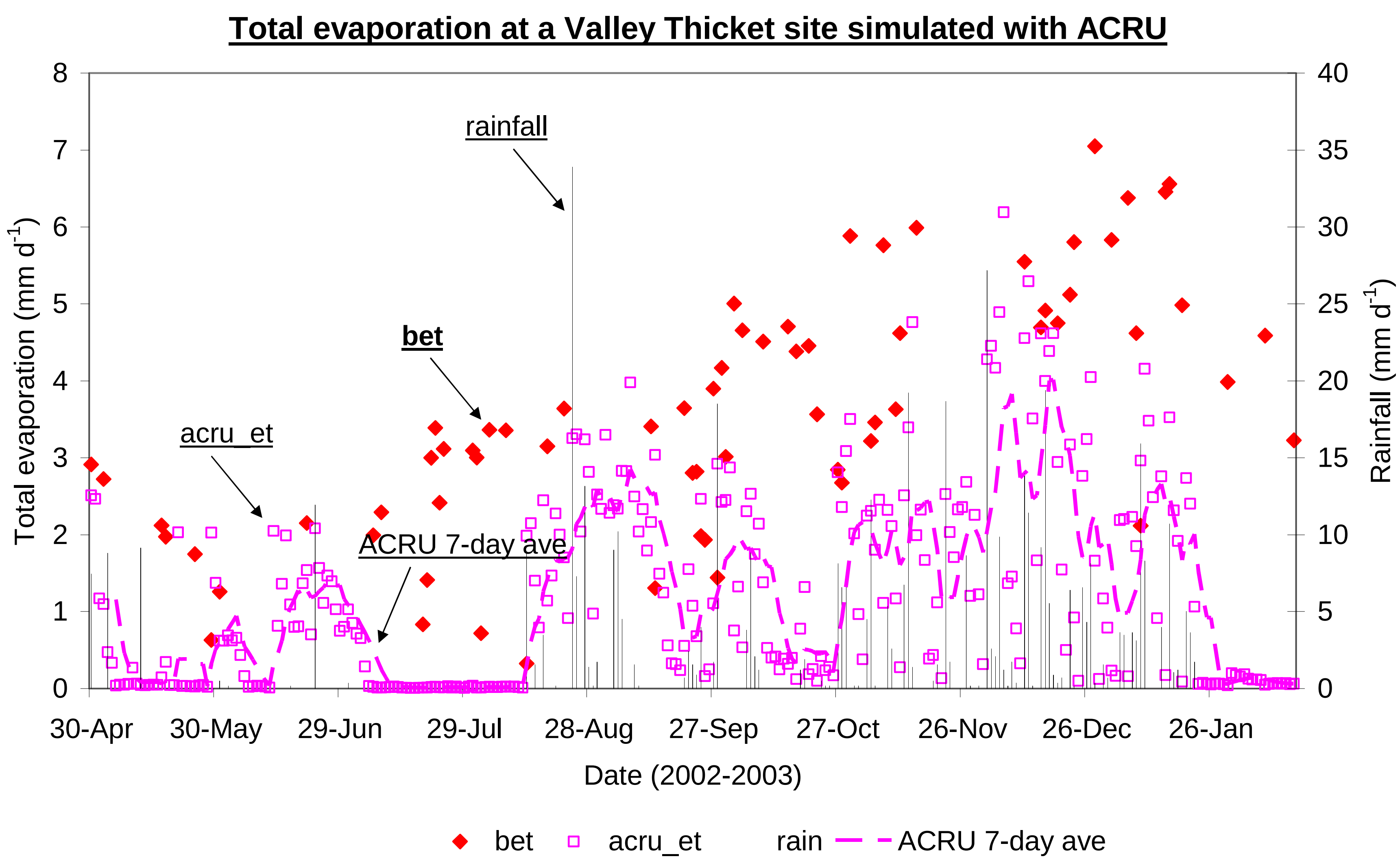


Figure 30 Seven-day averages of the total evaporation of a Valley thicket site simulated with *ACRU* (ACRU 7-day ave) and the daily actual total evaporation (bet) and daily total evaporation simulated with *ACRU* (acru_et) for the period 1 May 2002 to 15 February 2003. Bars represent daily rainfall

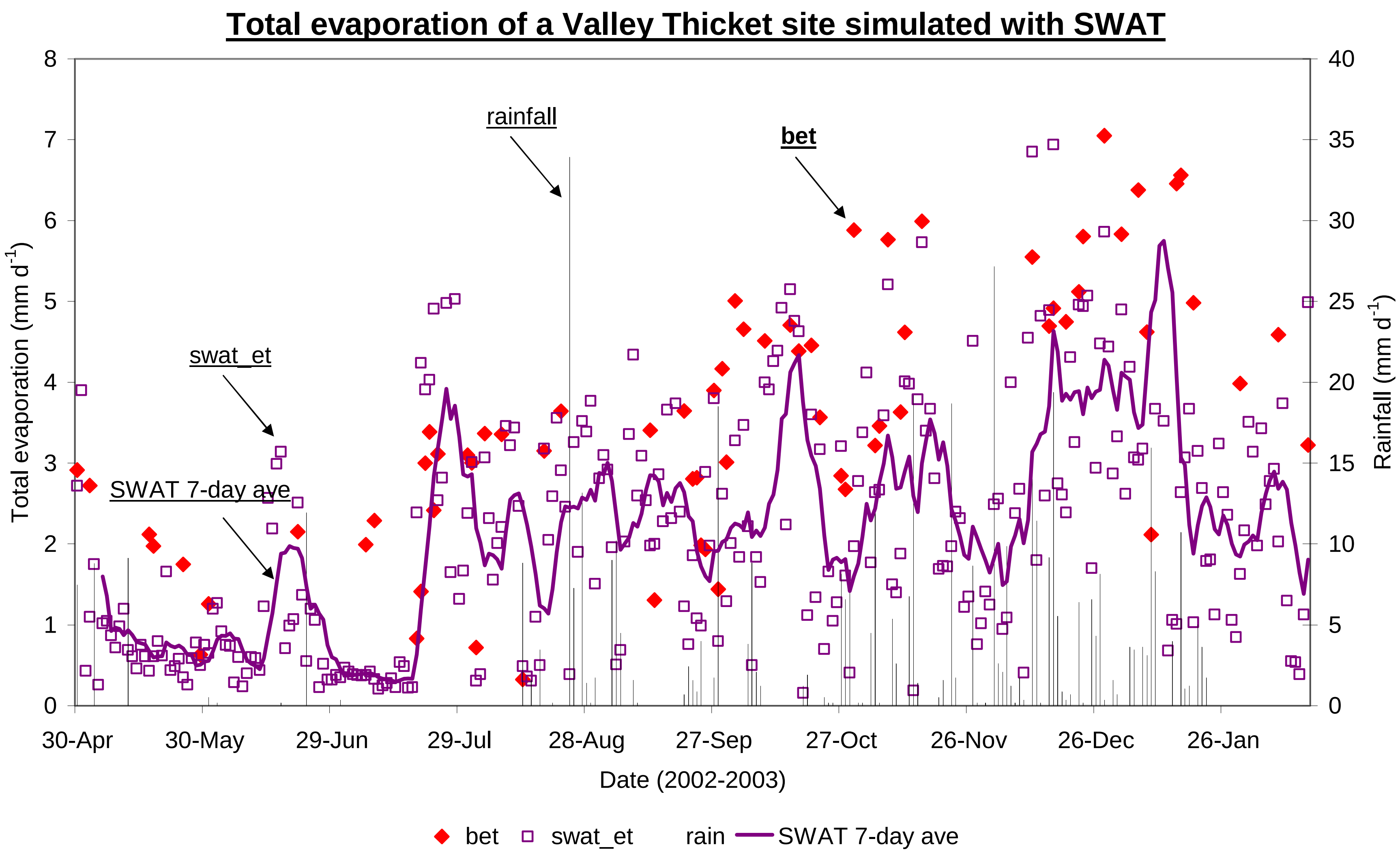


Figure 31 Seven-day averages of the total evaporation of a Valley thicket site simulated with *SWAT* (SWAT 7-day ave) and the daily actual total evaporation (bet) and daily total evaporation simulated with *SWAT* (swat_et) for the period 1 May 2002 to 15 February 2003. Bars represent daily rainfall

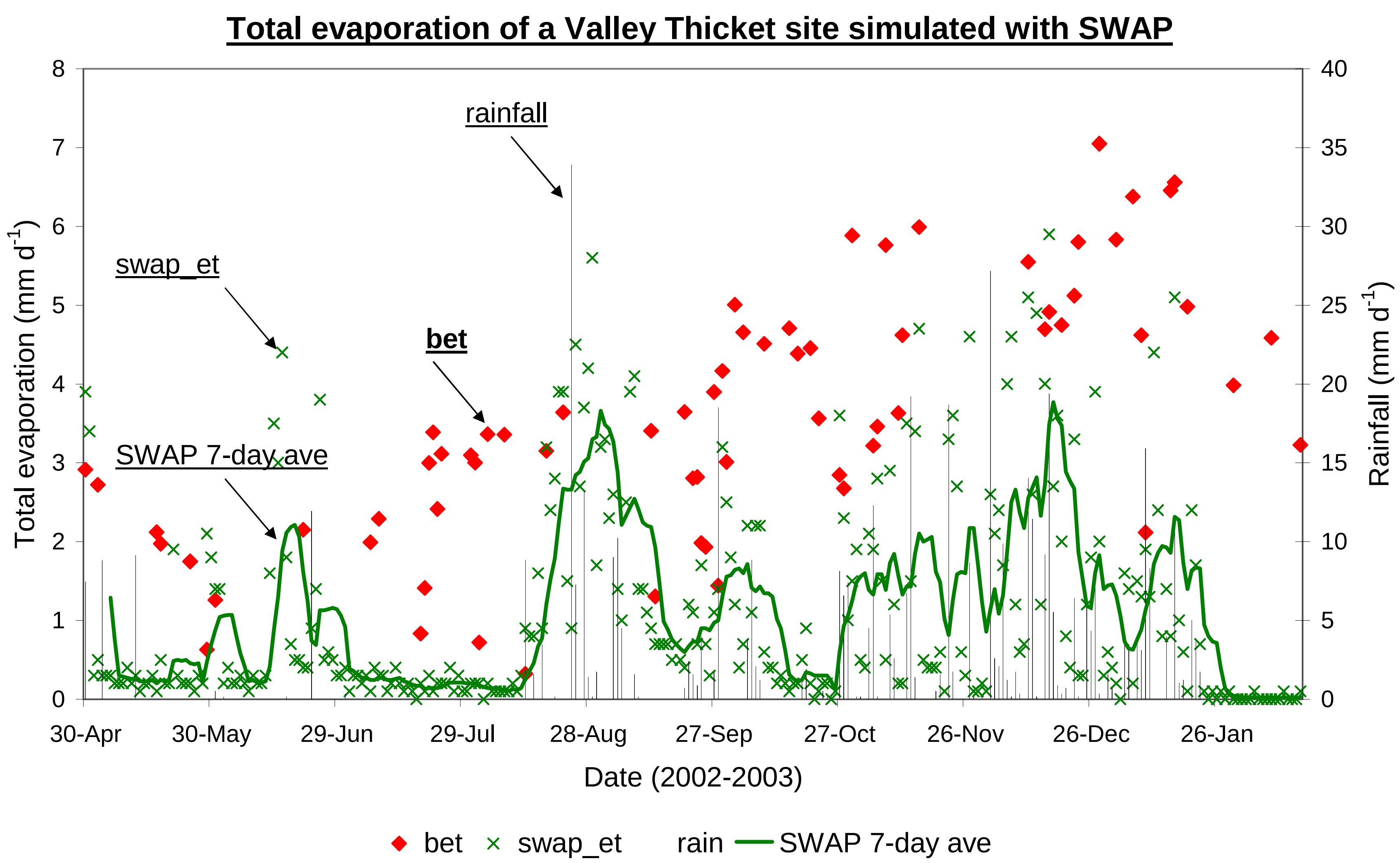


Figure 32 Seven-day averages of the total evaporation of a Valley thicket site simulated with *SWAP* (SWAP 7-day ave) and the daily actual total evaporation (bet) and daily total evaporation simulated with *SWAP* (swap_et) for the period 1 May 2002 to 15 February 2003. Bars represent daily rainfall

4.4.2 Possible reasons for differences in the actual total evaporation measured at a Valley Thicket site and the total evaporation simulated with *ACRU*, *SWAT* and *SWAP*

Possible reasons for differences in the actual total evaporation at a Valley Thicket site and the total evaporation simulated (Figures 29 and 32) include those listed for Moist Upland Grassland (Sections 4.3.2 and 4.3.3). These include leaf area index and crop coefficients (Figure 33), reference evaporation (Figure 34) and soil water availability (Figure 35). Other factors that possibly contributed to differences between the simulated and actual total evaporation at the Valley Thicket site, include:

1. **General input parameters used in the initial set up of the models**

   Due to the complexity of this vegetation type all parameters required by the different models were not available. In some instances vegetation parameters of similar plant functional and structural types were used, whereas other times values suggested by model developers or even average parameters were applied to this complex vegetation type.

   Due to limitations of the *SWAP* and *ACRU* models, it was impossible to distinguish between the different species (grass and trees/thicket) within this vegetation type. Therefore, average parameters were often applied in *ACRU* and *SWAP*. In contrast, *SWAT* allows for the parameterisation of different species (grass and trees/thicket) within hydrological response units. However, the question still remains to whether these vegetation parameters were representative of the specific vegetation composition and stage of succession of the Valley Thicket site studied.

2. **Effects of scale**

   Difference existed in the scale at which total evaporation was measured and simulated. Within *ACRU* and *SWAT* the water balance of valley thicket were simulated on a catchment scale, compared to a site scale with *SWAP*. However, the area of the total evaporation measured with the Bowen ratio energy balance technique depends on the height of the vegetation and the sensors.

3. **Discontinuous actual total evaporation data set**

   A discontinuous actual total evaporation data set, resulting from **sensor** malfunctioning, prohibited an accurate extended comparison between the measured and simulated total evaporation.

4.4.3 Conclusions and Recommendations for improved simulation of total evaporation at a Valley Thicket site

In order to improve the simulation of total evaporation with the ***ACRU*** model, the crop coefficients specified within this model for Valley Thicket need to be reassessed. In addition, the mechanisms by which the initial crop coefficients are reduced due to soil water stress need to be improved.

ACRU and ***SWAP*** use generalized vegetation parameters and do not allow detailed parameterisation of multi-layered, species-rich vegetation types. Therefore, to improve the simulation of the total evaporation of Valley Thicket, a more mechanistic crop growth routine, providing for complex species rich vegetation types, are required. In addition, the vegetation parameters required by these mechanistic crop growth models need to be measured for complex vegetation types such as Valley Thicket. Measurements of these vegetation parameters are also required for improved total evaporation simulations with ***SWAT***.

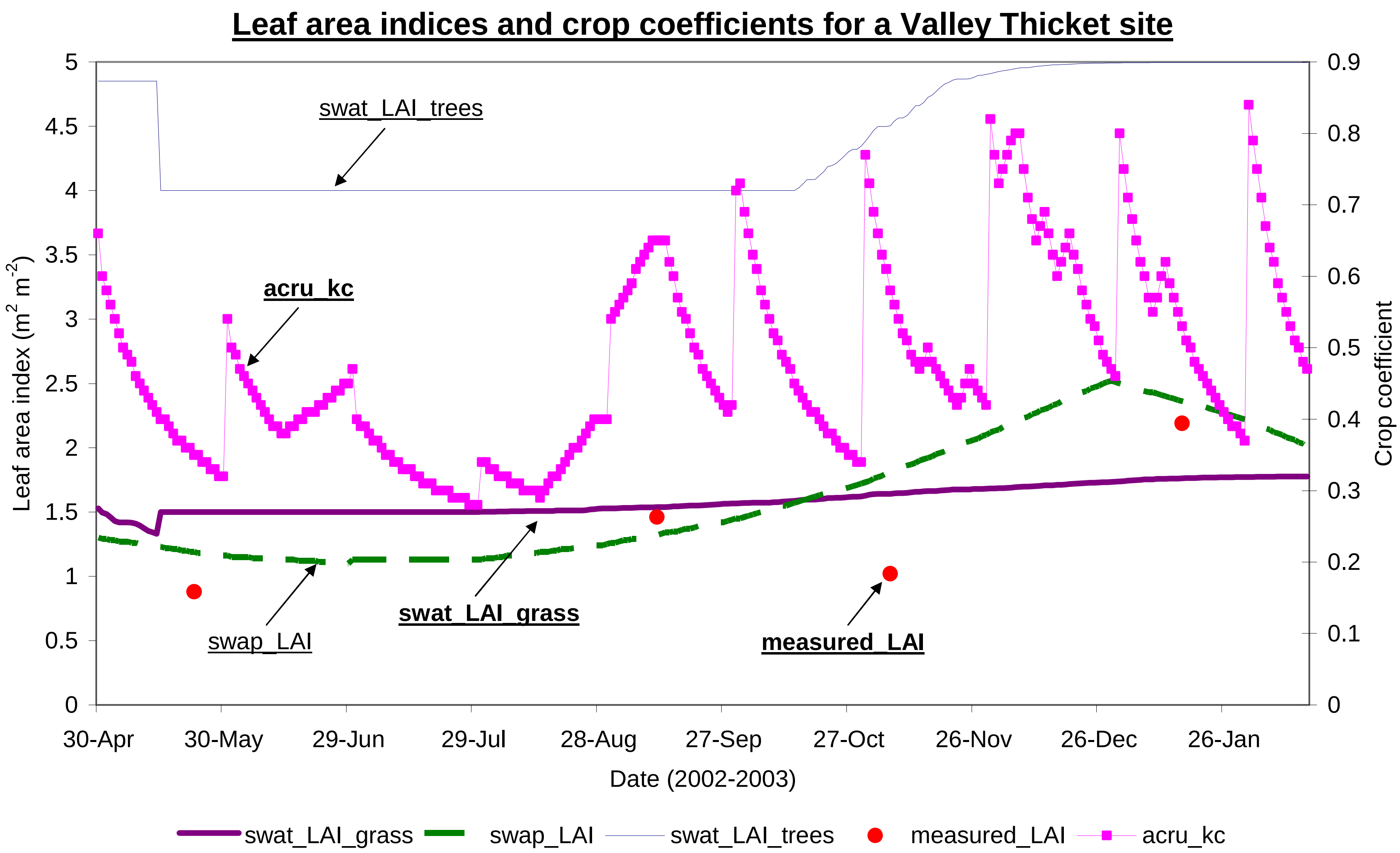


Figure 33 Leaf area indices (measured_LAI) measured at a Valley Thicket site and input into *SWAP* (swap_lai), output by *SWAT* (swat_lai) (separate for grass and trees) and crop coefficients used in *ACRU* and modified by a stress factor (acru_kc), for the period 1 May 2002 to 15 February 2003

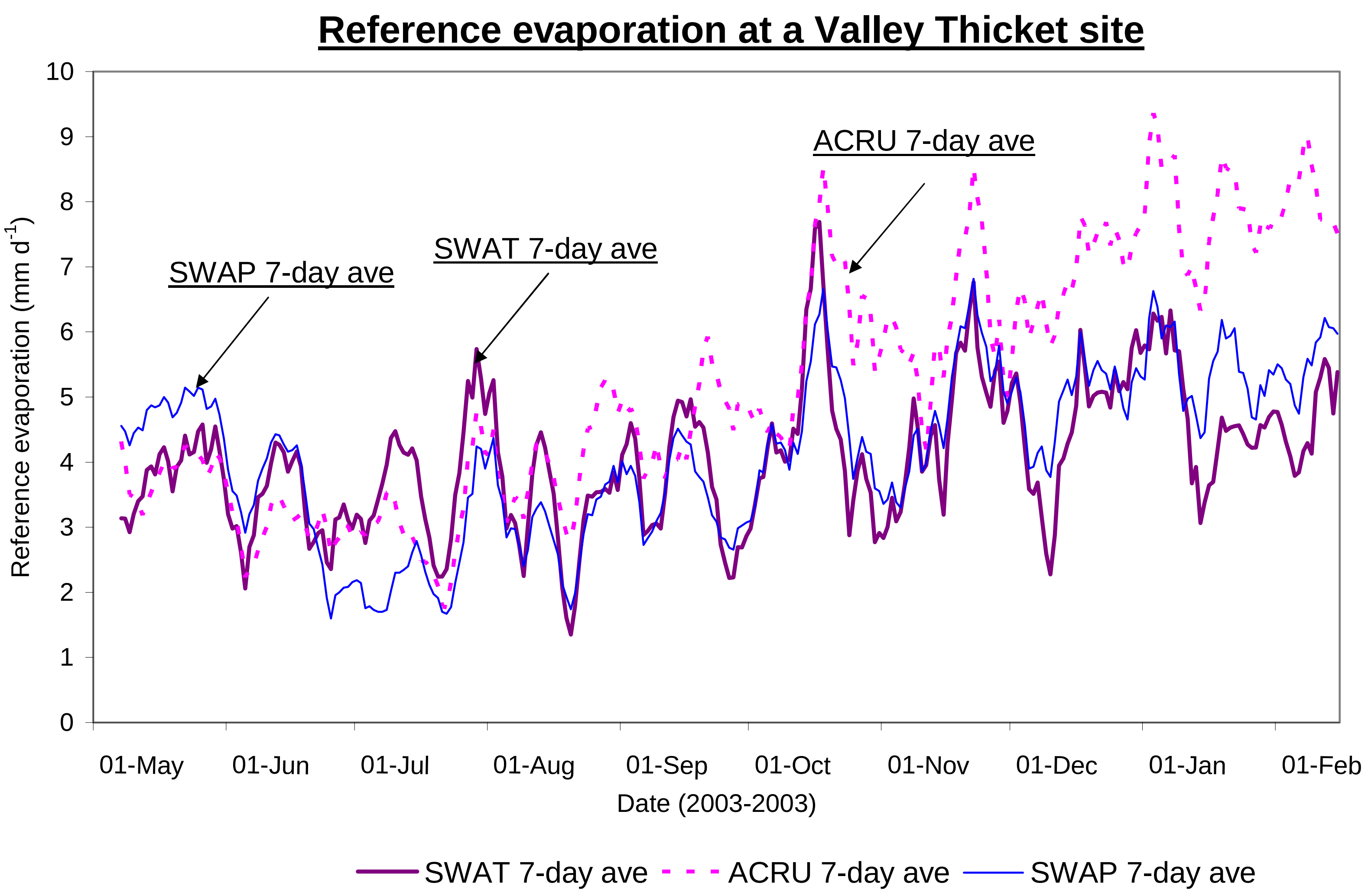


Figure 34 Seven-day average reference evaporation at a Valley Thicket site used in *ACRU* (ACRU_7-day ave), *SWAT* (SWAT 7-day ave) and *SWAP* (SWAP 7-day ave) for the period 1 May 2002 to 15 February 2003

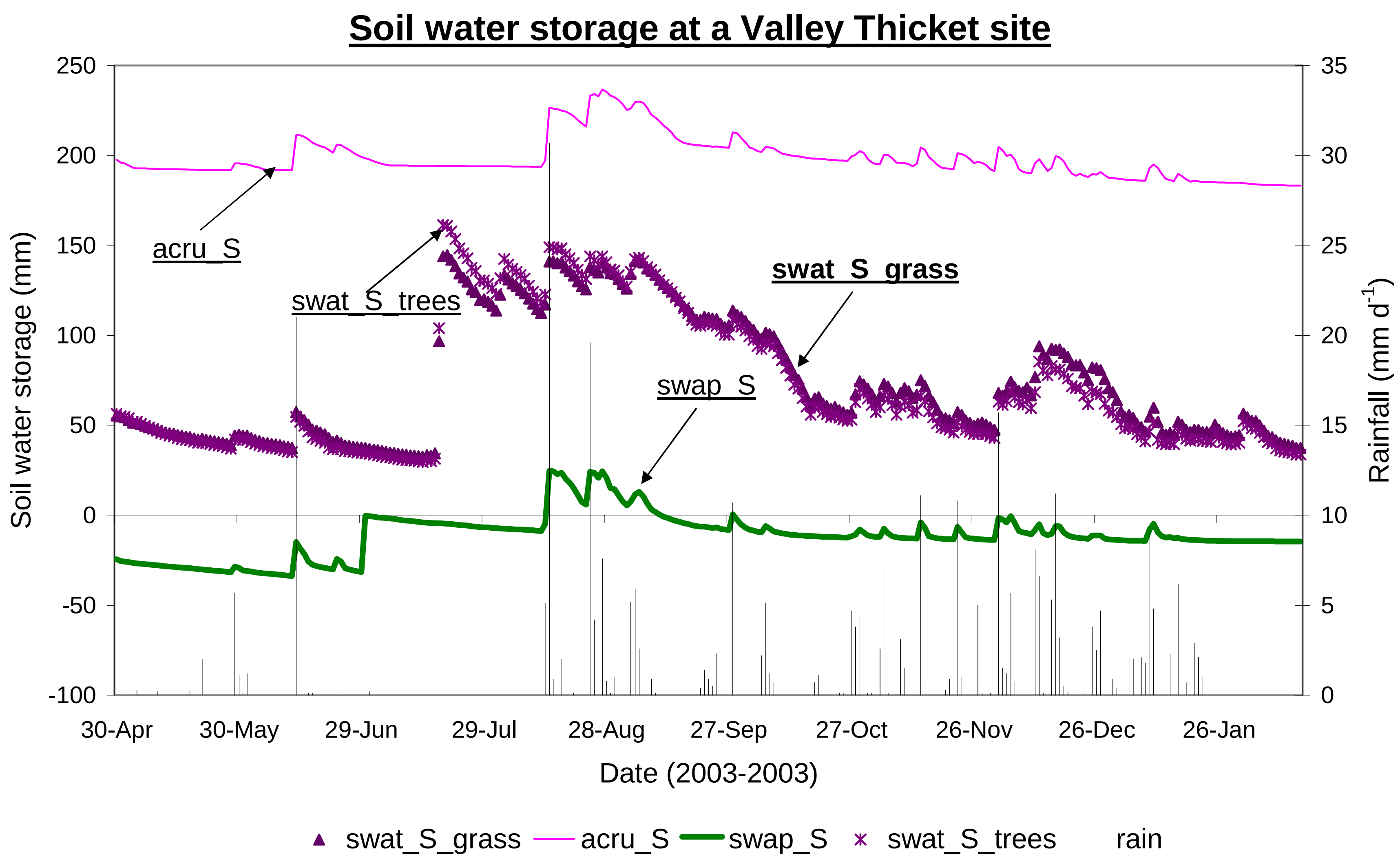


Figure 35 Soil water storage at a Valley Thicket site simulated by *ACRU* (acru_S), *SWAT* (swat_S) (separate for grass and trees) and *SWAP* (*SWAP*_S) and rainfall (bars) for the period 1 May 2002 to 15 February 2003. Bars represent daily rainfall

4.5 Total evaporation at a Coastal Bushveld/Grassland site

4.5.1 A comparison of the actual total evaporation of Coastal Bushveld/Grassland and the total evaporation simulated with *ACRU*, *SWAT* and *SWAP*

All three models underestimated the total evaporation at the Coastal Bushveld/Grassland site throughout the simulation period, when compared to the actual total evaporation (Figures 36 to 39). The trends simulated with the three models were similar. Occasional dissimilarities occurred within these trends in September and November 2002 and at the end of February 2003.

4.5.2 Possible reasons for the differences in total evaporation of Coastal Bushveld/Grassland compared to the actual total evaporation

The differences in total evaporation simulated with the models and the actual total evaporation at the Coastal Bushveld/Grassland site can be attributed to the same factors causing differences at the Moist Upland Grassland (Sections 4.3.2 and 4.3.3) and Valley Thicket sites (Section 4.4.2). These factors (Figures 40 to 42) together with the short actual total evaporation data set (June and July 2002 and the end of December 2002 to March 2003) affected the assessment of the accuracy of the total evaporation simulations at the Coastal Bushveld/Grassland site.

4.5.3 Conclusions and Recommendations for improved simulation of total evaporation at a Coastal Bushveld/Grassland site

High total evaporation rates measured at the Coastal Bushveld/Grassland site within this dry period could be explained by a larger soil water store and deeper root system. The larger soil water store could be the result of a deep soil profile, extending to more than 3 metres, and the high water holding capacity of the clayey soil layers. In addition, the root distribution of the tree component of the vegetation could have allowed for extraction of soil water from deeper soil layers. However, the models were configured to a maximum soil depth of 3 m, which limited the root distribution and the availability of soil water from deeper soil layers.

Within ***<u>ACRU</u>***, 75 % of the roots of the Coastal Bushveld/Grassland occur within the topsoil layer (at this site set to 0.3 m). When compared to the topsoil layer, less water is extracted by the remaining 25 % of the roots from the sub-soil layer (1.67 m), which has a larger soil water store. Due to this limitation, *ACRU* underestimated the total evaporation for Coastal Bushveld/Grassland. Therefore, to improve the total evaporation simulations for this vegetation type, the monthly average root distribution within the different soil layers need to be reassessed.

The total evaporation simulated with ***<u>SWAT</u>*** was limited by the reference evaporation (Figure 41) and soil water availability (Figure 42). In order to improve the total evaporation simulations for Coastal Bushveld/Grassland, the routines related to the reference evaporation and the soil water need to be improved. From the simulations at all the sites it is clear that the reference evaporation is generally underestimated with *SWAT* (Moist Upland Grassland and Valley Thicket – summer months; Coastal Bushveld/Grassland – all months).

In the ***<u>SWAP</u>*** simulations, the total evaporation of Coastal Bushveld/Grassland was similarly limited by the root distribution (70 %) and soil water availability in the upper soil layer (0.45 m). To improve the parameterisation of the root system for Coastal Bushveld/Grassland, root excavation studies should be under taken, or a parameter optimisation technique applied to determine the most appropriate root depth-density relationship for the model.

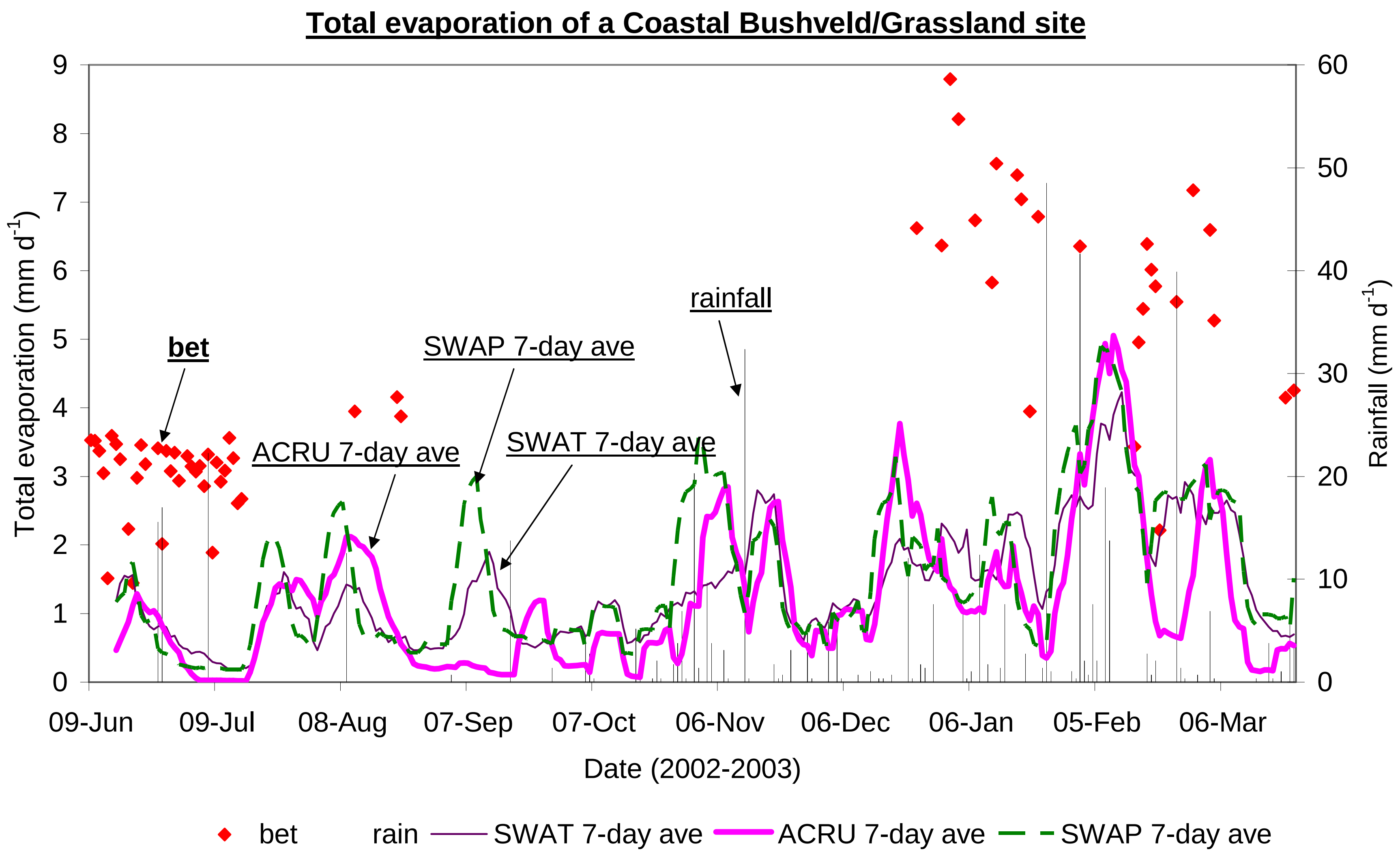


Figure 36 Seven-day averages of the total evaporation of a Coastal bushveld/grassland site simulated with *ACRU* (ACRU 7-day ave), *SWAT* (SWAT 7-day ave) and *SWAP* (SWAP 7-day ave) respectively, and the daily actual evaporation (bet) for the period 10 June 2002 to 25 March 2003. Bars represent daily rainfall

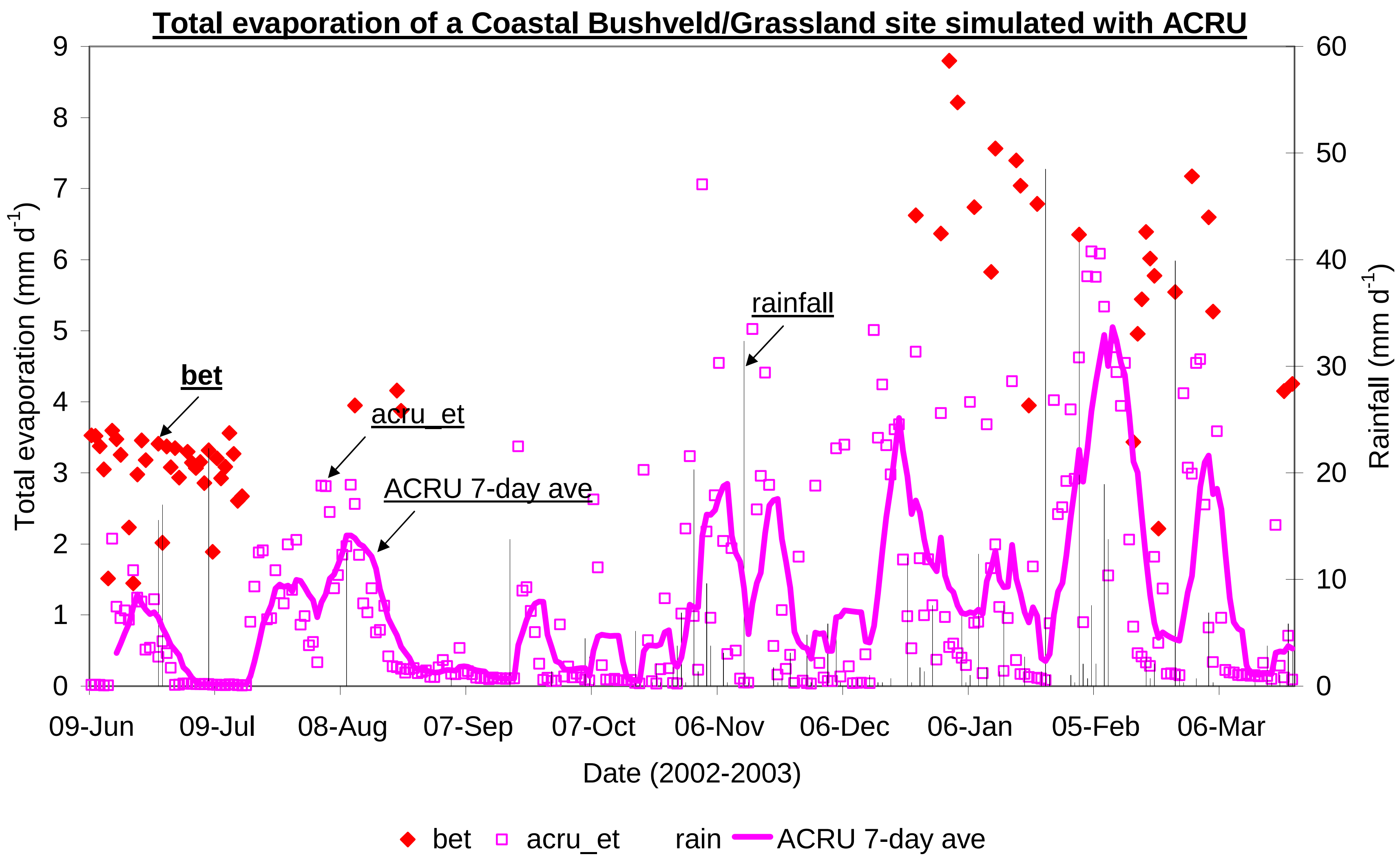


Figure 37 Seven-day averages of the total evaporation simulated with *ACRU* (ACRU 7-day ave) and the daily actual total evaporation (bet) and daily total evaporation simulated with *ACRU* (acru_et) for the period 10 June 2002 to 25 March 2003. Bars represent total rainfall

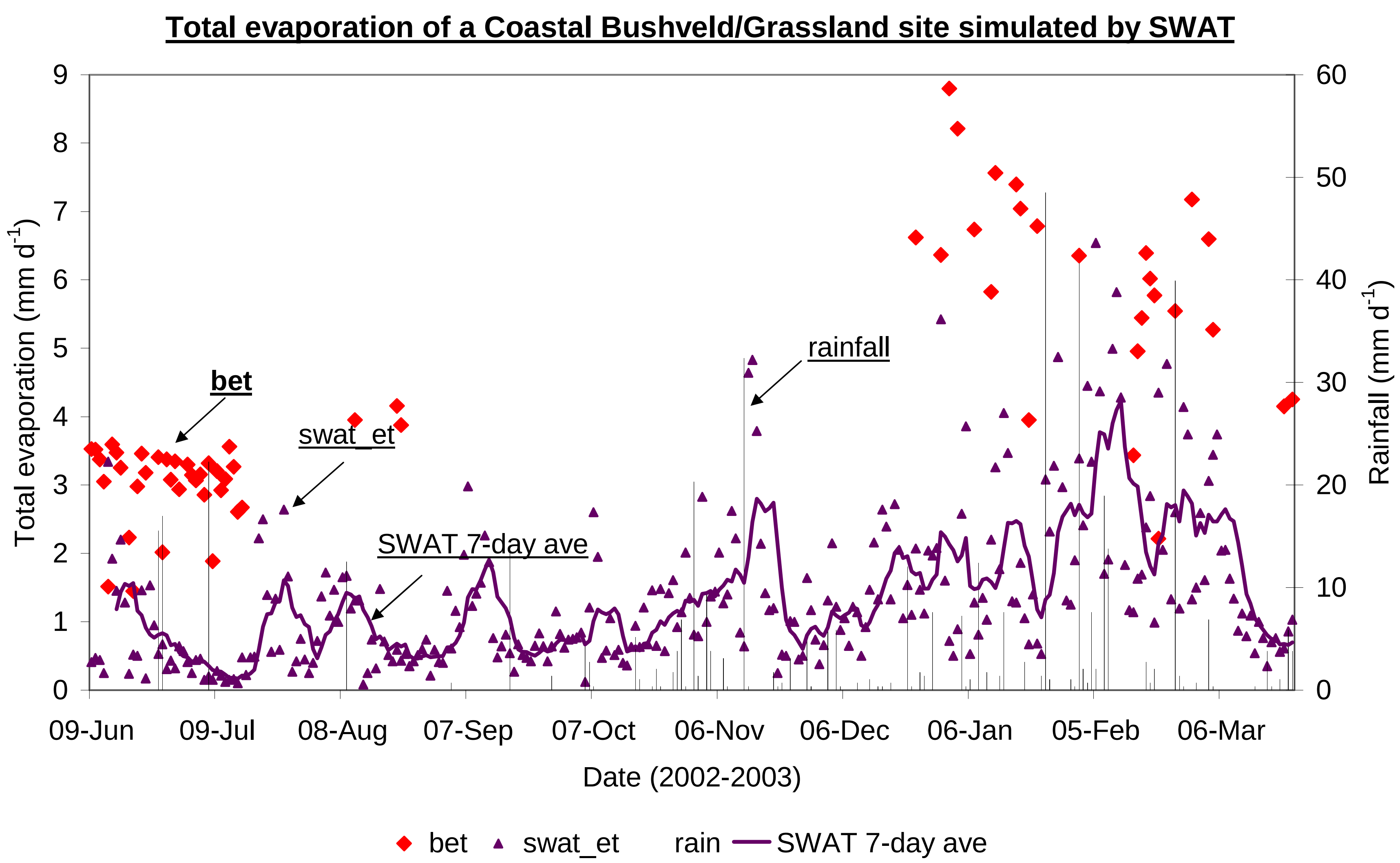


Figure 38 Seven-day averages of the total evaporation of a Coastal bushveld/grassland site simulated with *SWAT* (SWAT 7-day ave) and the daily actual total evaporation (bet) and daily total evaporation simulated with *SWAT* (swat_et) for the period 10 June 2002 to 25 March 2003. Bars represent total rainfall

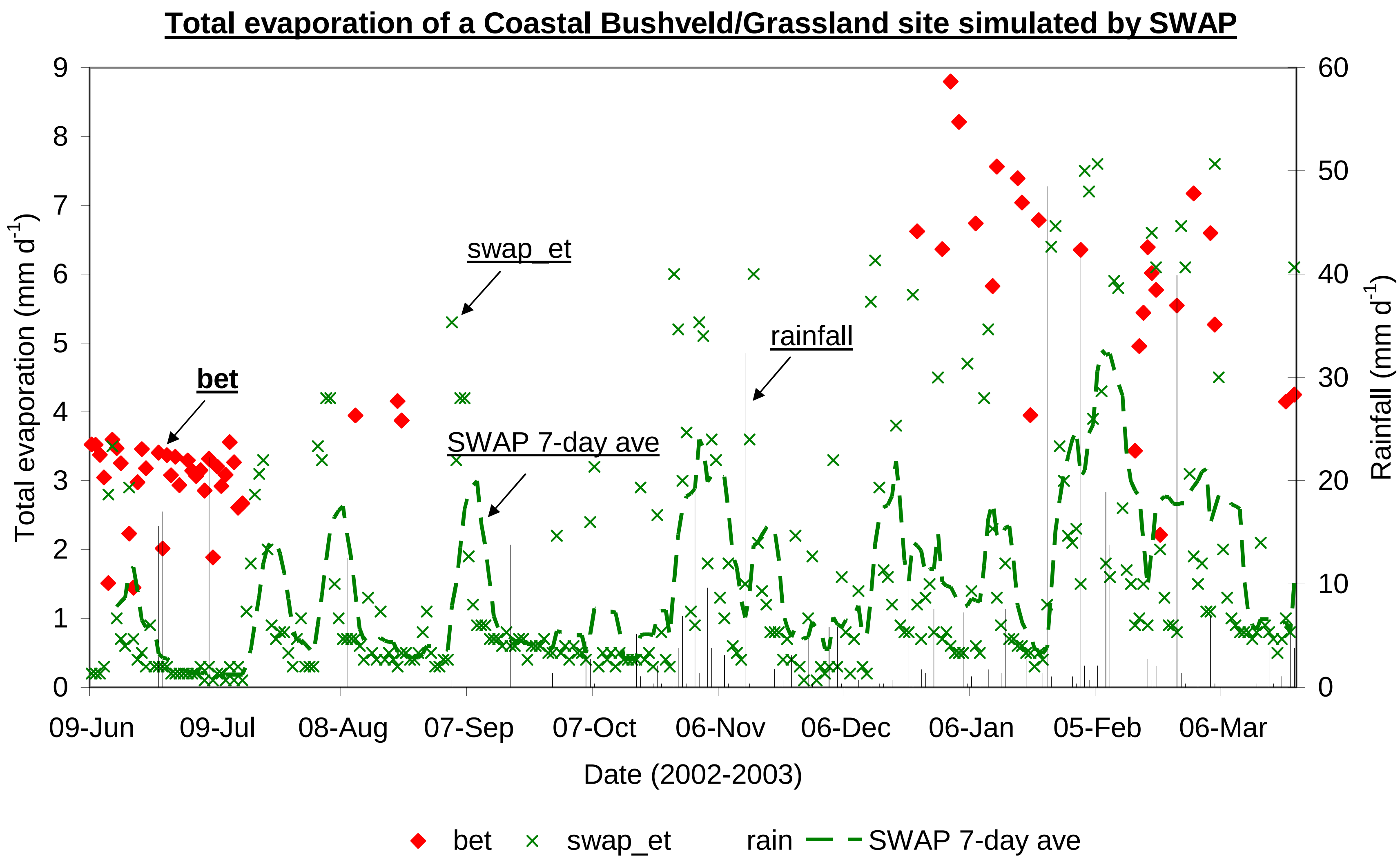


Figure 39 Seven-day averages of the total evaporation of a Coastal bushveld/grassland site simulated with *SWAP* (SWAP 7-day ave) and the daily actual total evaporation (bet) and daily total evaporation simulated with *SWAP* (swap_et) for the period 10 June 2002 to 25 March 2003. Bars represent total rainfall

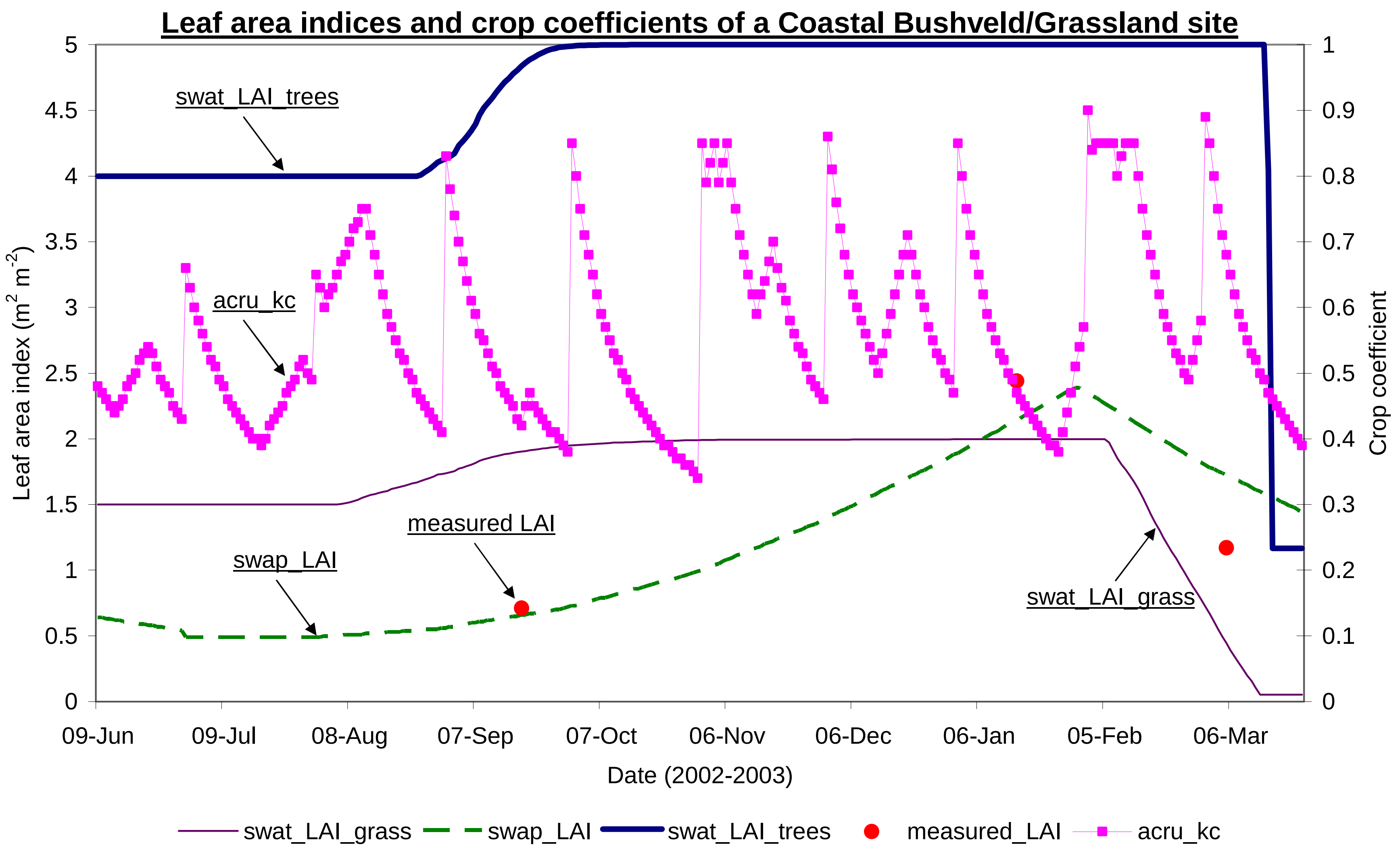


Figure 40 Leaf area indices measured (measured_LAI) at the Coastal Bushveld/Grassland site and input into *SWAP* (swap_lai), output by *SWAT* (swat_lai) (grass and trees separately) and crop coefficients used in *ACRU* modified by a stress factor (acru_kc) for the period 10 June 2002 to 25 March 2003

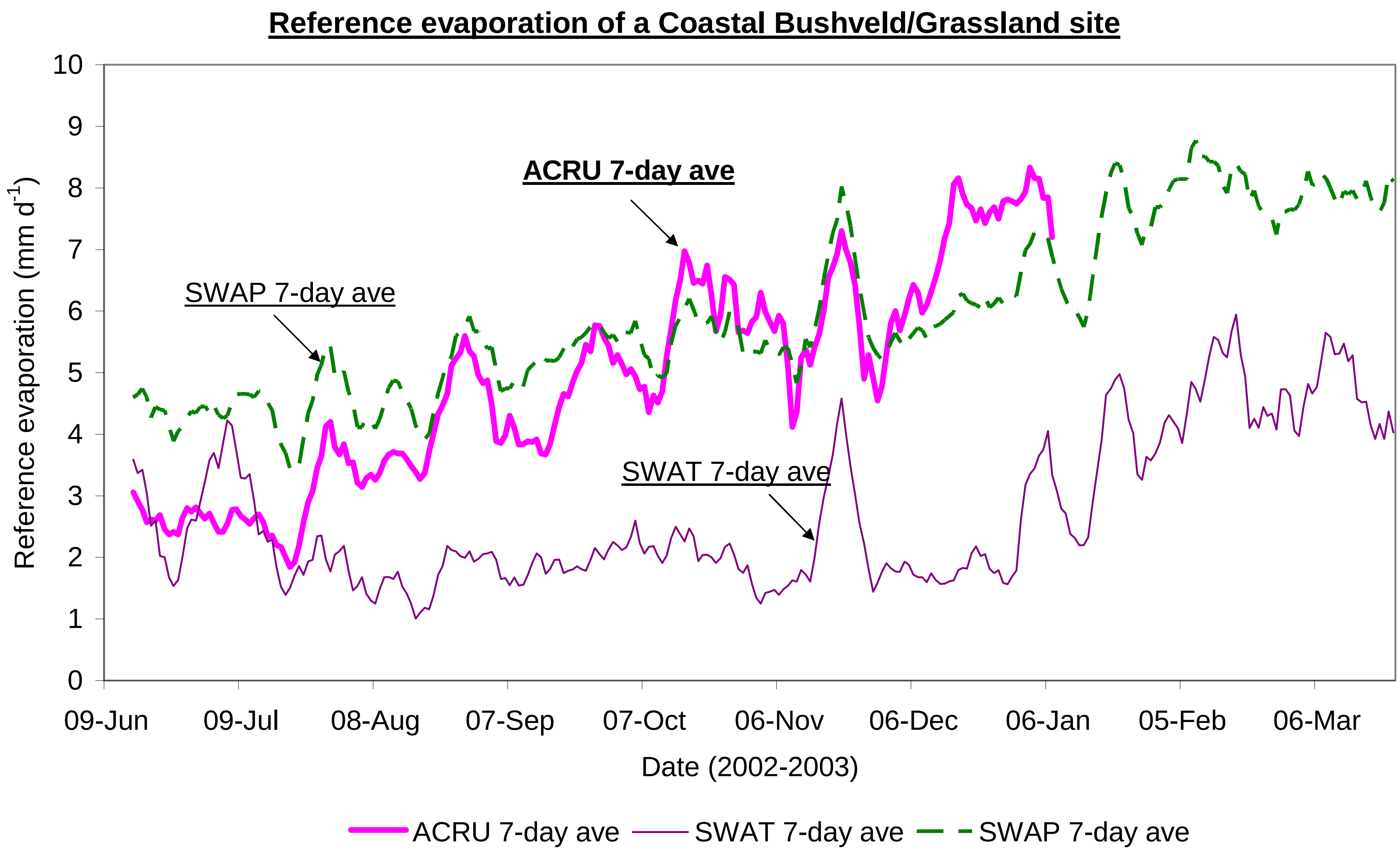


Figure 41 Seven-day averages of the reference evaporation at the Coastal Bushveld/Grassland site used in *ACRU* (ACRU 7-day ave), *SWAT* (SWAT 7-day ave) and *SWAP* (SWAP_7-day ave) for the period 10 June 2002 to 25 March 2003

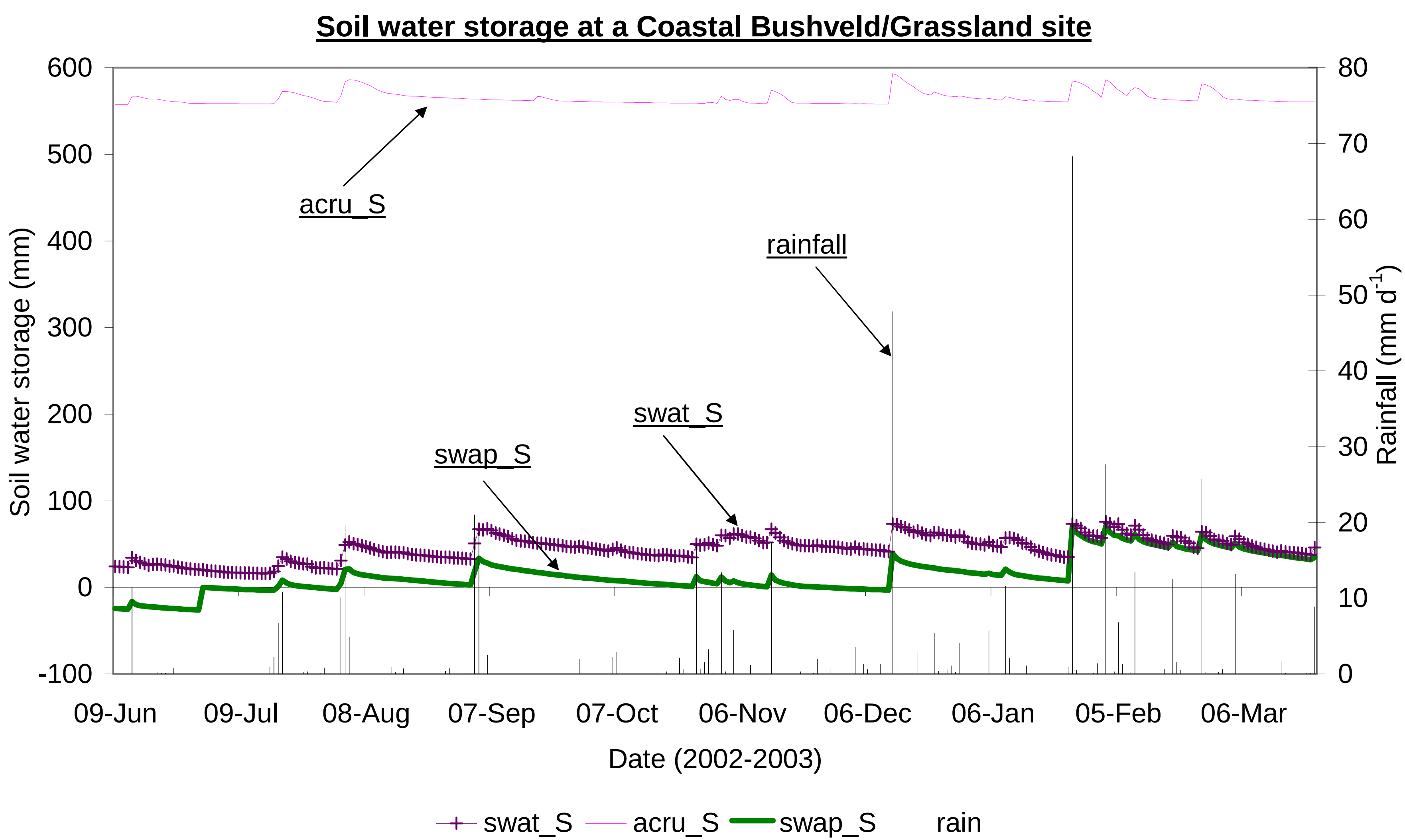


Figure 42 Soil water storage at the Coastal Bushveld/Grassland site simulated with *ACRU* (acru_S), *SWAT* (swat_S), *SWAP* (swap_S) and rainfall (bars) for the period 10 June 2002 to 25 March 2003

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

One of the aims of this project was to investigate available generic plant growth models and to recommend a model that simulates the plant growth, canopy conditions and total evaporation from natural veld types accurately. This study demonstrated that no single model can be recommended for accurate plant water use predictions of all natural veld types. This was concluded from the irregular model performances at each research site. Therefore, to improve future total evaporation simulations for Moist Upland Grassland, Valley Thicket and Coastal Bushveld/Grassland found in South Africa, it is suggested that model developments address the limitations highlighted for each model and vegetation type.

Firstly, within *ACRU,* the following needs to be addressed to improve the total evaporation simulations for natural veld types:

- Initial crop coefficients (Moist Upland Grassland, Valley Thicket), and the effect that soil water has on the final crop coefficients (all vegetation types); and the
- Current growth routines need to be replaced by a more mechanistic growth model (Valley Thicket and Coastal Bushveld/Grassland).

Secondly, for improved total evaporation simulations for natural veld types with *SWAT,* the following needs to be improved:

- Reference evaporation routine (Moist Upland Grassland and Coastal Bushveld/Grassland);
- Current growth routines need to be replaced by a more mechanistic growth model (all vegetation types); and
- Soil water storage component (Coastal Bushveld/Grassland).

Thirdly, the crop growth routines within *SWAP* need to be replaced by a more mechanistic crop growth model to improve the accuracy of the total evaporation simulations for complex, species rich vegetation types as Valley Thicket and Coastal Bushveld/Grassland.

A comparison of these three models showed that improved estimation of total evaporation from natural veld types is dependent upon accurate representation of the reference evaporation, crop growth routines, and soil water storage. Complex natural veld types such as Valley Thicket and Coastal Bushveld/Grassland, with different vegetation compositions and stages of succession, are not easily characterised by average vegetation parameters and cannot be adequately represented by simple systems.

Suggested improvements for the different vegetation types studied and listed in Chapter 4 (Sections 4.3.5, 4.4.3 and 4.5.3), are repeated below.

Suggested improvements specific to Moist Upland Grassland

A number of factors have been identified that affect the accuracy of the simulation of total evaporation of Moist Upland Grassland. By addressing these factors during model configuration, or through modifications to the *ACRU* and *SWAT* models, the accuracy of total evaporation simulations of Moist Upland Grassland could be improved.

Within the ***ACRU*** model, the initial crop coefficients specified for Moist Upland Grassland are always less than one. These crop coefficients specified will inevitably limit the total evaporation rates to less than the potential. These initial crop coefficients potentially need to be reviewed. In addition, soil water availability following the dry season influences the growth and total evaporation. At the start of the new rainy season, the soil water content is often less than 40 % of the Plant Available water, and hence the crop coefficients are reduced. Such conditions further reduce the total evaporation below potential evaporation rates.

Within the ***SWAT*** model, the factors influencing accurate total evaporation simulations of Moist Upland Grassland were the growth and reference evaporation routines. The growth parameters specified within the model resulted in abrupt changes in the growth pattern. This does not mimic the gradual die-back of the grasses when plant maturity is reached or the renewed growth of the grasses at the start of a new rainy season. These parameters need to be re-evaluated, and adjusted in order to mimic the growth of grass better. The reference evaporation formulation applied in *SWAT* often limits the reference evaporation rates to rates lower than the total evaporation rates measured for Moist Upland Grassland. Therefore, it is expected that the total evaporation simulated with *SWAT* will often be lower than that measured at the Moist Upland Grassland site.

Suggested improvements specific to Valley Thicket

In order to improve the simulation of total evaporation with the ***ACRU*** model, the crop coefficients specified within this model for Valley Thicket need to be reassessed. In addition, the mechanisms by which the initial crop coefficients are reduced due to soil water stress need to be improved.

ACRU and ***SWAP*** use generalized vegetation parameters and do not allow detailed parameterisation of multi-layered, species-rich vegetation types. Therefore, to improve the simulation of the total evaporation of Valley Thicket, a more mechanistic crop growth routine, providing for complex vegetation types, are required. In addition, the vegetation parameters required by these mechanistic crop growth models need to be measured for complex vegetation types such as Valley Thicket. Measurements of these vegetation parameters are therefore also required for improved total evaporation simulations with ***SWAT***.

Suggested improvements specific to Coastal Bushveld/Grassland

High total evaporation rates measured at the Coastal Bushveld/Grassland site within this dry period could be explained by a larger soil water store and deeper root system. The larger soil water store could be the result of a deep soil profile, extending to more than 3 metres, and the high water holding capacity of the clayey soil layers. In addition, the root distribution of the tree component of the vegetation could have allowed for extraction of soil water from deeper soil layers. However, the models were configured to a maximum soil depth of 3 m, which limited the root distribution and the availability of soil water from deeper soil layers.

Within ***ACRU***, 75 % of the roots occur within the topsoil layer (at this site set to 0.3 m), which is specified within the model for Coastal Bushveld/Grassland. When compared to the topsoil layer, less water is extracted by the remaining 25 % of the roots from the sub-soil layer (1.67 m), which has a larger soil water store. Due to this limitation, *ACRU* underestimated the total evaporation for Coastal Bushveld/Grassland. Therefore, to improve the total evaporation simulations for this vegetation type, the monthly average root distribution within the different soil layers need to be reassessed.

The total evaporation simulated with ***SWAT*** was limited by the reference evaporation and soil water availability. In order to improve the total evaporation simulations for Coastal Bushveld/Grassland, the routines related to the reference evaporation and the soil water need to be improved. From the simulations at all the sites it is clear that the reference evaporation is generally underestimated with *SWAT* (Moist Upland Grassland and Valley Thicket – summer months; Coastal Bushveld/Grassland – all months).

In the ***SWAP*** simulations, the total evaporation of Coastal Bushveld/Grassland was similarly limited by the root distribution (70 %) and soil water availability in the upper soil layer (0.45 m). To improve the parameterisation of the root system for Coastal Bushveld/Grassland, root excavation studies should be under taken, or a parameter optimisation technique applied to determine the most appropriate root depth-density relationship for the model.

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APPENDICES

Appendix I Parameterisation of the *ACRU* model

Table 2 Parameters used in *ACRU* for the simulation of grassland, Valley Thicket and Coastal Bushveld/Grassland sites

Group Description	Variable	COASTAL BUSHVELD/GRASSLAND	MOIST UPLAND GRASSLAND	VALLEY THICKET
Mode of simulation	ICELL	0 (Lumped)	0 (Lumped)	0 (Lumped)
Distributed Mode options	ISUBNO MINSUB MAXSUB LOOPBK	1 1 1 0	1 1 1 0	1 1 1 0
Flow routing options	IROUTE DELT	0 1440.0	0 1440.0	0 1440.0
Sub-catchment configuration	ICELLN IDSTRM PRTOUT	0 0 0	0 0 0	0 0 0
Rainfall file	IRAINF	Bon.comp	Comp.dat	Nood.comp
Rainfall information	FORMAT PPTCOR MAP	1 0 724	1 1 1299	1 0 843
Monthly rainfall adjustment factors	CORPPT	-	Jan-Dec : 1.06	-
Availability of observed streamflow data	IOBSTQ IOBSPK IOBOVR	0 0 0	1 0 0	0 0 0
Streamflow file	ISTRMF	-	-	-
Dynamic file name	DNAMIC	0	0	0
	IDYNFL	-	-	-
Catchment information	CLAREA ELEV ALAT ALONG IHEMI IQUAD	0.47 57.4 28.03 32.28 2 1	0.68 1950.0 29.00 29.25 2 1	0.25 838.0 29.32 30.83 2 1
Period of record for simulation	IYSTRT IYREND	1998 2002	1990 1995	1997 2002
Monthly means of daily maximum temperature	TMAX	30.7, 30.3, 29.7, 29.9, 26.2, 24.4, 24.2, 25.4, 26.4, 27.0, 28.0, 30.0	26.0, 25.6, 24.6, 22.3, 19.9, 17.3, 17.6, 19.7, 22.0, 23.1, 24.0, 25.6	26.1, 26.7, 25.7, 24.4, 22.4, 20.3, 20.5, 21.7, 22.8, 23.5, 24.2, 26.0
Monthly means of daily minimum temperature	TMIN	20.5, 20.6, 19.7, 17.3, 14.2, 11.1, 11.0, 12.8, 15.2, 16.6, 18.1, 19.7	13.9, 13.7, 12.4, 9.0, 5.5, 2.6, 2.4, 4.5, 7.5, 9.7, 11.4, 13.0	16.3, 16.4, 15.5, 13.1, 10.3, 7.5, 7.5, 9.1, 11.1, 12.4, 13.8, 15.4
Reference potential evaporation option	EQPET	109 (Linacre 1991, Daily)	102	109 (Linacre 1991, Daily)
Evaporation input availability control flags	IEIF ILRF IWDF IRHF ISNF IRDF IPNF	0 0 0 0 0 0 0	1 0 0 0 0 0 0	0 0 0 0 0 0 0
Monthly totals of A-pan equivalent evaporation	E	208.3, 176.3, 171.8, 134.8, 119.0, 95.9, 105.9, 132.8, 151.6, 176.5 180.1 210.1 (not used)	187.3, 158.8, 147.0, 122.3, 105.8, 95.5, 107.0, 134.4, 159.9, 174.4, 175.9, 198.5	175.8, 152.6, 147.9, 121.9, 106.8, 95.1, 102.8, 129.0, 144.6, 157.6, 157.3, 176.0 (not used)
Temperature adjustment for altitude	TELEV LRREG	1040.0 0	1040.0 0	1040 0
Mean lapse rates for min and max temperature	TMAXLR TMINLR	7.00 5.50	7.00 5.50	7.00 5.50
Mean daily wind speed ($m\ s^{-1}$)	WNDSPD	1.6	1.6	1.5
Penman equation option for S-tank or A-pan equivalent evaporation	SAPANC	0	1	0
Smoothed mean monthly A-pan/S-pan ratios	SARAT	1.26, 1.25, 1.26, 1.27, 1.30, 1.34, 1.36, 1.37, 1.35, 1.32, 1.28, 1.27	1.26, 1.25, 1.26, 1.27, 1.30, 1.34, 1.36, 1.37, 1.35, 1.32, 1.28, 1.27	1.26, 1.25, 1.26, 1.27, 1.30, 1.34, 1.36, 1.37, 1.35, 1.32, 1.28, 1.27
Pan adjustment option	PANCOR	1	0	1
	CORPAN	Jan-Dec : 1.10	1.00, 1.00, 0.90, 0.90, 0.95, 0.49, 0.44, 0.43, 0.45, 0.48, 0.52, 0.53	Jan-Dec : 1.10
Level of soils information	PEDINF	1	1	1
Soils texture information	ITEXT	7	11	3
Soil thickness information	PEDDEP	2	2	2
Soils information Depth of A horizon Depth of B horizon Wilting point topsoil Wilting point subsoil Field capacity topsoil Field capacity subsoil Porosity topsoil Porosity subsoil Redistribution of water from topsoil to subsoil.	 DEPAHO DEPBHO WP1 WP2 FC1 FC2 PO1 PO2 ABRESP	 0.33 1.67 0.269 0.280 0.312 0.326 0.447 0.465 0.40	 0.25 0.25 0.250 0.245 0.420 0.420 0.550 0.550 0.65	 0.30 1.76 0.096 0.086 0.191 0.189 0.479 0.458 0.45

Group Description	Variable	COASTAL BUSHVELD/GRASSLAND	MOIST UPLAND GRASSLAND	VALLEY THICKET
Redistribution of water from subsoil to to intermediate groundwater store.	BFRESP	0.40	0.50	0.45
Initial values of soil water retention constants	SMAINI SMBINI	0.00 0.00	80.00 80.00	0.00 0.00
Level of land cover information	LCOVER	1	1	1
	CROPNO	0	2030306	2040101
Determination pf canopy interception loss	INTLOS	1	1	1
Leaf area index information	LAIND	0	0	0
Monthly means of crop coefficients (Database parameters)	CAY	0.85, 0.85, 0.85, 0.85, 0.75, 0.65, 0.65, 0.75, 0.85, 0.85, 0.85, 0.85	0.70, 0.70, 0.65, 0.50, 0.20, 0.20, 0.20, 0.20, 0.35, 0.45, 0.55, 0.65	0.80, 0.80, 0.80, 0.70, 0.60, 0.50, 0.40, 0.40, 0.65, 0.75, 0.80, 0.80
Monthly means of leaf area index	ELAIM	Jan-Dec : 0.00	Jan-Dec : 0.00	Jan-Dec : 0.00
Canopy interception loss (mm) per rainday	VEGINT	3.10, 3.10, 3.10, 3.10, 2.50, 2.00, 2.00, 2.50, 3.10, 3.10, 3.10, 3.10	Jan-Dec : 1.30	2.20, 2.20, 2.20, 2.20, 2.00, 1.90, 1.90, 1.90, 2.20, 2.20, 2.20, 2.20
Fraction of active root system in topsoil horizon specified month by month	ROOTA	Jan-Dec : 0.75	0.92, 0.92, 0.92, 0.95, 1.00, 1.00, 1.00, 1.00, 0.95, 0.92, 0.92, 0.92	0.75, 0.75, 0.75, 0.75, 0.85, 0.90, 0.90, 0.90, 0.85, 0.75, 0.75, 0.75
Effective total rooting depth	EFRDEP	Defaulted to Depth of A and B horizons	Defaulted to Depth of A and B horizons	Defaulted to Depth of A and B horizons
Total evaporation control variables	EVTR FPAW	2 0	1 0	2 0
Fraction of PAW at which plant stress sets in	CONST	0.30	0.40	0.20
Critical leaf water potential	CRLEPO	0.00	0.00	0.00
Option for enhanced wet canopy evaporation	FOREST	0	0	0
Mean temperature threshold for active growth	TMPCUT	1.0	1.0	1.0
Unsaturated soil moisture redistribution	IUNSAT	1	1	1
Streamflow simulation control variables	QFRESP COFRU SMDDEP IRUN ADJIMP DISIMP STOIMP	0.30 0.009 0.00 1.0 0.020 0.00 1.00	0.30 0.012 0.00 1.0 0.00 0.00 1.00	0.30 0.009 0.00 1.0 0.010 0.022 1.00
Coefficient of initial abstraction	COIAM	Jan-Dec : 0.30	0.15, 0.15, 0.10, 0.20, 0.30, 0.30, 0.30, 0.30, 0.30, 0.35, 0.25, 0.25	0.25, 0.25, 0.30, 0.35, 0.35, 0.35, 0.35, 0.35, 0.35, 0.30, 0.25, 0.25
Abstraction option	IDOMR	0 (no abstraction)	0	0

Appendix II Parameterisation of the *SWAT* model

Table 3 Table describing some of the important input parameters used in *SWAT* in the simulation of the grassland, Valley Thicket and Coastal Bushveld/Grassland sites

Soil Parameters	COASTAL BUSHVELD/GRASSLAND		MOIST UPLAND GRASSLAND		VALLEY THICKET	
	Layer 1	Layer 2	Layer 1	Layer 2	Layer 1	Layer 2
Soil Landtype or Form	Ea 57		Hutton		Bb109	
Depth [mm]	330	2670	290	2000	240	2760
Bulk Density[vii] Moist [g cc^{-1}]	1.55	1.48	0.8	0.86	1.38	1.44
Available Water Capacity	0.04	0.05	0.11	0.06	0.1	0.1
Saturated Hydraulic Conductivity[viii] [mm hr^{-1}]	51	0.89	27.16	1.8	7.05	6.75
Organic Carbon [%]	5.43	0.69	8	5	0.26	0.05
Clay [%]	30.64	43	61	45	10.4	15.9
Silt [%]	39	30.1	20	28	12.99	15.2
Sand [%]	30.36	26.9	19	27	76.61	68.9
Rock Fragments [%]	2.36	7.37	2.36	7.37	10	35
Soil Albedo (Moist)	0.06	0.06	0.1	0.1	0.2	0.2
USLE K	0.39	0.39	0.34	0.34	0.52	0.52

Table 4 A list of the inputs required and used in *SWAT* in the simulation of the water balances of Moist Upland Grassland, Valley Thicket and Coastal Bushveld/Grassland

Landcover / Plant Growth Parameters		Coastal Bushveld / Valley Thicket		Grassland
		Tree Clusters	Grass Patches	
Biomass/Energy Ratio.	BIO_E	15.0000	34.0000	34.0000
Harvest index. (Fraction of the aboveground biomass that is removed during a harvest operation)	HVSTI	0.7600	0.9000	0.9000
Max leaf area index.	BLAI	5.0000	2.5000	2.0000
Fraction of the plant growing season (heat units) corresponding to the 1st. Point on the optimal leaf area development curve.	FRGRW1	0.0500	0.0500	0.0500
Fraction of the max. leaf area index corresponding to the 1st. point on the optimal leaf area development curve.	LAIMX1	0.0500	0.1000	0.1000
Fraction of the plant growing season corresponding to the 2nd. point on the optimal leaf area development curve.	FRGRW2	0.4000	0.2500	0.2500
Fraction of the max. leaf area index corresponding to the 2nd. point on the optimal leaf area development curve.	LAIMX2	0.9500	0.7000	0.7000
Fraction of growing season when leaf area starts declining.	DLAI	0.9900	0.8000	0.3500
Max canopy height.	CHTMX	6.0000	0.7000	1.0000
Max root depth.	RDMX	3.0000	2.0000	2.0000
Optimal temp for plant growth.	T_OPT	30.0000	25.0000	25.0000
Min temp plant growth.	T_BASE	10.0000	12.0000	12.0000
Min value of USLE C factor applicable to the land cover/plant.	USLE_C	0.0010	0.0030	0.0030
Max stomatal conductance (in drought condition). ($m.s^{-1}$)	GSI	0.0020	0.0050	0.0050
Vapour pressure deficit corresponding to the fraction maximum stomatal conductance defined by FRGMAX	VPDFR	4.0000	4.0000	4.0000
Fraction of maximum stomatal conductance that is achievable at a high vapour pressure deficit.	FRGMAX	0.7500	0.7500	0.7500
Rate of decline in radiation use efficiency per unit increase in vapour pressure deficit.	WAVP	8.0000	10.0000	10.0000
Elevated CO2 atmospheric concentration.	CO2HI	660.0000	660.0000	660.0000
Biomass-energy ratio corresponding to the 2nd. point on the radiation use efficiency curve.	BIOEHI	16.0000	39.0000	39.0000
Plant residue decomposition coefficient.	RSDCO_PL	0.0500	0.0500	0.000
SCS runoff curve number for moisture condition II.	CN2	73.0000	79.0000	61.0000
Minimum lai during dormancy	ALAIMIN	4.0000	0.1000	0.1000
The fraction of accumulated biomass, that is leaf mass.	BIOLEAF	0.3000	-	-
Initial leaf area index.	ALAI	4.0000	1.8000	2.0000
Initial dry weight biomass. (kg/ha)	BIO_MS	10000.0000	10000.0000	10000.0000
Total number of heat units or growing degree days needed to bring plant to maturity.	PHU	3000.0000	2000.0000	2500.0000

Appendix III Parameterisation of the *SWAP* model

Table 5 Inputs required by *SWAP* in order to simulate the site soil water balances of Moist Upland Grassland, Valley Thicket and Coastal Bushveld/Grassland

Parameter	Moist Upland Grassland	Valley Thicket	Coastal Bushveld/Grassland
Start of simulation run	01/01/1989	02/06/1997	05/04/1997
End of simulation run	10/09/1995	17/04/2003	03/04/2003
First month of agricultural year	7	7	7
Latitude	29.0° South	29.32° South	28.04° South
Altitude	1950m	805m	57m
Use ETRef from meteo files	Yes	Yes	Yes
Simulation of lateral drainage	No	No	No
Number of crops per season	1	1	1
Type of crop model	Simple	Simple	Simple
Emergence of crop	01/07	01/07	01/07
Forced end of crop growth	30/06	30/06	30/06
Length of crop cycle (d)	365 or 366	365 or 366	365 or 366
Extinction coefficient: Diffuse visible radiation Direct visible radiation	 0.4 0.4	 0.5 0.5	 0.5 0.5
Yield response as a function of development stage	1.0	1.0	1.0
Water and salt stress functions: No water extraction at higher pressure heads (cm) H below which water extraction starts for top layer (cm) H below which water extraction starts for sub layers (cm) H at which water uptake reduction starts at high Tpot (cm) H at which water uptake reduction starts at low Tpot (cm) No water extraction at lower pressure heads (cm) Level of high atmospheric demand (cm d^{-1}) Level of high atmospheric demand (cm d^{-1}) Minimum canopy resistance (s m^{-1}) ECsat at which salt stress starts (dS m^{-1}) Decline of rootwater uptake above (% $^{-1}$ dS^{-1} m)	 -10 -25 -25 -300 -1000 -15000 1.1 0.1 70 2.0 0.1	 -10 -25 -25 -500 -1500 -15000 1.1 0.1 70 0.6 0.1	 -10 -25 -25 -500 -1500 -15000 1.1 0.1 70 0.6 0.1
Interception coefficient Von Hoyningen-Hune and Braden (cm)	0.25	0.35	0.35

Parameter	Moist Upland Grassland	Valley Thicket	Coastal Bushveld/Grassland
Root depth *vs* density (relative)	0.25 0.90 1.00 0.10	0.15 0.70 0.27 0.15 0.30 0.05 1.00 0.10	0.15 0.70 0.27 0.15 0.30 0.05 1.00 0.10
Ponding thickness (cm)	5	5	5
Reduction in soil evaporation to…	Maximum Darcy flux	Maximum Darcy flux	Maximum Darcy flux
Richards equation time discretazation: Minimum time step (d) Maximum time step (d) Type of scheme	 1.00E-05 0.16 Richards equation solved until convergence	 1.00E-05 0.16 Richards equation solved until convergence	 1.00E-05 0.16 Richards equation solved until convergence
Number of soil layers	2	4	3
Number of soil compartments	40	40	40
Hysteresis	No	No	No
Similar media scaling	No	No	No
Preferential flow: Immobile water Soil cracks	 No No	 No No	 No No
Vertical distribution drainage flux	No	No	No
Initial moisture conditions: pressure head at each compartment (cm)	-1000	-3000	-3000
Maximum rooting depth (cm)	50	**300**	**200**

Table 6 Growth information required in the simple model set up for Moist Upland Grassland (MUG), Valley Thicket (VT) and Coastal Bushveld/Grassland (CBG)

Development stage	Leaf area index			Crop height (cm)			Rooting depth (cm)		
	MUG	VT	CBG	MUG	VT	CBG	MUG	VT	CBG
0.0									
0.17	2.76	1.13	0.49	1.0	500.0	360.0	0.0	250.0	250.0
0.33	2.56	1.24	0.55	1.0	500.0	360.0	0.0	250.0	250.0
0.50	2.33	1.43	0.71	1.0	500.0	360.0	0.0	150.0	150.0
0.67	1.1	1.71	0.98	80.0	500.0	360.0	25.0	100.0	100.0
0.83	1.36	2.08	1.36	80.0	500.0	360.0	25.0	50.0	50.0
1.00	1.76	2.52	1.85	120.0	500.0	360.0	25.0	50.0	50.0
1.17	1.76	2.24	2.40	120.0	500.0	360.0	25.0	50.0	50.0
1.33	1.96	1.84	1.82	120.0	500.0	360.0	25.0	50.0	50.0
1.50	2.26	1.53	1.34	80.0	500.0	360.0	25.0	100.0	100.0

Development stage	Leaf area index			Crop height (cm)			Rooting depth (cm)		
1.67	2.6	1.30	0.97	80.0	500.0	360.0	0.0	150.0	150.0
1.83	2.76	1.16	0.70	80.0	500.0	360.0	0.0	250.0	250.0
2.00	2.73	1.10	0.54	80.0	500.0	360.0	0.0	250.0	250.0

Table 7 Soil layer properties at the Moist Upland Grassland, Valley Thicket and Coastal Bushveld/Grassland sites

Parameter	Moist Upland Grassland		Valley Thicket				Coastal Bushveld/Grassland		
Depth below soil surface (cm)	**25**	**50**	**20**	**50**	**200**	**300**	**20**	**40**	**200**
Sand (%)	0.27	0.88	0.39	0.30	0.24	0.88	0.77	0.69	0.27
Silt (%)	0.28	0.08	0.30	0.27	0.29	0.10	0.13	0.15	0.28
Clay (%)	0.45	0.04	0.31	0.43	0.47	0.03	0.10	0.16	0.45
Organic matter (%)	0.00	0.00	0.05	0.01	0.00	0.00	0.00	0.00	0.00
Residual soil water content (cm^3 cm^{-3})	0.089	0.07	0.1009	0.0982	0.00	0.06	0.00	0.00	0.089
Saturated soil water content (cm^3 cm^{-3})	0.43	0.38	0.45	0.36	0.4	0.32	0.30	0.33	0.43
Saturated hydraulic conductivity (cm d^{-1})	1.0	189.48	4.4	4.488	5.256	57.72	27.72	10.20	1.0
Alpha main drying curve (cm^{-1})	0.01	0.0046	0.00044	0.0001	0.000852	0.0057	0.0272	0.0029	0.01
Exponent in hydraulic conductivity function	0.187	0.3824	0.0626	0.174441	0.059187	0.4147	0.0792	0.0956	0.187
Parameter n	1.23	1.6191	1.0668	1.2113	1.06291	1.7086	1.0860	1.1057	1.23
Alpha main wetting curve (cm^{-1})	0.01	0.0046	0.00044	0.0001	0.000852	0.0057	0.0272	0.0029	0.01

Additional information used in the *SWAP* simulations

Atmospheric inputs

SWAP requires the following climatic input data: daily total solar radiant density (kJ m^{-2}), daily minimum and maximum air temperature (°C), average daily relative humidity (kPa), average daily windspeed (m s^{-1}), daily total rainfall (mm d^{-1}) and daily total reference evapotranspiration (mm d^{-1}). Climatic data was collected at the Valley Thicket and Coastal Bushveld/Grassland sites for the periods 06/03/2002 to date, and 25/04/2002 to date respectively. The remaining and missing data were obtained from SASEX weather stations in close proximity. At the Moist Upland Grassland site, climatic data was collected for the period 01/01/1990 to 10/09/1995, and patched for the remaining period. The reference evapotranspiration was calculated within the *SWAP* model, using the Penman-Monteith equation (Van Dam et al., 2000).

Plant data inputs

The Moist Upland Grassland consist of a homogenous (single layer) grassland canopy, whereas the Valley Thicket and Coastal Bushveld/Grassland veld types are multilayer, hetereogenous vegetation types and consist of multi species tree clumps with grassland in between. *SWAP*, does not allow the simulation of growth of an understorey canopy separate from the main canopy, and it also does not make provision for overlap between more than one growing season. Therefore, for the modelling exercises at the Valley Thicket and Coastal Bushveld/Grassland, the simulation inputs combined the tree and grassland information

Simple model

SWAP has three crop growth model options with varying degrees of complexity and detail required (Van Dam et al., 2000). Due to data limitations at both research sites, the simple crop growth model was selected for simulations at both sites.

Soil data inputs

The soil forms identified at the Moist Upland Grassland, Valley Thicket and Coastal Bushveld/Grassland sites were Katspruit and Champagne (Moist Upland Grassland), and Cartref (Valley Thicket) and Willowbrook (Coastal Bushveld/Grassland) respectively.

Water

The bottom boundary conditions at Moist Upland Grassland, Valley Thicket and Coastal Bushveld/Grassland were set to simulate free drainage of the soil profile.

ENDNOTES

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[i] The impact of a change in vegetation on the streamflow is generally measured against a baseline vegetation. Natural veld types as described by Acocks (1988) and Low and Rebelo (1996) are often used as baseline vegetation. However, agricultural crops and forestry species are also used.

[ii] The model CS616 water content reflectometer is the later version of the model CS615 sensor.

[iii] Mechanistic implies a physically based crop growth model which is supply/demand limited.

[iv] Empirical implies a model which requires crop factors, crop coefficients or LAI as model input in order to simulate crop growth. Such inputs are based on observed, experimental or practical information.

[v]The Penman-Monteith evapotranspiration refers to the evapotranspiration from a dry, extensive, uniform canopy, optimally supplied by water as defined by Allen et al. (1998).

[vi] The intermediate zone is the lowest active root horizon.

[vii] Bulk density estimated from Total Porosity

[viii] Saturated hydraulic conductivity estimated using RETC program, based on estimates of particle sizes and bulk density of the soil