FACILITATING IRRIGATION SCHEDULING BY MEANS OF THE SOIL WATER BALANCE MODEL

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EXECUTIVE SUMMARY

Introduction

In large areas of South Africa, irrigation is required in order to achieve optimal yields. Crop water requirements need to be accurately quantified to improve the efficiency of irrigation water management.

The best estimates of crop water use result from direct measurements, but this is not always feasible on a large scale. The next most accurate approach would be one which integrates our understanding of the soil-plant-atmosphere continuum as mechanistically as possible. Taking the supply of water from the soil-root system, and the demand from the canopy-atmosphere system into account is essential to properly describe crop water use. The Penman-Monteith reference crop evaporation (Smith, Allen and Pereira, 1996) together with a mechanistic crop growth model, which uses soil water and grows a realistic canopy and root system provides the best possible estimate of the soil water balance. This approach has been out of reach of irrigators due to the specialist knowledge required to run the models. This high management cost can be drastically reduced by packaging the model in an extremely user-friendly format, eliminating the need for a detailed understanding of the intricacies of the soil-plant-atmosphere continuum. The benefits will be increased too, because of the accuracy of the mechanistic, and therefore universally valid, estimation procedure.

The interest in scheduling irrigations with crop growth computer models is rapidly increasing particularly since personal computers have become accessible to crop producers. Most of the existing models, however, either are crop specific or do not simulate daily crop water use. Some models are relatively simple to use for planning purposes, but do not allow real-time scheduling. Other models accurately describe the complexity of natural processes. This makes them suitable for research purposes, but they are generally not applicable in practice due to the large amount of input data required and lack of a user-friendly interface.

The Soil Water Balance (SWB) model is a mechanistic, real-time, generic crop, soil water balance, irrigation scheduling model. It is based on the improved generic crop version of the NEW Soil Water Balance (NEWSWB) model (Campbell and Diaz, 1988). SWB gives a detailed description of the soil-plant-atmosphere continuum, making use of weather, soil and crop management data. It thus largely overcomes the problems of other models for irrigation scheduling as indicated above. However, since SWB is a generic crop growth model, parameters specific for each crop have to be determined.

Aims

In order to make the SWB model more generally applicable and accessible, the following objectives were identified for this project:

i) To determine parameters for specific crops which are commonly irrigated in South Africa, and include them in the SWB database;
ii) To identify further development needs in respect of SWB in order to meet user requirements;
iii) To automate the acquisition of input weather data from automatic weather stations in order to facilitate and make scheduling more convenient;
iv) To evaluate SWB using independent data sets obtained from South African researchers and organizations;
v) To develop a user-friendly Windows 95 interface for easy technology transfer;
vi) To compile a comprehensive user manual;
vii) To compile a comprehensive user help facility; and
viii) To identify further research and model development needs which are not satisfied in this project.

Approach

Calibration and validation of SWB with independent data sets of relevance for irrigation scheduling was required in order to establish the reliability of the model in representing the real-world system. Three approaches were followed in order to meet these requirements:

i) An extensive literature search of Water Research Commission publications and others was carried out. Personal contacts with South African researchers and organizations were also made in order to obtain data sets.

ii) In the absence of useful data sets for some crops, field trials were carried out in order to collect data for the determination of specific crop growth parameters.

iii) An alternative model for estimating the soil water balance was developed for crops for which data sets were not available in the literature or through personal contacts, and where it was not possible to set up field trials to determine specific crop growth parameters. This model is based on the crop factor approach recommended by the FAO (Food and Agricultural Organization of the United Nations, Rome, Italy). It was developed in order to include more crops in the SWB crop database, by making use of the database of crop factors available in FAO publications.

Data sets for the validation of SWB were therefore sought for two types of model:

i) Crop growth and soil water balance model making use of specific crop growth parameters; and

ii) FAO-based model making use of FAO crop factors.

Methodology

Severe difficulties were encountered in the attempt to obtain complete, reliable and useable data sets for the validation of SWB. In most cases, available data sets were incomplete, in others potential collaborators were reluctant to make data available.

The following South African researchers are gratefully acknowledged for making complete independent data sets available for the calibration and validation of SWB:

i) Dr M Hensley (Institute for Soil, Climate and Water - Agricultural Research Council, Glen):

- Dry land maize grown at Setlagole, Ermelo and Kroonstad.

ii) Prof S Walker (University of the Orange Free State, Bloemfontein) and Dr TP Fyfield (Institute for Soil, Climate and Water - Agricultural Research Council, Pretoria):

- Irrigated wheat grown at Roodeplaat.

iii) Prof ATP Bennie (University of the Orange Free State, Bloemfontein):

- Irrigated maize, peanuts, peas, potato and wheat grown at Bloemfontein.
- Irrigated and dry land soybean grown at Castana (Iowa, USA).

iv) Dr MG Inman-Bamber (formerly South African Sugar Association Experiment Station, Mount Edgecombe; presently CSIRO, Townsville, Australia):

- Sugarcane grown at Pongola.

v) Ms T Volschenk (Agricultural Research Council - Infruitec, Stellenbosch):

- Apples grown at Elgin.

vi) Mr A Nel (Grain Crops Research Institute - Agricultural Research Council, Potchefstroom):

- Sunflower grown at Potchefstroom.

vii) Dr GC Green and Mr HM du Plessis (Water Research Commission):

- Citrus.

In the absence of useful data sets for vegetables, a field trial was set up at Roodeplaat in cooperation with Mr W van Wyk (Department of Agriculture - Directorate of Plant and Quality

Control, Pretoria). The objective was to determine specific crop growth parameters for several irrigated vegetable species, and include them in the database of SWB.

In the absence of time consuming and therefore expensive growth analysis data, a simpler modelling approach was required. An FAO-based crop factor procedure has therefore been developed and combined with the mechanistic SWB model, thereby still allowing evaporation and transpiration to be modelled separately as supply- and demand-limited processes. The crop factor model does not grow the canopy mechanistically and therefore the effect of water stress on canopy size is not simulated. The simpler crop factor model should, however, still perform satisfactorily if the estimated canopy cover closely resembles that found in the field.

The FAO model was mainly developed in order to include more crops in the SWB crop database, by making use of the database of basal crop coefficients, growth periods, root depths, crop heights, stress factors and potential yields available in FAO publications (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen, Smith, Pruitt and Pereira, 1996). In particular, tree crops were critical as growth analyses for trees are seldom available.

A field trial was carried out at Hatfield in order to determine FAO crop parameters for peach trees. Specific crop growth parameters for peaches were not determined as it was not possible to carry out growth analysis due to the limited number of trees and limited time available.

Results

Data obtained from the field trials were used to calibrate SWB.

Weather, soil and growth analysis data collected at Roodeplaat, were used to determine specific crop growth parameters for six winter vegetables and 19 varieties of summer vegetables. Guidelines for the determination of vapour pressure deficit corrected dry matter-water ratio, radiation conversion efficiency, specific leaf area, leaf-stem dry matter partitioning parameter, canopy extinction coefficient for solar radiation, maximum rooting depth and growing day degrees for the completion of phenological stages, are given in this study.

Weather data and canopy cover measurements obtained in the field trial at Roodeplaat were used to determine FAO crop factors for vegetables, and include them in the SWB database. Guidelines for the determination of FAO basal crop coefficients and length of growth stages are also given in this study.

Field measurements obtained in the Hatfield trial, were used to determine FAO basal crop coefficients and growth periods for first and second leaf peach trees.

Independent data sets obtained from South African researchers and organizations, were used to validate the model.

Simulations were carried out for agronomic, vegetable and tree crops, using both the crop growth and FAO-type model. Reasonable predictions of soil water deficit, root depth, leaf area index, total above ground and harvestable dry matter were obtained with SWB. Differences in crop water use and growth were observed for different cultivars. The crop growth model proved to be suitable for deficit irrigation simulations. Soil water deficit predicted with the FAO-type model was generally higher than that calculated with the crop growth model under water stress conditions, as the FAO model does not account for smaller canopy size. Caution should be exercised against blind acceptance of the FAO parameters as local conditions, management and cultivars are likely to influence crop growth periods and basal crop coefficients. They should, however, give a reasonable first estimate of the behaviour of the system.

The following improvements to SWB have been made:

i) Conversion of the old DOS version of the model to the efficient 32 bit Delphi Windows 95 version.

ii) "Marriage" of the mechanistic soil water balance model to the FAO basal crop coefficient approach. This brings with it the advantage of immediate inclusion of several new crops into SWB's crop database. The parameters for these crops are available from international research on updating FAO 24 (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996).

iii) The standardized FAO Penman-Monteith grass reference evapotranspiration was included in SWB, as well as standardized options for estimating missing weather data (Smith, 1992b; Smith et al., 1996).

iv) Estimation of yield with the FAO model under conditions of water stress.

v) Calculation of the soil water balance when only a fraction of the surface is wetted (micro- or drip irrigation).

vi) Calculation of non-instantaneous drainage.

The user-friendly interface, on-line help tool, range and error checking, as well as comprehensive output graphs should allow the user to easily make real-time use of the output results. The context sensitive help tool describes how to operate the model (enter input data, run simulations, and print or create results and recommendations) and most of the technical procedures used by SWB to estimate crop growth and calculate the soil water balance. Recommended ranges for input data and general information are also given.

Product

SWB (Version 1.0) is available for use with Windows 95 on an IBM-PC or compatible computer. The minimum requirement is 16 Mb RAM . The program is supplied in executable code on 3.5-inch disks or CD, including a comprehensive user's guide and technical manual. Copies of the program are available through John G. Annandale, Dept. Plant Production and Soil Science, Univ. of Pretoria, 0001 Hatfield, South Africa (e-mail address: annan@scientia.up.ac.za).

The cost of the CD and user's guide and technical manual is R500, if SWB is used for commercial purposes. Bona fide researchers and government extension officers are charged R100 to cover duplication costs.

The source code of the model is available from Dr N Benadé. All data presented in this report are stored in the databases of SWB.

The following special features are included in the model:

i) A stand-alone ETo calculator which allows one to calculate the FAO Penman-Monteith grass reference evapotranspiration without running SWB.

ii) Soil water deficit can be calculated from measurements with the neutron water meter using the neutron probe scheduler as a stand-alone tool.

iii) Soil water deficit can be calculated from measurements with tensiometers using the tensiometer scheduler as a stand-alone tool.

iv) Soil water deficit can be calculated from measurements of gravimetric soil water content using the gravimetric scheduler as a stand-alone tool.

v) Volumetric soil water content at field capacity and permanent wilting point can be calculated from the percentage silt and clay, using empirical equations calibrated for soils in the Free State.

vi) Simulated values of fractional interception of radiation and volumetric soil water content can be updated real-time with measured data. In order to facilitate the estimation and update of fractional interception of radiation (canopy cover), a database of photos of crops at different phenological stages was included in the help file.

vii) Recommendations for irrigation scheduling are created and can be printed in SWB.

viii) A database of specific crop growth parameters and FAO crop factors is included in SWB.

ix) An address database is available.

x) Weather data can be imported into SWB from comma delimited, tab delimited or space delimited files. The order in which the data appear in the file can be specified, so standardization of data files is not important. While importing weather data, the program checks for data out of range.

Technology transfer

The main target group includes farmers as well as irrigation officers and consultants. Several commercial farmers and irrigation officers are already using or are planning to use SWB for real-time irrigation scheduling. Small-scale commercial farmers are also potential users, as well as small-scale subsistence farmers, provided they are advised by irrigation officers.

The model needs to be used extensively in the field now so that users can give valuable feedback as to it's user-friendliness and accuracy.

Conclusions and needs for further research

The revised objectives of the project have been met. A database for most crops commonly irrigated in South Africa was generated and included in SWB. A user-friendly irrigation scheduling tool was created that can be applied in practice.

Further research needs concern the introduction of specific crop growth parameters for cotton and some important tree crops. Different cultivars for crops already existing in the SWB database could also be included. Crop growth parameters refinement should be ongoing.

Deficit irrigation strategies can be accurately simulated with the mechanistic crop growth model. An economic subroutine can therefore be included in SWB in order to facilitate economic optimization target yields and irrigation strategies.

Specific requirements for some crops can be included in SWB. For example, irrigation scheduling of factory tomato and tobacco for yield and quality optimization can be modelled. Photoperiod should be included in SWB for crops like potatoes. Existing specific crop growth models can be merged to SWB in order to obtain more accurate simulations of the soil water balance and crop growth. A two-dimensional soil water balance and energy interception model is needed to predict water requirements of trees accurately.

Inclusion of a nitrogen balance will also assist irrigators quantifying possible N leaching and crop N requirements. Other useful additions include taking electricity tariffs (ruralflex) into account when recommending irrigations. Due to the fact that weather data is already in the database, disease, insect and frost warnings can also be added to make the tool even more valuable to the producer.

Agricultural development can be enhanced by making seasonal rather than real-time estimates with SWB available to farmers that do not own an automatic weather station and computer.

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Mr HM du Plessis	Water Research Commission
Prof LK Oosthuizen	University of the Orange Free State, Bloemfontein
Prof ATP Bennie	University of the Orange Free State, Bloemfontein
Mr FC Olivier	Institute for Soil, Climate and Water - Agricultural Research Council, Pretoria
Mr R Kuschke	Institute for Soil, Climate and Water - Agricultural Research Council, Pretoria
Dr A Singels	South African Sugar Association Experiment Station, Mount Edgecombe

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- Prof ATP Bennie (University of the Orange Free State, Bloemfontein),
- Dr MG Inman-Bamber (formerly South African Sugar Association Experiment Station, Mount Edgecombe; presently CSIRO, Townsville, Australia),
- Ms T Volschenk (Agricultural Research Council - Infruitec, Stellenbosch)
- Mr FC Olivier (Institute for Soil, Climate and Water - Agricultural Research Council, Pretoria),
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a	-	Campbell's coefficient of the log-log water retention function
ADL	-	Allowable depletion level
Alt	-	Altitude (m)
a_n	-	Leaf absorptance of near infrared radiation
a_p	-	Leaf absorptance of photosynthetically active radiation
a_s	-	Leaf absorptance of solar radiation
b	-	Campbell's coefficient of the log-log water retention function
CDM	-	Canopy dry matter (kg m^{-2})
CDM_i	-	Canopy dry matter daily increment (kg m^{-2})
D	-	Index of agreement of Willmott
DAP	-	Days after planting
Dec	-	Solar declination (rad)
DevStage	-	Length of crop development stage (days)
Df	-	Drainage factor
D_i	-	Amount of water that penetrates the deeper soil layer (mm)
DM	-	Dry matter production (kg m^{-2})
DM_i	-	Daily increment of total dry matter (kg m^{-2})
DOY	-	Day of year
Dr	-	Drainage (mm)
D_{rel}	-	Relative distance of the earth from the sun
DWR	-	Dry matter-water ratio (Pa)
dz	-	Soil layer thickness (m)
E	-	Actual evaporation (mm)
e_a	-	Actual vapour pressure (kPa)
E_c	-	Radiation conversion efficiency (kg MJ^{-1})
EMDD	-	Emergence day degrees
e_s	-	Saturated vapour pressure (kPa)
ET	-	Evapotranspiration (mm)
ET_{lys}	-	Water loss measured with the lysimeter (mm)
ETo	-	FAO reference evapotranspiration (mm)
E^*	-	Maximum dimensionless loss rate
f	-	Layer root fraction
FAO	-	Food and Agricultural Organization of the United Nations (Rome, Italy)
f_c	-	Cloudiness factor
f_I	-	Irrigated fraction of the surface ground (fraction of wetted area)
FI	-	Fractional interception of radiation
FI_{evap}	-	Fractional interception of radiation by photosynthetically active and senesced leaves
FI_{transp}	-	Fractional interception of radiation by photosynthetically active leaves
f_l	-	Leaf partitioning factor
FLDD	-	Day degrees at end of vegetative growth
f_r	-	Fraction of dry matter partitioned to roots
G	-	Soil heat flux (°C)
g	-	Gravitational acceleration (9.8 m s^{-2})

GDD	-	Growing day degrees
GDD_i	-	Growing day degrees daily increment
Hc	-	Crop height (m)
H_cGrad	-	Gradient of crop height increase during the development stage
H_cIni	-	FAO initial crop height (m)
Hc_{max}	-	Maximum crop height (m)
HDM	-	Harvestable dry matter (kg m^{-2})
HDM_i	-	Harvestable dry matter daily increment (kg m^{-2})
H_U	-	Height at which wind speed is measured (m)
I	-	Irrigation amount (mm)
I_c	-	Amount of precipitation intercepted by the canopy (mm)
IniStage	-	Length of crop initial stage (days)
K	-	Canopy radiation extinction coefficient
K_{bd}	-	Canopy extinction coefficient of black leaves and diffuse radiation
K_{PAR}	-	Canopy extinction coefficient of photosynthetically active radiation
K_s	-	Canopy extinction coefficient of total solar radiation
Kc	-	FAO crop coefficient
Kcb	-	FAO basal crop coefficient
$K_{cb}DownGrad$	-	Gradient of FAO basal crop coefficient decrease during the late-season stage
$K_{cb}Ini$	-	FAO basal crop coefficient for initial stage
$K_{cb}Late$	-	FAO basal crop coefficient for end-season stage
$K_{cb}Mid$	-	FAO basal crop coefficient for mid-season stage
$K_{cb}UpGrad$	-	Gradient of FAO basal crop coefficient increase during the development stage
Kc_{max}	-	FAO maximum crop coefficient
Ky	-	FAO stress factor
LAI	-	Leaf area index
$LAIage_i$	-	Age of leaf area index generated on day "i"
LAI_i	-	Leaf area index daily increment
Lat	-	Latitude (deg)
LateStage	-	Length of crop end-season stage (days)
LDM	-	Leaf dry matter (kg m^{-2})
LDM_i	-	Leaf dry matter daily increment (kg m^{-2})
Loss	-	Soil water loss by transpiration (fraction of soil volume)
MAE	-	Mean absolute error
MidStage	-	Length of crop mid-season stage (days)
MTDD	-	Maturity day degrees
N	-	Number of observations
n	-	Duration of the crop stage
NIR	-	Near infrared radiation (0.7-3 μm)
NWM	-	Neutron water meter
P	-	Precipitation (mm)
P_a	-	Atmospheric pressure for a given altitude (kPa)
PAR	-	Photosynthetically active radiation (0.4-0.7 μm)
PART	-	Stem-leaf partitioning parameter (m^2 kg^{-1})
PE	-	Potential evaporation (mm)

PET	-	Potential evapotranspiration (mm)
PT	-	Potential transpiration (mm)
PWP	-	Permanent wilting point
P_0	-	Standard atmospheric pressure at sea level (101.3 kPa)
R	-	Runoff (mm)
R_a	-	Extraterrestrial radiation (MJ m^{-2} day^{-1})
RD	-	Root depth (m)
RDGrad	-	Gradient of root depth increase during the development stage
RDIni	-	Initial root depth (m)
RDM	-	Root dry matter (kg m^{-2})
RDM_i	-	Root dry matter daily increment (kg m^{-2})
RD_{max}	-	Maximum root depth (m)
Rg	-	Specific gas constant for dry air (286.9 J kg^{-1} K^{-1})
RGR	-	Root growth rate (m^2 $kg^{-0.5}$)
R_h	-	Hedgerow spacing (m)
RH_{max}	-	Daily maximum relative humidity (%)
RH_{min}	-	Daily minimum relative humidity (%)
RMSE	-	Root mean square error
R_n	-	Net radiation (MJ m^{-2} day^{-1})
R_{nl}	-	Long-wave net radiation (MJ m^{-2} day^{-1})
R_{ns}	-	Short-wave net radiation (MJ m^{-2} day^{-1})
rpf	-	Reproductive partitioning fraction
R_s	-	Solar radiation (MJ m^{-2} day^{-1})
R_{so}	-	Short-wave radiation during bright sunshine (MJ m^{-2} day^{-1})
r^2	-	Coefficient of determination
S	-	Runoff curve number (mm)
SDM	-	Stem dry matter (kg m^{-2})
SDM_i	-	Stem dry matter daily increment (kg m^{-2})
SI	-	Stress index
SLA	-	Specific leaf area (m^2 kg^{-1})
SWB	-	Soil Water Balance model
SWD	-	Soil water deficit (mm)
T	-	Actual transpiration (mm)
T_a	-	Air temperature (°C)
T_{avg}	-	Daily average air temperature (°C)
T_b	-	Base temperature (°C)
T_{cutoff}	-	Cutoff temperature (°C)
T_d	-	Dry bulb temperature (°C)
TDM	-	Top dry matter (kg m^{-2})
T_f	-	Temperature factor for light limited crop growth (°C)
T_{lo}	-	Temperature for optimum light-limited crop growth (°C)
T_{max}	-	Daily maximum air temperature (°C)
T_{min}	-	Daily minimum air temperature (°C)
TransDD	-	Day degrees of transition period from vegetative to reproductive growth
Transl	-	Factor determining translocation of dry matter from stem to grain
Tr_{max}	-	Maximum transpiration rate (mm day^{-1})
T_w	-	Wet bulb temperature (°C)

T_0	-	Standard temperature at sea level (293 K)
T^*	-	Dimensionless actual water uptake
U	-	Wind speed ($m\ s^{-1}$)
U_2	-	Wind speed measured at 2 m height ($m\ s^{-1}$)
U^*	-	Dimensionless root uptake rate
VPD	-	Vapour pressure deficit (Pa)
Wc	-	Width of the hedgerow canopy (m)
wsf	-	Water stress factor
Y	-	Crop yield ($t\ ha^{-1}$)
yLAI	-	Leaf area index of senesced leaves
$yLAI_i$	-	Daily increment of leaf area index of senesced leaves
Y_{pot}	-	Potential yield ($t\ ha^{-1}$)
Y_{red}	-	Percentage yield reduction (%)
$Y_{rel(Init)}$	-	Relative yield for initial stage
$Y_{rel(Dev)}$	-	Relative yield for development stage
$Y_{rel(Mid)}$	-	Relative yield for mid-season stage
$Y_{rel(Late)}$	-	Relative yield for late-season stage
z	-	Soil depth (m)

α	-	Adiabatic lapse rate ($K\ m^{-1}$)
γ	-	Psychrometer constant ($kPa\ °C^{-1}$)
Δ	-	Slope of the saturation vapour pressure curve ($Pa\ °C^{-1}$)
ΔQ	-	Soil water storage (mm)
Δt	-	Daily time step (1 day)
ϵ	-	Clear sky emissivity of the earth's surface
θ	-	Actual volumetric soil water content
θ_{ad}	-	Air dry volumetric soil water content
θ_{fc}	-	Volumetric soil water content at field capacity
θ_{pwp}	-	Volumetric soil water content at permanent wilting point
θ_{sat}	-	Volumetric soil water content at saturation
λ	-	Latent heat of vaporization ($MJ\ kg^{-1}$)
ρ_w	-	Water density ($Mg\ m^{-3}$)
ρ_b	-	Bulk density ($Mg\ m^{-3}$)
σ	-	Stefan-Boltzmann constant ($4.9 \times 10^{-9}\ MJ\ m^{-2}\ K^{-4}$)
Ψ_{avg}	-	Root weighted average soil matric potential ($J\ kg^{-1}$)
Ψ_{fc}	-	Soil matric potential at field capacity ($J\ kg^{-1}$)
Ψ_{lm}	-	Leaf water potential at maximum transpiration ($J\ kg^{-1}$)
Ψ_m	-	Soil matric potential ($J\ kg^{-1}$)
Ψ_{pwp}	-	Soil matric potential at permanent wilting point ($J\ kg^{-1}$)
Ψ_x	-	Xylem water potential ($J\ kg^{-1}$)
ω_s	-	Sunset hour angle (rad)

CHAPTER 1

INTRODUCTION

1.1 Problem

In large areas of South Africa, irrigation is required in order to achieve optimal yields. Optimization of irrigation water management is necessary for structural (irrigation system design), economic (saving of water and energy), and environmental reasons (risk of salinization, fertilizer and nutrient leaching). The direct objectives of irrigation water management are to determine the amount of irrigation water to supply the crop and the timing of this irrigation.

Several methods for irrigation scheduling are reviewed in the literature. They can be classified as soil, plant and atmosphere based approaches. Examples are monitoring soil water by means of tensiometers (Cassel and Klute, 1986), electrical resistance and heat dissipation soil water sensors (Campbell and Gee, 1986; Bristow, Campbell and Calissendorf, 1993; Jovanovic and Annandale, 1997), or neutron water meters (Gardner, 1986). Crop water requirements can also be determined by monitoring atmospheric conditions (Doorenbos and Pruitt, 1992), and plant water status is often used as an indicator of when to irrigate (Clark and Hiler, 1973; Bordovsky, Jordan, Hiler and Howell, 1974; Stegman, Schiele and Bauer, 1976; O'Toole, Turner, Namuco, Dingkuhn and Gomez, 1984).

The best estimates of crop water use result from direct measurements, but this is not always feasible on a large scale. The next most accurate approach would be one which integrates our understanding of the soil-plant-atmosphere continuum as mechanistically as possible. Taking the supply of water from the soil-root system, and the demand from the canopy-atmosphere system into account is essential to properly describe crop water use. The Penman-Monteith reference crop evaporation (Smith, Allen and Pereira, 1996) together with a mechanistic crop growth model, which uses soil water and grows a realistic canopy and root system provides the best possible estimate of the soil water balance. This approach has been out of reach of irrigators due to the specialist knowledge required to run the models. This high management cost can be drastically reduced by packaging the model in an extremely user-friendly format, eliminating the need for a detailed understanding of the intricacies of the soil-plant-atmosphere continuum. The benefits will be increased too, because of the accuracy of the mechanistic, and therefore universally valid, estimation procedure.

A mechanistic approach to estimating crop water use has several advantages over the more empirical methods often used. Using thermal time to describe crop development removes the need to use different crop factors for different planting dates and regions. Splitting evaporation and transpiration solves the problem of taking irrigation frequency into account. Deficit irrigation strategies, where water use is supply-limited, can also be more accurately described.

1.2 Background (Historical perspective)

The interest in scheduling irrigations with crop growth computer models is rapidly increasing particularly since personal computers have become accessible to crop producers (Bennie, Coetzee, van Antwerpen, van Rensburg and du T. Burger, 1988; Singels and de Jager, 1991a, b and c; Hodges and Ritchie, 1991; Smith, 1992a; Campbell and Stockle, 1993; Annandale, van der Westhuizen and Olivier, 1996; Crosby, 1996). Crop models have been developed with different levels of complexity depending on the specific requirements (Whisler, Acock, Baker, Fye, Hodges, Lambert, Lemmon, McKinion and Reddy, 1986). A comprehensive review of wheat models was reported by Walker, Fyfield, MacDonald and Thackrah (1995), whilst Mottram and de Jager (1994) reported an overview of soil water balance and reference evapotranspiration models. Several models were also described in the Agronomy Monograph No. 31 of the American Society of Agronomy. Advantages and disadvantages as well as research needs were discussed in this publication.

Most of the existing models, however, either are crop specific or do not simulate daily crop water use. Some models are relatively simple to use for planning purposes, but do not allow real-time scheduling. Other models accurately describe the complexity of natural processes. This makes them suitable for research purposes, but they are generally not applicable in practice due to the large amount of input data required and lack of a user-friendly interface.

The Soil Water Balance (SWB) model is based on the improved generic crop version of the NEW Soil Water Balance (NEWSWB) model (Campbell and Diaz, 1988). A brief description with more detail can be found in the literature (Campbell and Stockle, 1993). A user-friendly version of SWB has been developed by Benadé, Annandale and van Zijl (1997).

SWB is a mechanistic, real-time, generic crop, soil water balance, irrigation scheduling model. It gives a detailed description of the soil-plant-atmosphere continuum, making use of weather, soil and crop databases. It thus largely overcomes the problems of other models for irrigation scheduling as indicated above. However, since SWB is a generic crop growth model, parameters specific for each crop have to be determined. A database of crop specific growth parameters was generated during a field trial carried out at Kromdraai (Witbank) where a wide range of annual crops and pasture species were irrigated with lime-treated acid mine drainage (Barnard, Rethman, Annandale, Mentz and Jovanovic, 1998).

1.3 Objectives of the project

In order to make the SWB model more generally applicable and accessible, two main objectives were initially identified for this project:

1) To determine parameters for specific crops which are commonly irrigated in South Africa, and include them in the SWB database; and

2) Further development of the mechanistic, generic crop model in order to facilitate

irrigation scheduling.

In order to achieve the main objectives, the following specific aims were initially identified:

2.1) To identify further development needs in respect of SWB in order to meet user requirements;

2.2) To automate the acquisition of input weather data from automatic weather stations in order to facilitate and make scheduling more convenient;

2.3) To incorporate an economic subroutine in order to facilitate economic optimization of cropping areas, target yields and irrigation strategies;

2.4) To identify specific requirements of specific crops and to adapt SWB to accommodate them;

2.5) To identify all relevant irrigated crops and determine parameters for them;

2.6) To identify institutions/persons who are doing or have done research with regards to the relevant crops and to confer in respect of making data available and/or taking additional measurements during existing experiments;

2.7) To calculate parameters for crops for which applicable data sets can be obtained;

2.8) To estimate parameters for crops for which data sets are not obtainable or incomplete;

2.9) To evaluate crop parameters;

2.10) To publish crop parameters in the final report;

2.11) To identify further research and model development needs which are not satisfied in this project.

Due to the departure of the main researcher, the original specific aims listed above had to be modified during the course of the project. The new research team stated the following objectives:

i) To determine parameters for specific crops which are commonly irrigated in South Africa, and include them in the SWB database;

ii) To identify further development needs in respect of SWB in order to meet user requirements;

iii) To automate the acquisition of input weather data from automatic weather stations in order to facilitate and make scheduling more convenient;

iv) To evaluate SWB using independent data sets obtained from South African researchers and organizations;

v) To develop a user-friendly Windows 95 interface for easy technology transfer;

vi) To compile a comprehensive user manual;

vii) To compile a comprehensive user help facility; and

viii) To identify further research and model development needs which are not satisfied in this project.

Objective i) includes the initial specific aims 2.5), 2.7), 2.8) and 2.10). Relevant irrigated crops for which parameters have been determined are summarized in Table 5.1 and discussed in Chapter 5.

Objective iv) includes the initial specific aims 2.6) and 2.9).

The initially stated specific aims 2.3), 2.4) and 2.11) were included in objective viii).

Objectives v), vi) and vii) were not stated in the original proposal, and they were included in line with the original main objective 2), to improve the user-friendliness of the final product.

1.4 Approach

Data sets of relevance for irrigation scheduling were required to generate the database of specific crop growth parameters and calibrate SWB. Independent data sets were required to validate SWB and to establish the reliability of the model in representing the real-world system. Three approaches were followed in order to meet these requirements:

i) An extensive literature search of Water Research Commission publications and others was carried out in order to collect data for the calibration and validation of SWB. Personal contacts with South African researchers and organizations were also made in order to obtain data sets. This is discussed in Chapter 3.

ii) In the absence of useful data sets for some crops, field trials were carried out in order to collect data for the determination of specific crop growth parameters and calibration of the model. This is discussed in Chapter 4.

iii) An alternative model for estimating the soil water balance was developed for crops for which data sets were not available in the literature or through personal contacts, and where it was not possible to set up field trials to determine specific crop growth parameters. This model is based on the crop factor approach recommended by the FAO (Food and Agricultural Organization of the United Nations, Rome, Italy). It was developed in order to include more crops in the SWB crop database, by making use of the database of crop factors available in

FAO publications. The FAO-based model is described in Section 2.2.

Data sets for the validation of SWB were therefore sought for two types of model:

i) Crop growth and soil water balance model making use of specific crop growth parameters; and

ii) FAO-based model making use of FAO crop factors.

CHAPTER 2

DESCRIPTION OF THE MODEL

Simulations with SWB can be run using two types of model:

i) The crop growth, mechanistic model calculates crop growth and soil water balance parameters.
ii) The FAO-type crop factor model calculates the soil water balance without simulating dry matter production mechanistically.

The two models are described below.

2.1 Crop growth model

SWB performs the calculation of the water balance and crop growth using three units, namely weather, soil and crop.

Weather unit:

The weather unit of SWB calculates the Penman-Monteith grass reference daily evapotranspiration (ETo) according to the recommendations of the Food and Agriculture Organization (FAO) of the United Nations (Smith et al., 1996; Smith, 1992b).

Soil unit:

In the soil unit of SWB, potential evapotranspiration (PET) is divided into potential evaporation and potential transpiration by calculating canopy radiant interception from simulated leaf area (Ritchie, 1972). This represents the upper limits of evaporation and transpiration and these processes will only proceed at these rates if atmospheric demand is limiting. Supply of water to the soil surface or plant root system may, however, be limiting. This is simulated in the case of soil water evaporation, by relating evaporation rate to the water content of the surface soil layer. In the case of transpiration, a dimensionless solution to the water potential based water uptake equation is used (Campbell and Norman, 1998). This procedure comes up with a root density weighted average soil water potential which characterizes the water supply capabilities of the soil-root system. This solution has been shown to work extremely well by Annandale et al. (1996). If actual transpiration is less than potential transpiration the crop has undergone stress and leaf area development will be reduced. **This makes the crop growth model of SWB very suitable for predicting crop water requirements when deficit irrigation strategies are applied.** The only inputs needed for the water uptake solution are an estimate of the maximum possible transpiration rate and the leaf water potential required to maintain that rate.

The multi-layer soil component of the model ensures a realistic simulation of the infiltration and crop water uptake processes. A cascading soil water balance is used once canopy interception and surface runoff have been accounted for.

Crop unit:

In the Crop unit, SWB calculates crop dry matter accumulation in direct proportion to transpiration corrected for vapour pressure deficit (Tanner and Sinclair, 1983). It also calculates radiation-limited growth (Monteith, 1977) and takes the lower of the two. This dry matter is partitioned to roots, stems, leaves and grain or fruits. Partitioning depends on phenology calculated with thermal time and modified by water stress.

A detailed, technical description of the model (weather, soil and crop units) can be found in Appendix A.

2.2 FAO model

Specific crop growth parameters can be determined using weather, soil and growth analysis data, as will be discussed in Section 4.1.3. In the absence of such time consuming and therefore expensive growth analysis data, a simpler modelling approach is required. An FAO-based crop factor procedure has therefore been developed and combined with the mechanistic SWB model, thereby still allowing evaporation and transpiration to be modelled separately as supply- and demand-limited processes. The crop factor model does not grow the canopy mechanistically and therefore the effect of water stress on canopy size is not simulated. The simpler crop factor model should, however, still perform satisfactorily if the estimated canopy cover closely resembles that found in the field.

The FAO model was mainly developed in order to include more crops in the SWB crop database by making use of the database of basal crop coefficients, growth periods, root depths, crop heights, stress factors and potential yields available in FAO publications (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen, Smith, Pruitt and Pereira, 1996). In particular, tree crops were critical as growth analyses for trees are seldom available.

SWB calculates crop potential evapotranspiration as follows:

$$PET = ETo\ Kc_{max} \tag{1}$$

Kc_{max} represents the maximum value for the FAO crop factor (Kc) following rain or irrigation. It is selected as the maximum of the following two expressions (Allen et al., 1996):

$$Kc_{max} = 1.2 + [0.04\ (U_2 - 2) - 0.004\ (RH_{min} - 45)]\ (Hc / 3)^{0.3} \tag{2}$$

$$Kc_{max} = Kcb + 0.05 \tag{3}$$

U_2 - Mean daily wind speed at 2 m height (m s^{-1})
RH_{min} - Daily minimum relative humidity (%)

Hc - Crop height (m)
Kcb - Basal crop coefficient

The upper limit of Kc_{max} is set at 1.45.

The FAO model partitions PET into potential crop transpiration (PT) and potential evaporation from the soil surface (PE), and estimates fractional interception of radiation (FI) using the following equations:

$$PT = Kcb\ ETo \qquad \text{(Allen et al., 1996)} \quad (4)$$

$$FI = PT / PET \quad (5)$$

$$PE = (1 - FI)\ PET \quad (6)$$

Water loss by evaporation (E) is assumed to occur only from the top soil layer. It proceeds at the potential rate until volumetric soil water content (θ) reaches the permanent wilting point (PWP). Thereafter, it is equal to the product of PE and the square of the fraction of the remaining evaporable water down to air dryness which is taken as 30% of PWP (Campbell and Diaz, 1988). No root water uptake is calculated for the uppermost soil layer. SWB assumes that layer water uptake is weighted by root density when soil water potential is uniform (Campbell and Diaz, 1988). Water loss by crop transpiration (T) is calculated as a function of maximum transpiration rate (Tr_{max}) and leaf water potential at Tr_{max} (Ψ_{lm}) (Campbell, 1985). It represents the lesser of root water uptake or maximum loss rate. Tr_{max} and Ψ_{lm} are input parameters that can be easily estimated from one's experience with the crop. In this way, a mechanistic supply- and demand-limited water uptake calculation was linked to an FAO crop factor approach with a minimal addition of crop input parameters required.

The FAO model assumes Kcb, root depth (RD) and Hc are equal to the initial values during the initial crop stage. During the crop development stage, they increase linearly from the end of the initial stage until the beginning of the mid-season stage, when they attain maximum values. They remain constant at this maximum during the mid-season stage. During the late-season stage, Kcb decreases linearly until harvest when it reaches the value for late-season stage, whilst RD and Hc remain constant at their maximum value. The following crop parameters need therefore to be known: Tr_{max}, Ψ_{lm}, Kcb for the initial, mid- and late-season stages, crop growth periods in days for initial, development, mid- and late-season stages, initial and maximum RD, as well as initial Hc and maximum crop height (Hc_{max}).

The FAO model estimates crop yield under water stress conditions as a function of the stress factor (Ky) for the specific crop stage and potential yield (crop specific input parameter). The procedure recommended by the FAO was used as a basis (Smith, 1992a) for the calculation of crop yield. This is described in detail in Appendix A.

Basal crop coefficients, root depths, crop heights, stress factors and growth periods are available in FAO publications (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996). These parameters were included in the SWB database and they are presented in Table B2 (Appendix B).

2.3 Required input parameters

Management, weather and soil data are required as input in order to run both the crop growth and the FAO model of SWB. The SWB model includes a database of specific crop growth parameters and FAO crop factors for a wide range of species (Tables B1 and B2, Appendix B). These are, therefore, not essential input data.

Management data:

Input data related to crop management include the following information:

- i) Starting date of the simulation;
- ii) Planting date;
- iii) Daily irrigations (mm);
- iv) Required irrigation timing and amount;
- v) Irrigation system; and
- vi) Area of the field (ha).

Soil data:

The following soil input data must be entered:

- i) Runoff curve number (mm);
- ii) Drainage fraction and maximum drainage rate (mm d^{-1});
- iii) Soil layer
    - thickness (m),
    - volumetric soil water content at field capacity and permanent wilting point,
    - initial volumetric water content, and
    - bulk density (Mg m^{-3}).

Weather data:

The following data are essential inputs:

- i) Latitude (°N or °S);
- ii) Maximum daily temperature (°C);
- iii) Minimum daily temperature (°C); and
- iv) Precipitation (mm).

In the absence of measured data of solar radiation, wind speed and vapour pressure, SWB estimates these parameters as a function of available weather data according to the FAO recommendations (Smith, 1992b; Smith et al., 1996).

Detailed definitions and functions of the input data required to run SWB, are presented in Appendix A.

CHAPTER 3

DATA COLLECTION

Validation of SWB was required in order to establish its adequacy in representing the real-world system, given the objectives of the model development and the intended use, and according to the definition given by Oosthuizen, Botes, Bosch and Breytenbach (1996). The guidelines recommended by CAMASE (1995) were used to establish the usefulness and relevance of the model for irrigation scheduling purposes.

SWB was firstly debugged. Independent data sets of relevance for irrigation scheduling were then required in order to validate SWB. These were sought both in the literature and from South African researchers and organizations.

Severe difficulties were encountered in obtaining useable data sets. In some cases, available data sets were incomplete, in others potential collaborators were reluctant to make data available.

3.1 Ideal data set for model validation

A complete, reliable and useable data set for the validation of a mechanistic, crop growth, water balance model should include management, soil, crop and weather data.

Management data:

i) Location;
ii) Planting date; and
iii) Daily irrigations (mm).

Soil data:

i) Soil layer thickness (cm);
ii) Volumetric soil water content at field capacity and permanent wilting point per soil layer;
iii) Initial volumetric soil water content per soil layer; and
iv) Bulk density per soil layer (Mg m^{-3}).

Soil texture data can be used to estimate volumetric soil water content at field capacity and permanent wilting point (Bennie et al., 1988).

A general description of the soil and topographical characteristics of the area should suffice to estimate the runoff curve number, drainage fraction and maximum drainage rate.

Crop data:

Growth analysis data (crop height, canopy cover, dry matter production per plant organ and leaf area index) are required to evaluate the crop growth subroutine of the model. Phenology, maximum transpiration and minimum leaf water potential at maximum transpiration are also required.

Weather data:

The following weather data are essential:

i) Maximum daily temperature (°C);
ii) Minimum daily temperature (°C); and
iii) Precipitation (mm).

Solar radiation, wind speed and vapour pressure measurements are also required, but not essential as SWB can estimate them from available weather data (Smith, 1992b; Smith et al., 1996).

Weather data are particularly important because they directly affect both crop growth and development, as well as the soil water balance. It was interesting to note that almost none of the references searched included daily weather data sets. Weather data can be easily obtained from the Weather Bureau for certain locations. This data, however, lack reliability because both daily temperatures and in particular rainfall could vary over very short distances. Weather data represent the starting point of the model daily time step loop. The ideal would be to obtain weather data recorded at sites where crops are grown.

3.2 Literature search

Water Research Commission reports and other publications related to research in agricultural water management, were studied for independent data sets that could be used to validate SWB.

Nel, Burgers and Naudé (1981) reported soil and irrigation data, as well as planting, emergence and harvesting dates for some horticultural crops. Weather and canopy data were not reported.

Wessels (1982) reported weekly evapotranspiration, irrigation and rainfall, as well as tensiometer readings and yield of cabbage grown in lysimeters. Daily weather and irrigation data are, however, indispensable to get reliable simulations with the daily time step SWB model. The soil data is incomplete for the purpose of this study.

Hensley and de Jager (1982) reported yield and water balance for wheat and maize, but no weather data and growth analyses were found.

De Jager, van Zyl, Bristow and van Rooyen (1982) reported planting dates, soil data, soil water contents, as well as irrigations and rainfall for wheat grown in the Free State. Leaf area index was shown on graphs and no weather data was reported.

Boedt and Laker (1985) reported planting dates, soil data, root depth and yields for several crops, but no weather data and only daily patterns of soil water content in the soil profile were found.

Nel, Fischer, Annandale and Steynberg (1986) reported comprehensive sets of data for several crops grown under the rain shelter at the Hatfield experimental station. Weather data from the station in Hatfield are also available for the period of the trial.

Steynberg (1986) studied the growth, development and water use efficiency of maize grown at Hatfield. He reported planting dates, leaf area index, total dry matter production as well as harvestable dry matter, but no irrigation data was reported and soil data are incomplete for the purpose of this study.

De Jager, van Zyl, Kelbe and Singels (1987) reported graphically and numerically complete data sets for wheat grown in the Free State, and used them to validate PUTU. Daily weather data are, however, not available in their study.

Meyer, Oosterhuis, Berliner, Green and van der Merwe (1987) used weighing lysimeters to measure water use of wheat and soybean. No data was found in their study.

Dent, Schulze and Angus (1988) verified the ACRU model using data sets obtained from the Institute for Soil, Climate and Water - Agricultural Research Council - Pretoria, and the Summer Grain Centre of the Dept. of Agriculture and Water Supply - Cedara.

Human and de Bruyn (1988) studied the effect of water stress on photosynthesis of maize, cotton, peanuts, wheat and sunflower grown in pots. The data sets are, however, incomplete for the purpose of this study. It is also very difficult to extrapolate pot data to field conditions.

Van Zyl, de Jager and Maree (1989) reported on several experiments carried out during the growing season of wheat. No daily weather data for the season, as well as soil, growth analysis and irrigation data were, however, reported.

Vanassche and Laker (1989) reported monthly weather data, no record of irrigation amounts and only final yield for wheat and maize grown at Craddock.

Berliner, Nel and van der Merwe (1990) carried out several experiments on soybean and spring wheat at Roodeplaat, but reported soil, weather and crop data only on graphs.

Oosthuizen (1991) used the PUTU (de Jager et al., 1987) and BEWAB (Bennie et al., 1988) crop models for an economical evaluation of irrigation scheduling strategies for wheat, maize and cotton, but no data were reported. Similarly, Oosthuizen et al. (1996) used the PUTU and IBSNAT (IBSNAT, 1986) models for analysing the economics of crop production of wheat, maize and soybean. They reported only actual and simulated data of yield and change in soil water content.

Burgers and Kirk (1993) reported soil data and soil water content per layer, but no weather, irrigation and growth analysis data were published.

Moolman (1993) evaluated three solute and water transport models, namely BURNS (Burns, 1974), LEACHM (Wagenet and Hutson, 1989) and TETRans (Corwin and Waggoner, 1990), but no crop growth analysis and weather data were reported. Similarly, Moolman and de Clercq (1993) reported only a few example tables of weather and irrigation input data, as well as soil water measurements, but no complete data set is available.

Steynberg, Nel and Rethman (1993) studied water use efficiency of irrigated temperate pastures at Hatfield. They reported planting dates and yields, as well as soil water deficit on graphs, but no irrigation data and growth analysis are available.

Mottram and de Jager (1994) used on-farm and research station experiments to validate PUTU (de Jager et al., 1987), but reported no weather data and growth analysis. They also used wheat data obtained from the Institute for Soil, Climate and Water - Agricultural Research Council - Pretoria, to validate PUTU.

Annandale et al. (1996) calibrated and validated SWB for green peas.

Mkhize, Vanassche and Laker (1996) measured soil water content for citrus and reported data graphically. No weather, irrigations and growth analysis data are available.

Barnard et al. (1998) calibrated SWB for 10 annual crops and 10 pasture species irrigated with lime-treated acid mine drainage.

Bennie, Hoffman, Coetzee and Vrey (1994) reported soil properties and growth analyses for dry land maize, wheat, sunflower, grass and natural pasture grown at Bloemfontein, Petrusburg, Hoopstad and Tweespruit. Weather data, however, were not reported, and only one example table on soil water measurements was found in the publication. The complete data set was reported to be available from the authors, and Prof ATP Bennie was therefore approached (Section 3.3).

Walker et al. (1995) used data for wheat to validate BEWAB (Bennie et al., 1988). Prof S Walker was approached for the complete data sets (Section 3.3).

3.3 Personal contacts

The following South African researchers made complete independent data sets available for the validation and calibration of SWB:

i) Dr M Hensley (Institute for Soil, Climate and Water - Agricultural Research Council, Glen):

- Dry land maize grown at Setlagole, Ermelo and Kroonstad.

ii) Prof S Walker (University of the Orange Free State, Bloemfontein) and Dr TP Fyfield (Institute for Soil, Climate and Water - Agricultural Research Council, Pretoria):

- Irrigated wheat grown at Roodeplaat.

iii) Prof ATP Bennie (University of the Orange Free State, Bloemfontein):

- Irrigated maize, peanuts, peas, potato and wheat grown at Bloemfontein.

iv) Dr MG Inman-Bamber (formerly South African Sugar Association Experiment Station, Mount Edgecombe; presently CSIRO, Townsville, Australia):

- Sugarcane grown at Pongola.

v) Ms T Volschenk (Agricultural Research Council - Infruitec, Stellenbosch):

- Apples grown at Elgin.

vi) Mr A Nel (Grain Crops Research Institute - Agricultural Research Council, Potchefstroom):

- Sunflower grown at Potchefstroom.

vii) Dr GC Green and Mr HM du Plessis (Water Research Commission):

- Citrus.

Incomplete data sets were obtained from Mr Dup Haarhoff (South-West Cooperative, Kimberley) for several crops grown in the Northern Cape.

Dr M Dippenaar (Tobacco and Cotton Research Institute - Agricultural Research Council, Rustenburg), Dr E Hoffman (Tropical and Subtropical Crops Research Institute - Agricultural Research Council, Nelspruit) and Dr MA Smit (Grain Crops Research Institute - Agricultural Research Council, Potchefstroom), were approached, but unfortunately they were not able to make complete data sets available.

CHAPTER 4

FIELD TRIALS

In the absence of crop parameters and independent data sets available in the literature, two field trials were carried out in order to calibrate SWB. A field trial set up at Roodeplaat was used to determine crop parameters for vegetables, whilst a field trial carried out at the Hatfield experimental station was used to determine FAO crop factors for peach trees.

4.1 Roodeplaat vegetables trial

Mechanistic crop growth models require specific crop input parameters which are not readily available for all crops and conditions. In particular, there is a lack of information on crop specific parameters for vegetables.

A field trial was set up at Roodeplaat. The objective was to determine crop growth parameters for several vegetable species, and include them in the crop growth parameter database of SWB. Mr W van Wyk (Department of Agriculture - Directorate of Plant and Quality Control, Pretoria) made available his field trial and was responsible for crop management (plant protection, fertilization and weed control).

Field measurements were used to determine the following specific crop growth parameters: vapour pressure deficit corrected dry matter-water ratio (DWR), radiation conversion efficiency (E_c), specific leaf area (SLA), leaf-stem dry matter partitioning parameter (PART), canopy extinction coefficient for solar radiation (K_s), maximum rooting depth (RD_{max}) and growing day degrees (GDD) for the completion of phenological stages.

The field trial at Roodeplaat and the determination of specific crop growth parameters is described in the following Chapters.

4.1.1 Experimental set-up

The field trial was established at Roodeplaat (25°35' S, 28°21' E, altitude 1165 m), 30 km NE of Pretoria. The climate of the region is one of summer rainfall (October-March), with an average of about 650 mm y^{-1}. January is the month with the highest average maximum temperature (30°C), whilst July is the month with the lowest average minimum temperature (1.5°C). Frequent occurrence of frost is experienced during winter months. The soil is a 1.2 m deep clay loam Red Valsrivier (Soil Classification Working Group, 1991), with a clay content between 27% and 31% and a water holding capacity of about 300 mm m^{-1}.

Six winter vegetable species were grown during the 1996 season on 5 x 12 m plots. During the 1996/97 summer season, 19 cultivars covering 10 crop species were grown on 4 x 5 m plots.

Crops, cultivars, planting and harvest dates, as well as row spacings are summarized in Table 4.1. Irrigations were carried out weekly with an overhead sprinkler system.

Agronomic practices commonly used in the area were followed. The field was ploughed (0.3 m) and a rotovator was used to prepare a 0.15 m deep seedbed. Vegetables planted by seeding were thinned a few weeks after planting. At planting winter crops received 27 kg N ha^{-1}, 40 kg P ha^{-1} and 53 kg K ha^{-1} in the form of 2:3:4 (30), and all but the beetroot received a top dressing of 112 kg ha^{-1} in the form of LAN (28). Cabbage was treated with metazachlor (Pree) at 2 ℓ ha^{-1} and onions with oxadiazon (Ronstar) at 4 ℓ ha^{-1} for weed control, two days after transplanting. In addition, cabbage was treated with the insecticide carbofuran (Curaterr) at 2 g m^{-1} row length. At planting summer crops received 34 kg N ha^{-1}, 50 kg P ha^{-1} and 66 kg K ha^{-1} in the form of 2:3:4 (30). On 23 December 1996, four varieties of sweet corn, two varieties of bush beans and the runner beans received a top dressing of 84 kg ha^{-1} in the form of LAN (28). Before planting, all summer vegetables were sprayed with Dual at 2 ℓ ha^{-1} for weed control. The eggplant, green and chilli pepper, as well as three varieties of tomato were occasionally sprayed with Karate plus Metasystox for pest control.

4.1.2 Field measurements

Soil water deficit (SWD) to field capacity was measured with a neutron water meter Model 503DR CPN Hydroprobe (Campbell Pacific Nuclear, California, USA) [Mention of manufacturers is for the convenience of the reader only and implies no endorsement on the part of the authors, their sponsors nor the University of Pretoria]. The neutron water meter was calibrated for the site and weekly readings were taken in the middle of each plot, for 0.2 m soil layers down to 1.0 m. Rain gauges were installed in order to measure irrigation (I) and rainfall (P).

Fractional interception (FI) of photosynthetically active radiation (PAR, 0.4-0.7 μm) was measured weekly with a sunfleck ceptometer (Decagon Devices, Pullman, Washington, USA), making one reference reading above each canopy and 10 readings beneath each canopy. Growth analyses were carried out fortnightly, by harvesting plant material above 1 m^2 of ground surface at representative sites, with no replications due to the small plot size. Harvestable fresh mass was measured directly after sampling, and dry matter of plant organs after drying in an oven at 60 °C for 4-5 days. Leaf area index (LAI) was measured with an LI 3100 belt driven leaf area meter (LiCor, Lincoln, Nebraska, USA). Outer, green leaves of lettuce and cabbage were assumed to be photosynthetically active. Phenological development was also monitored for each crop.

Weather data were recorded using an automatic weather station (Mike Cotton Systems, Cape Town, South Africa) located a few hundred meters from the trial site. Solar radiation (R_s) was measured with an MCS 155-1 sensor, and wet (T_w) and dry bulb air temperature (T_d) with two MCS 152 thermistors. Hourly averages were stored with an MCS 120-02EX data logger. The weather station was made available by Dr JM Steyn (Agricultural Research Council - Roodeplaat Vegetable and Ornamental Plant Institute - Potato Programme).

TABLE 4.1

PLANTING AND HARVEST DATES, AND ROW SPACINGS FOR SIX WINTER AND 19 SUMMER VEGETABLE CULTIVARS (ROODEPLAAT, 1996/97)

Crop	Planting date	Harvest date	Row spacing (m)
Onions (*Allium cepa* cv. Mercedes)	2 May 1996*	20 Sep. 1996	0.15 x 0.2
Cabbage (*Brassica oleracea* cv. Grand Slam)	2 May 1996*	20 Sep. 1996	0.5 x 0.5
Carrots (*Daucus carota* cv. Kuroda)	7 May 1996	11 Oct. 1996	0.3
Beetroot (*Beta vulgaris* cv. Crimson Globe)	7 May 1996	11 Oct. 1996	0.3
Lettuce (*Lactuca sativa* cv. Great Lakes)	7 May 1996*	6 Sep. 1996	0.4 x 0.5
Swisschard (*Beta vulgaris* cv. Ford Hook Giant)	7 May 1996	11 Oct. 1996	0.3
Sweet corn (*Zea mays Saccharata* cv. Cabaret)	11 Dec. 1996	12 Feb. 1997	1.0
Sweet corn (*Zea mays Saccharata* cv. Jubilee)	12 Nov. 1996	5 Feb. 1997	1.0
Sweet corn (*Zea mays Saccharata* cv. Paradise)	12 Nov. 1996	5 Feb. 1997	1.0
Sweet corn (*Zea mays Saccharata* cv. Dorado)	9 Dec. 1996	12 Feb. 1997	1.0
Beans bush (*Phaseolus limensis* cv. Provider)	12 Nov. 1996	20 Jan. 1997	1.0
Beans bush (*Phaseolus limensis* cv. Bronco)	27 Nov. 1996	27 Jan. 1997	1.0
Beans runner (*Phaseolus coccineus* cv. Lazy Housewife)	27 Nov. 1996	12 Feb. 1997	1.0
Pumpkin (*Cucurbita pepo* cv. Miniboer)	12 Nov. 1996*	5 Feb. 1997	1 x 0.5
Pumpkin (*Cucurbita pepo* cv. Minette)	12 Nov. 1996*	5 Feb. 1997	1 x 0.5
Marrow (*Cucurbita maxima* cv. President)	12 Nov. 1996*	5 Feb. 1997	1 x 0.5
Marrow (*Cucurbita maxima* cv. Long White Bush)	12 Nov. 1996*	5 Feb. 1997	1 x 0.5
Squash (*Cucurbita moschata* cv. Table Queen)	12 Nov. 1996*	5 Feb. 1997	1 x 0.5
Squash (*Cucurbita moschata* cv. Waltham)	12 Nov. 1996*	12 Feb. 1997	1 x 0.5
Tomato table (*Lycopersicon esculentum* cv. Zeal)	29 Nov. 1996*	20 Feb. 1997	1 x 0.5
Tomato processing (*Lycopersicon esculentum* cv. P747)	29 Nov. 1996*	20 Feb. 1997	1 x 0.5
Tomato processing (*Lycopersicon esculentum* cv. HTX14)	29 Nov. 1996*	20 Feb. 1997	1 x 0.5
Eggplant (*Solanum melongena* cv. Black Beauty)	19 Dec. 1996*	4 Mar. 1997	1 x 0.5
Green pepper (*Capsicum annuum* cv. King Arthur)	19 Dec. 1996*	4 Mar. 1997	1 x 0.5
Chilli pepper (*Capsicum annuum* cv. Super Cayenne)	19 Dec. 1996*	4 Mar. 1997	1 x 0.5

* Transplanted

4.1.3 SWB parameter determination: Example with vegetables

Several of the parameters needed by crop modellers to simulate growth and water use of the vegetable crops have been calculated. A database of specific crop growth parameters required by SWB has been generated. Specific crop growth parameters obtained in this trial are summarized in Table B1 (Appendix B). These parameters could also be used in other models. Some modelling approaches, however, may require the calculation of other parameters and for this purpose the growth analysis, soil water and weather data are available from the authors.

Examples of how to determine specific crop growth parameters for SWB are presented below.

Vapour pressure deficit corrected dry matter-water ratio:

DWR is a crop specific parameter determining water use efficiency. Tanner and Sinclair (1983) recommended that the relation between DM production and crop transpiration should be corrected to account for atmospheric conditions, in particular for vapour pressure deficit (VPD). DWR was therefore calculated as follows:

$$DWR = (DM\ VPD) / ET \qquad (7)$$

DM (kg m^{-2}) was measured at harvest, whilst VPD represents the seasonal average. Both VPD and DWR are in Pa. Seasonal crop evapotranspiration (ET) in mm is equivalent to kg m^{-2}.

ET was obtained using the following equation for weekly time intervals:

$$ET = P + I - R - Dr - \Delta Q \qquad (8)$$

where R is runoff, Dr is drainage and ΔQ represents the soil water storage. All terms are expressed in mm. R was assumed to be negligible as no high intensity rain occurred and the irrigation system application rate did not exceed the soil infiltration rate. SWB was used to estimate Dr. A positive sign for ΔQ indicates a gain in soil water storage. ΔQ was calculated from soil water content measurements with the neutron water meter.

Evaporation from the soil surface should not be included in the calculation of DWR, as unlike transpiration, it is not tightly linked to photosynthesis and therefore dry matter production. The portion of soil water lost by evaporation could be substantial in vegetables, particularly at the beginning of the season when canopy cover is partial. Root dry matter was also not measured and was therefore also not included in the calculation of DWR. For these reasons, the calculated DWR values should be seen as lower limits and would need to be increased to give reliable simulations in SWB.

Daily VPD was calculated from measurements of T_w and T_d, adopting the following procedure recommended by the FAO (Smith, 1992b):

$$VPD = [e_s(T_{max}) + e_s(T_{min})] / 2 - e_a \tag{9}$$

e_s	-	Saturated vapour pressure (kPa)
T_{max}	-	Maximum daily temperature (°C)
T_{min}	-	Minimum daily temperature (°C)
e_a	-	Actual vapour pressure (kPa)

e_s at T_{max} and T_{min} was calculated by replacing air temperature (T_a) with T_{max} and T_{min} in the following equation (Tetens, 1930):

$$e_s = 0.611 \exp[17.27\, T_a / (T_a + 237.3)] \tag{10}$$

e_a was calculated from measured daily average T_w and T_d, using the following equation (Bosen, 1958):

$$e_a = e_s(T_w) - 0.0008\,(T_d - T_w)\,P_a \tag{11}$$

where P_a is atmospheric pressure in kPa, and e_s at T_w was calculated using T_w in Eq. (10). P_a was calculated as follows (Burman, Jensen and Allen, 1987):

$$P_a = P_0\,[(T_0 - \alpha\ Alt) / T_0]^{g/(\alpha\ Rg)} \tag{12}$$

P_0	-	Standard atmospheric pressure at sea level (101.3 kPa)
T_0	-	Standard temperature at sea level (293 K)
α	-	Adiabatic lapse rate (K m^{-1})
Alt	-	Altitude (m)
g	-	Gravitational acceleration (9.8 m s^{-2})
Rg	-	Specific gas constant for dry air (286.9 J kg^{-1} K^{-1})

The adiabatic lapse rate was assumed to be 0.0065 K m^{-1} for saturated air.

Radiation conversion efficiency:

E_c is a crop specific parameter used to calculate dry matter production under conditions of radiation-limited growth (Monteith, 1977) as follows:

$$DM = E_c\,FI\,R_s \tag{13}$$

Figure 4.1 represents DM of cabbage as a function of the daily cumulative product of FI and R_s. FI was measured with the ceptometer and R_s with the MCS 155-1 sensor. E_c is the slope of the regression line forced through the origin. The high coefficient of determination (r^2) indicates that E_c is a relatively constant and predictable parameter under conditions of good water supply (Monteith, 1994). E_c values also represent a lower limit, as root dry matter is once again not accounted for.

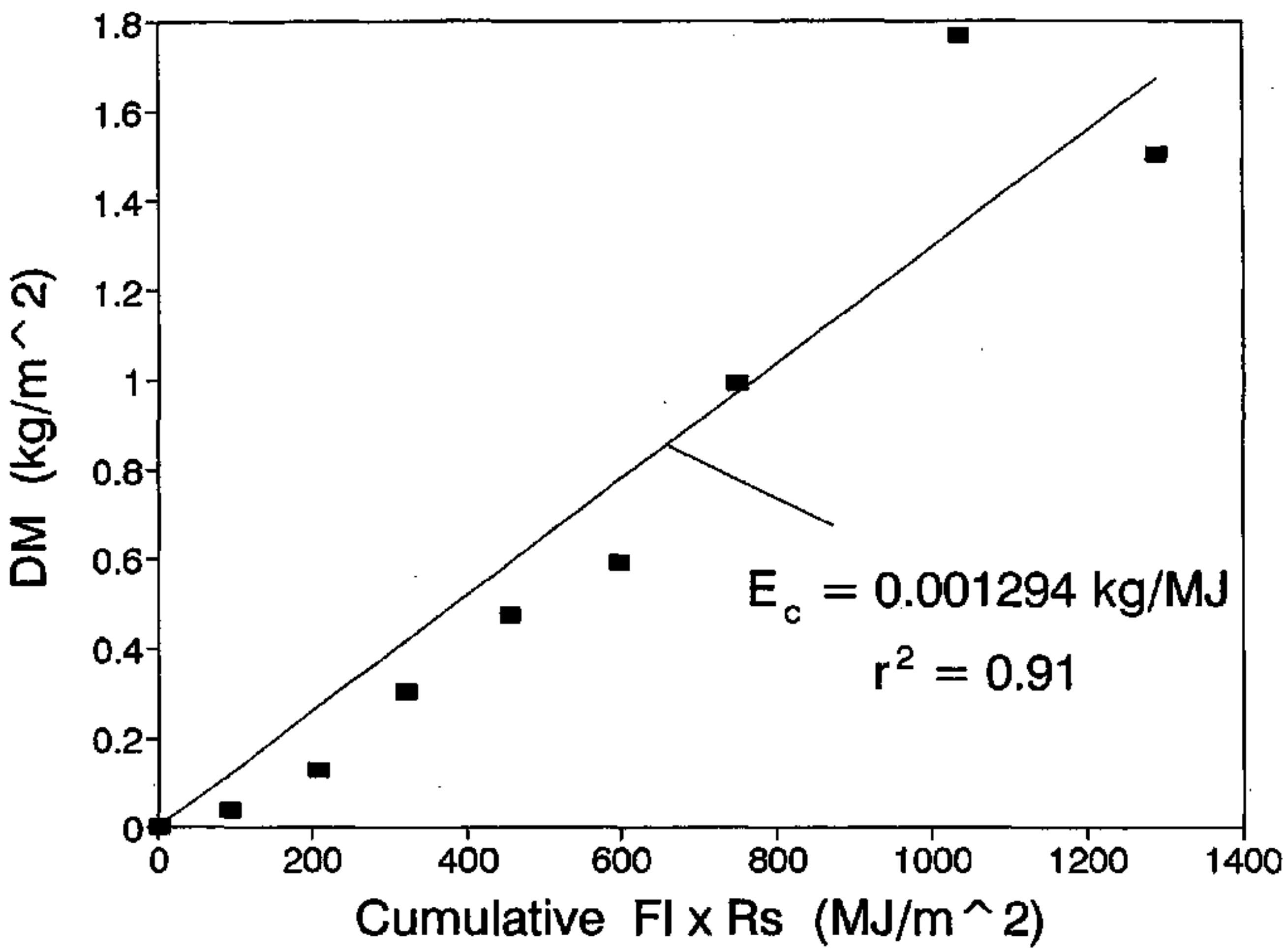


Figure 4.1

Dry matter (DM) production of cabbage as a function of the cumulative product of fractional interception and solar radiation (FI x R_s). Radiation conversion efficiency (E_c) and the coefficient of determination (r^2) are shown

Specific leaf area and leaf-stem partitioning parameter:

SWB calculates daily increments of DM as either transpiration-limited (Eq. 7) or radiation-limited (Eq. 13), and water stress affected partitioning of assimilates to the different plant organs. DM is preferentially partitioned to reproductive sinks and roots (Appendix A). The remaining DM is partitioned to canopy dry matter (CDM, dry matter of leaves plus stems). SWB calculates leaf (LDM) and stem dry matter (SDM) as follows:

$$LDM = CDM / (1 + PART\ CDM) \qquad (14)$$

$$SDM = CDM - LDM \qquad (15)$$

LDM is used to calculate LAI as follows:

$$LAI = SLA\ LDM \qquad (16)$$

where SLA is the specific leaf area in $m^2\ kg^{-1}$. LAI is then used to calculate FI, which is required for partitioning of potential evapotranspiration into potential transpiration and potential evaporation from the soil surface (Appendix A).

SLA and PART have to be known in order to calculate DM partitioning with SWB. Growth analysis data were used to determine these parameters. SLA was calculated as the seasonal average of the ratio of LAI and LDM. Caution should be exercised in the use of seasonal average SLA as this parameter typically has a decreasing trend during the season (Figure 4.2). PART was determined as a function of SLA, LAI and CDM, by combining Eqs. (14) and (16). Figure 4.3 represents the correlation between CDM and (SLA CDM) / LAI - 1 for cabbage. The slope of the regression line which is forced through the origin, represents PART in $m^2\ kg^{-1}$.

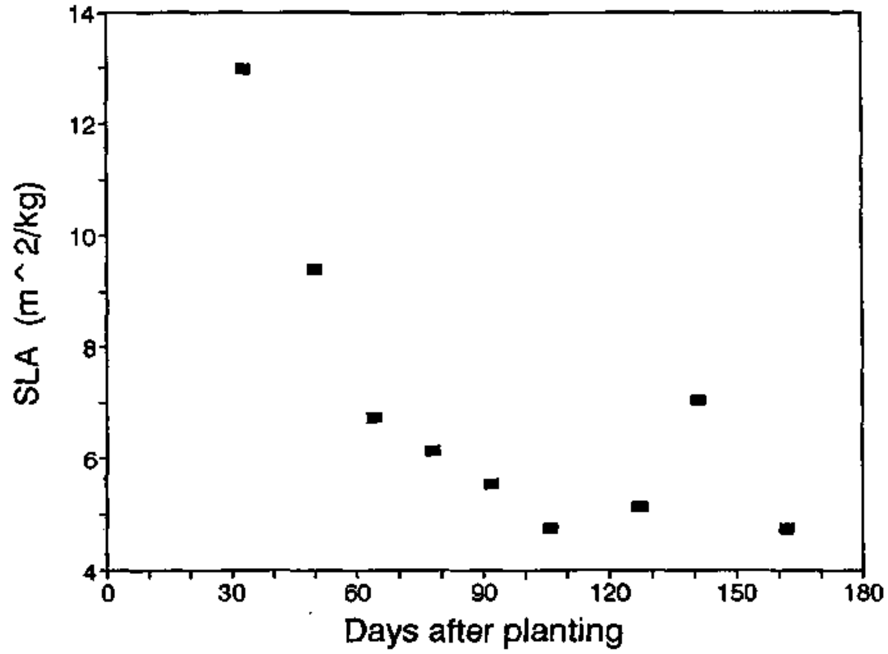


Figure 4.2
Measured values of specific leaf area (SLA) during the growing season of cabbage

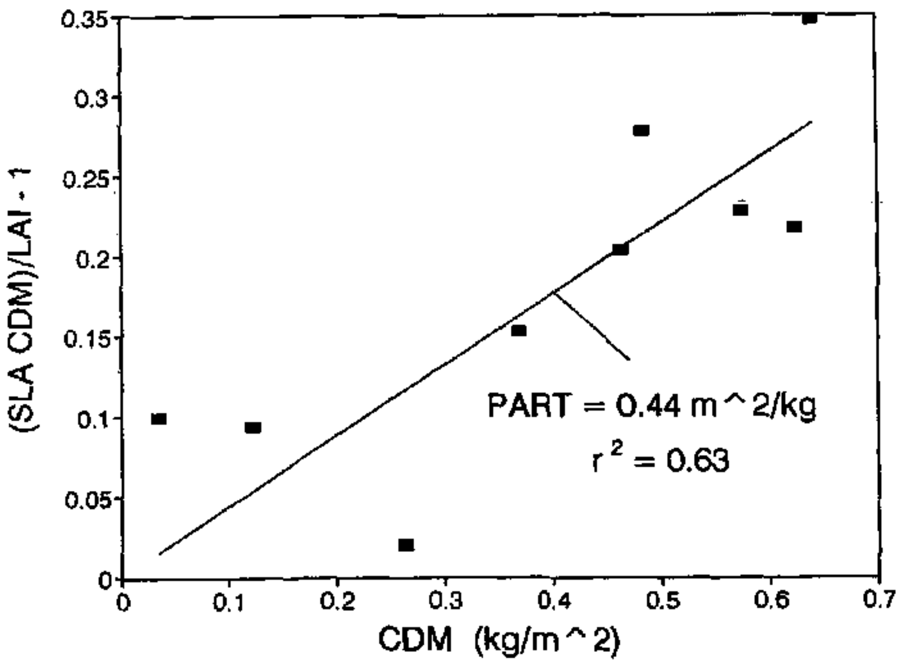


Figure 4.3
Determination of the leaf-stem dry matter partitioning parameter (PART) as a function of canopy dry matter (CDM), specific leaf area (SLA) and leaf area index (LAI) for cabbage. The slope of the regression line (PART) and the coefficient of determination (r^2) are shown

Canopy radiation extinction coefficient:

The basic equation describing transmission of a beam of solar radiation through the plant canopy is similar to Bouguer's law (Campbell and van Evert, 1994):

$$FI = 1 - e^{-K\,LAI} \tag{17}$$

where K is the canopy extinction coefficient. Values of K have been calculated using field measurements of LAI and FI. Guidelines for determining K in the field are given by Jovanovic and Annandale (1998). Figure 4.4 represents FI values as a function of LAI for cabbage. The calculated value of K was 1.17, and the coefficient of determination of the exponential function (r^2) was 0.81.

The value of K calculated from FI measurements with the ceptometer, is for photosynthetically active radiation. The canopy extinction coefficient for PAR (K_{PAR}) can be used to calculate photosynthesis as a function of intercepted PAR. K_s is, however, required for predicting radiation-limited dry matter production (Monteith, 1977) and for partitioning ET into evaporation from the soil surface and crop transpiration (Ritchie, 1972). The procedure recommended by Campbell and van Evert (1994) was used to convert K_{PAR} into K_s:

$$K_s = K_{bd} \sqrt{a_s} \tag{18}$$

$$K_{bd} = K_{PAR} / \sqrt{a_p} \tag{19}$$

$$a_s = \sqrt{a_p\, a_n} \tag{20}$$

K_{bd}	-	Canopy radiation extinction coefficient for 'black' leaves with diffuse radiation
a_s	-	Leaf absorptance of solar radiation
a_p	-	Leaf absorptance of PAR
a_n	-	Leaf absorptance of near infrared radiation (NIR, 0.7-3 μm)

The value of a_p was assumed to be 0.8, whilst a_n was assumed to be 0.2 (Goudriaan, 1977). a_s is the geometric mean of the absorptances in the PAR and NIR spectrum.

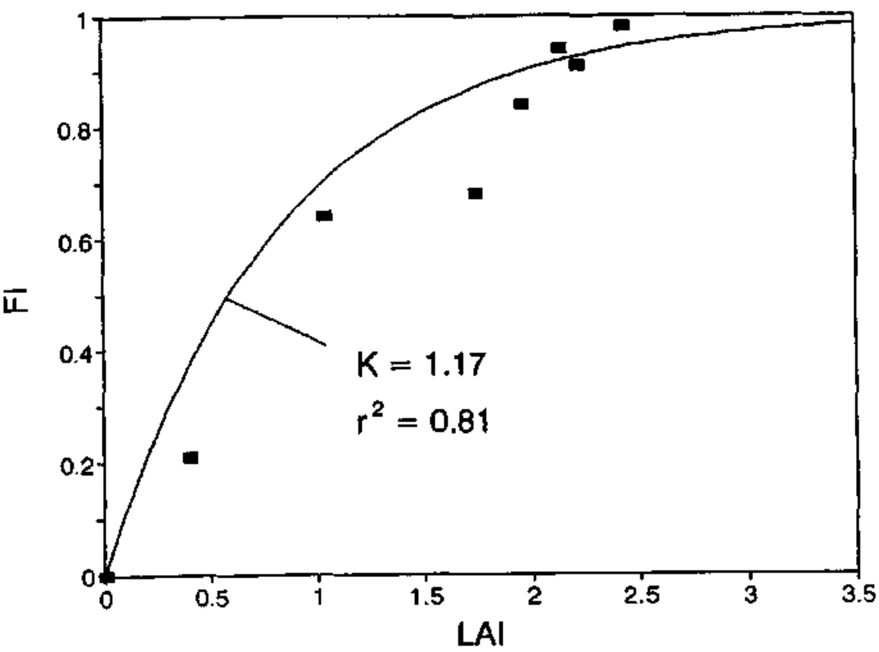


Figure 4.4

Correlation between leaf area index (LAI) and fractional interception (FI) of radiation measured with the ceptometer for cabbage. Canopy extinction coefficient (K) and the coefficient of determination of the exponential regression function (r^2) are shown

Rooting depth and thermal time requirements:

Root depth was estimated from weekly measurements of soil water extraction with the neutron meter. It was assumed to be equal to the depth at which 90% of soil water depletion occurred during weekly periods.

GDD (d °C) was determined from daily average air temperature (T_{avg}), after Monteith (1977):

$$GDD = (T_{avg} - T_b)\,\Delta t \qquad (21)$$

where T_b is the base temperature in °C and Δt is one day. Values of T_b recommended by Knott (1988), and Campbell and Norman (1998) were used. Thermal time accumulation occurred every day of the season for all crops, as T_{avg} was never lower than the minimum temperature required for development (T_b). T_{avg} also never exceeded the optimum temperature for crop development (T_{cutoff}). T_{cutoff} values recommended by Knott (1988) were used. GDD required for emergence was calculated for crops planted by seeding (carrots, beetroot and swisschard), whilst GDD until harvest was determined for all crops. Day degrees required for flowering and maturity were not determined for crops that were harvested during the vegetative stage.

4.1.4 FAO model parameter determination: Example with vegetables

Field measurements carried out for the trial at Roodeplaat (Section 4.1.2) were used to determine FAO model parameters for vegetables. In addition, Hc was measured at the end of the growing season for winter vegetables, and weekly for summer vegetables.

FAO Kcb's and growth periods were determined for 25 vegetable cultivars using a simple canopy cover-based equation. Weather data and crop height were used to calculate crop PET, whilst fractional interception of radiation was used to calculate Kcb values, and to determine the end of the initial stage, as well as the start and end of the mid-season stage. The procedure can be easily and cheaply applied to determine FAO type crop parameters for any species. FAO Kcb's, root depths, crop heights and growth periods determined in the field trial at Roodeplaat were included in the FAO crop parameter database of SWB, and are summarized in Table B2 (Appendix B).

Examples of how to determine FAO crop parameters for SWB are presented below.

Canopy development and root depth:

Figure 4.5 represents measured values of FI and estimated RD during the growing season of onions and green pepper. RD was estimated from weekly measurements of θ with the neutron meter. It was assumed to be equal to the depth at which 90% of soil water depletion occurred during weekly periods. Estimated RD values were different from those recommended by Green (1985) for transplanted onions, in particular for the initial stage. Smith (1992a) recommended RD values of 0.25 m for the initial crop stage.

Crop height and potential evapotranspiration:

ETo was calculated using the SWB model and weather input data collected from the weather station, and used to determine PET with Eqs. (1) and (2). In the absence of measurements during the growing season, it was assumed that Hc of onions increased linearly from planting until harvest. A third order polynomial was fitted through the measured data of Hc for green pepper ($r^2 = 0.97$) and used to calculate PET. The same procedure was used to calculate PET for the other winter and summer vegetables. Initial Hc values were assumed to be 0.01 m for crops planted by seeding (Smith, 1992a) and 0.05 m for transplanted crops.

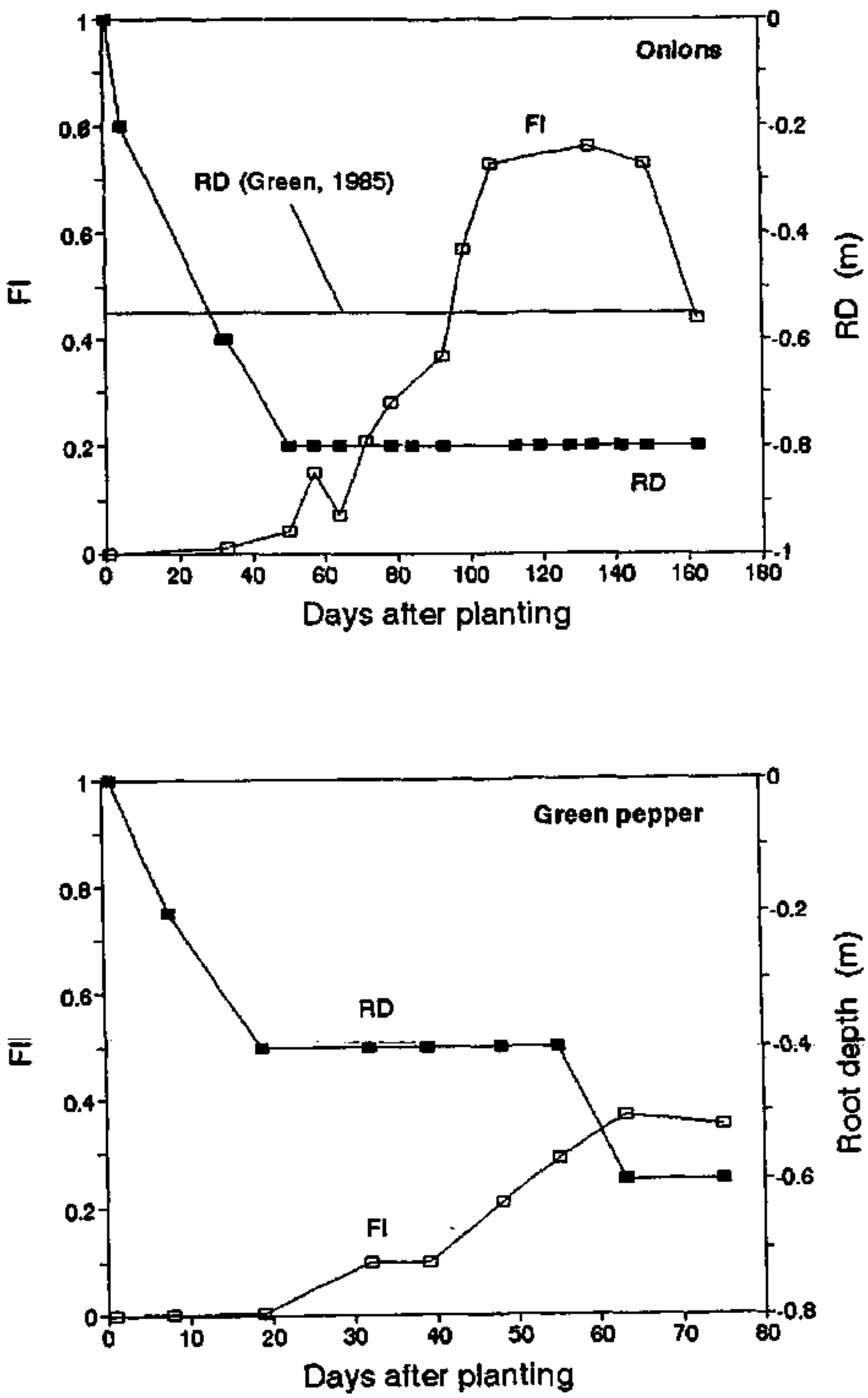


Figure 4.5

Measured values of canopy cover (FI) and estimated root depth (RD, depth at which 90% of weekly soil water depletion occurred) during the growing season of onions and green pepper. Root depth recommended by Green (1985) is also presented for onions

Basal crop coefficients and growth periods:

Figure 4.6 presents values of FI and Kcb for onions and green pepper. A third order polynomial was fitted through the measured data points of FI for both crops. The coefficients of determination were 0.94 for onions and 0.97 for green pepper. Daily Kcb was calculated from FI, Hc and weather data using the following equation derived from Eqs. (4) and (5):

$$Kcb = FI\ PET / ETo \tag{22}$$

The following procedure was used to determine Kcb's for the initial, mid-season and late-season stages, and the lengths of growth stages in days for onions and green pepper (Figure 4.6):

i) Initial stage:	Length of stage from planting until FI = 0.1. Kcb equal to calculated daily Kcb at FI = 0.1.
ii) Crop development stage:	Length of stage from end of initial stage until FI is 90% of maximum FI.
iii) Mid-season stage:	Length of stage from end of development stage until canopy cover drops to the same value it had at the beginning of the mid-season period (90% of maximum FI). Kcb equal to average daily Kcb calculated with Eq. (22) during the mid-season stage.
iv) Late-season stage:	Length of stage from end of mid-season stage until end of growing season. Kcb equal to calculated daily Kcb at end of growing season.

The duration of the late-season stage and Kcb for the late-season stage was not determined for green pepper as the crop was harvested during the mid-season stage, before leaf senescence occurred (Figure 4.6). Doorenbos and Pruitt (1992) stated that the beginning of the mid-season stage can be recognized in the field when the crop has attained 70 to 80% groundcover. They also stated that full groundcover occurs when the FAO crop coefficient (Kc) approaches a maximum. Many vegetables do not reach 70% groundcover during the growing season. The mid-season stage was therefore assumed to start when FI became equal to 90% of maximum FI.

Initial Kcb's were generally in the range of those recommended by Allen et al. (1996). Differences in length of crop growth stages were observed between the data obtained in the Roodeplaat trial and those published by the FAO (Doorenbos and Pruitt, 1992; Smith, 1992a) for most vegetables, due to the different cultivars and conditions under which the experiments were carried out.

Caution should be exercised against blind acceptance of the FAO parameters as local conditions, management and cultivars are likely to influence crop growth periods and Kcb's.

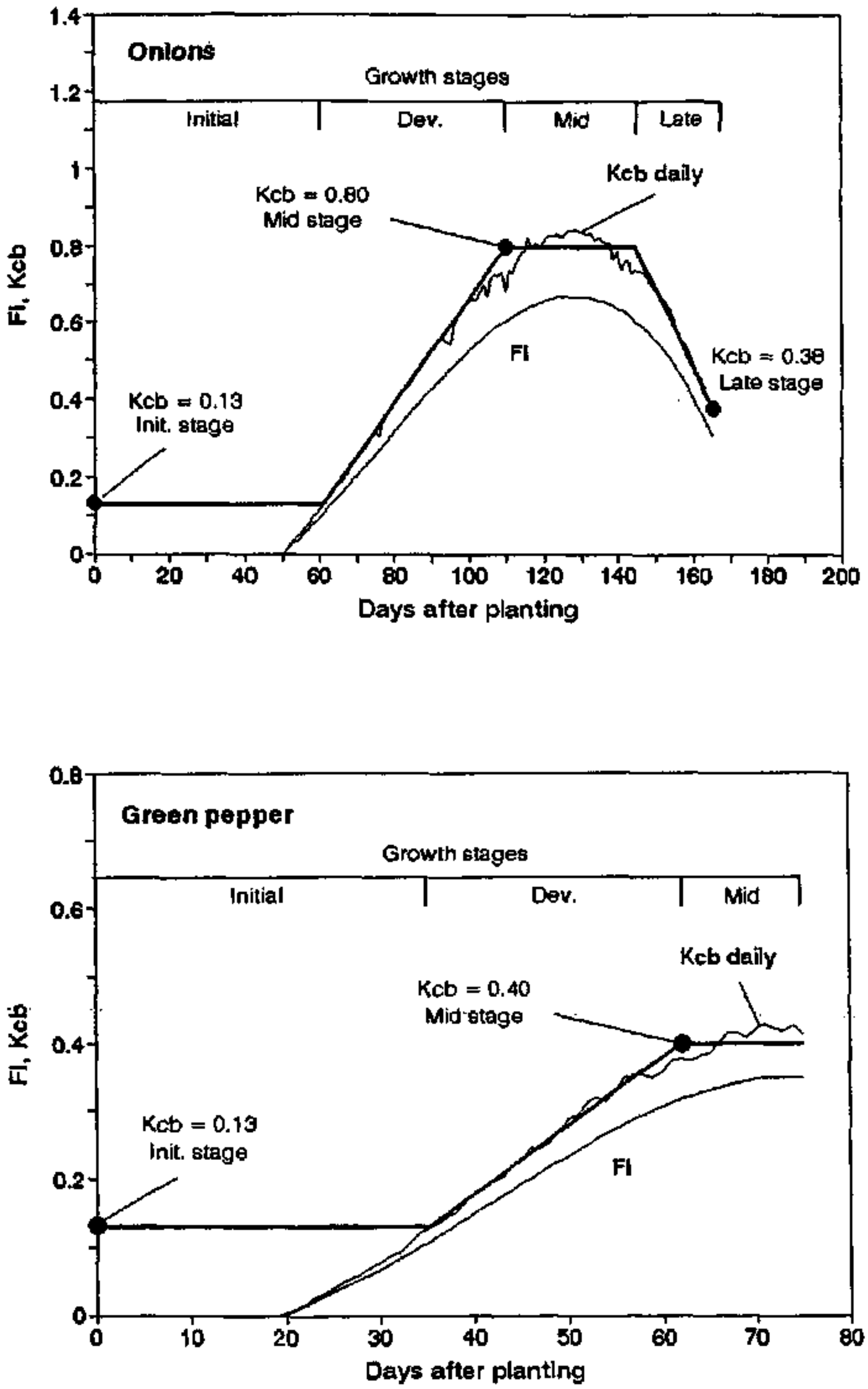


Figure 4.6

Daily values of canopy cover (FI) and basal crop coefficient (Kcb daily), and estimated Kcb values for four growth stages of onions and green pepper (initial, crop development, mid-season and late-season stages)

4.2 Hatfield peach trial

A field trial was carried out at Hatfield in order to determine FAO crop parameters for peach trees. Specific crop growth parameters for peaches were not determined as it was not possible to carry out growth analysis due to the limited number of trees and limited time available.

Field measurements were used to determine FAO basal crop coefficients (Kcb) and growth periods for first and second leaf peach trees.

4.2.1 Experimental set-up

A peach field trial was carried out during the 1996/97 and 1997/98 seasons at the Hatfield Experimental farm (25°45' S, 28°16' E, altitude 1372 m). This is a summer rainfall region (October-March) with an average of 670 mm y^{-1}. The monthly average maximum temperature is 30 °C (January), with a monthly average minimum of 1.5 °C (July). Frost occurs during the winter.

The soil is a sandy loam (28% clay, 10% silt and 62% sand) Hutton (Soil Classification Working Group, 1991) with depths generally in excess of 1.2 m (a small portion having scattered hard plinthic formations at ≈ 1.1 m). Soil analysis revealed adequate P (120 mg kg^{-1}), pH(H_2O) being 6.4 and sufficient Ca, Mg and K (580, 140 160 mg kg^{-1} respectively).

Young grafted peach trees (*Prunus persica* cv. Transvaalia) were planted on 6 September 1996 in a high density 4.5 x 1 m hedgerow pattern. The tree row orientation was in a E-SE to W-NW axis (110° - 290°). At planting the trees were cut back to ≈ 250 mm above the soil surface. As the trees developed during the growing period, steps were taken to promote the central leader growth pattern and develop lower horizontal branches. During July 1997, the trees were cut back to a height of 2 m and pruned to a central leader system. By 7 August 1997 trees were at 80% blossom and reached full bloom on 12 August 1997. From this date the canopy developed throughout the summer.

During the establishment period (first 3 weeks) the trees were basin irrigated manually with a hose pipe. They were irrigated daily during the first week, and subsequently reducing the irrigation frequency to once per week by the third week. Micro-jets (DT-Spreader 360°/12 stream) covering a 2 m large band, were installed under the trees during January 1997 and used for irrigation thereafter.

At planting, 57 g Superphosphate (10.5% P) $tree^{-1}$ was incorporated in the planting hole. Nitrogen was supplied monthly at rate of 20, 30, 40 and 50 g LAN (28% N) $tree^{-1}$ during October, November, December 1996 and January 1997 with irrigation. Trees were monitored for visual signs of trace element deficiencies (Zn and Mn) and light cover (≈ 0.2 ℓ $tree^{-1}$) foliar sprays containing ZnO, $MnSO_4$ and spray urea were applied when necessary.

The fruitlets were counted on 15 September 1997 to establish the extent of fruit removal which was done on 25 September 1997. The fruit was harvested on 17 and 18 November 1997.

4.2.2 Field measurements

Two mechanical weighing lysimeters were used to measure water loss by evapotranspiration. The surface dimensions of the lysimeters were 2 x 2 m. The depth was 0.9 m. Two trees were planted in each lysimeter. Load cells coupled to a Campbell Scientific CR10 data logger (Campbell Scientific, Logan, Utah, USA) were attached within the lever mechanism to automate recording weight changes. Each load cell was supplied with an independent constant voltage source through a transformer which converts 220 V AC to $\approx$ 16 V DC. This was used to charge a 12 V 6.5 A h lead acid motorcycle battery as an emergency supply in the case of power failure. From the 12 V DC battery the power passed through an electronic voltage stabilizing circuit designed and fabricated by personnel of the University of Pretoria Engineering Faculty electronics workshop. As a precaution, the voltage supplied to each load cell was monitored hourly by the data logger.

The lysimeters were calibrated with sand bags of known mass before the beginning of the trial. The voltage output from each load cell was recorded as an equivalent depth of water on the basis that one litre per m^2 is equivalent to 1 mm. The data logger was programmed to read at 10 s intervals and average these values every 15 min. Each lysimeter had a drainage pipe to allow excess water which had percolated through the profile to be removed. This drainage water was directed over a tipping bucket meter, where each tip was counted by means of a reed switch. Thus it was possible to monitor drainage.

The following weather data were monitored and recorded hourly with a CR10 data logger:

- i) Temperature and relative humidity with an HMP35C sensor;
- ii) Wind speed with an R.M. Young cup anemometer;
- iii) Solar radiation with an LI 200X pyranometer (LiCor, Lincoln, Nebraska, USA); and
- iv) Rainfall with a Rimco R/TBR tipping bucket rain gauge.

The data logger was programmed to automatically calculate hourly average saturation vapour pressure, vapour pressure and vapour pressure deficit. The logged daily data was regularly downloaded using a lap-top computer to calculate daily short grass evapotranspiration (ETo).

Irrigation amounts were recorded with a volumeter.

Volumetric soil water content was monitored twice per week with a neutron water meter model 503DR CPN Hydroprobe. In four sites in the portion of the orchard surrounding the lysimeter, sets of 12 similar neutron probe access tubes were installed both in the row and at right angles to the tree row, in such a manner that the soil water content across the whole area (tree rooting and irrigation area, as well as the inter-row region) could be monitored.

4.2.3 FAO model parameter determination for peach trees

As the lysimeter only covered 2 m of the 4.5 m row spacing and thus did not account for 2.5 m of the inter-row which was normally dry and had low evaporative losses, crop evapotranspiration was calculated as follows:

$$ET = ET_{lys} 2 / 4.5 = ET_{lys} 0.444 \qquad (23)$$

ET_{lys} - Water loss measured with the lysimeter (mm)

The daily FAO crop coefficient (Kc) was then determined as follows:

$$Kc = ET / ETo \qquad (24)$$

Daily calculated Kc values for the first two growing seasons of peach trees are shown in Figures 4.7 and 4.8. FAO basal crop coefficients (Kcb) for the various growth stages were determined by fitting an appropriate line through the lower values of Kc, which were assumed to reflect the conditions where the soil surface was dry (negligible evaporation), but there was sufficient water not to restrict transpiration. The longer development period during the first season was expected since it was necessary to develop the tree structure.

FAO basal crop coefficients and length of growth stages for peaches were included in the FAO crop factors database of SWB (Table B2, Appendix B).

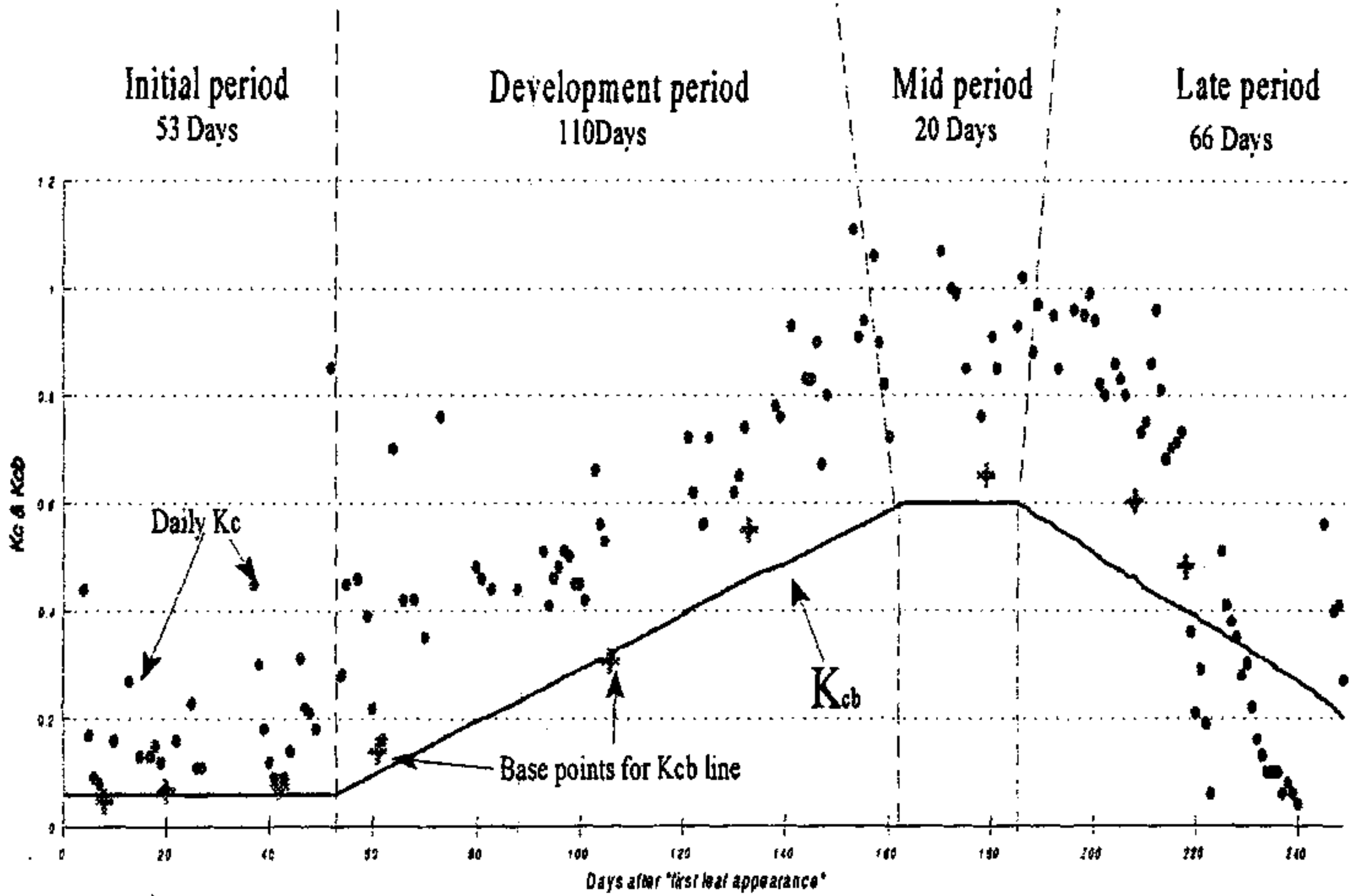


Figure 4.7

Daily FAO crop factors (Kc) and basal crop coefficients (Kcb), as well growth periods for first leaf season of peaches.

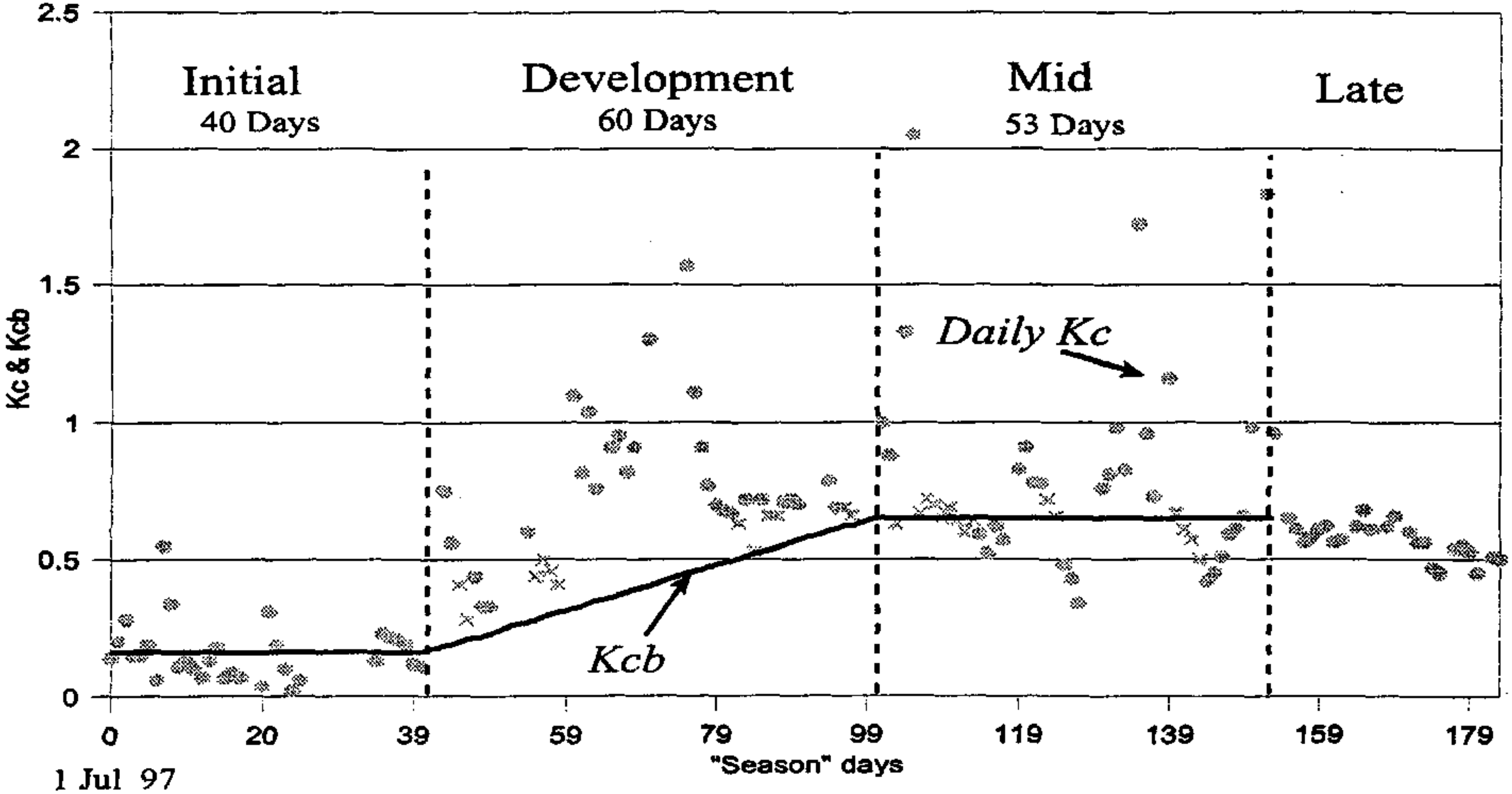


Figure 4.8

Daily FAO crop factor (Kc) and basal crop coefficient (Kcb), as well growth periods for second leaf season of peaches.

CHAPTER 5

MODEL SIMULATIONS

Independent data sets obtained from South African researchers and organizations, were used to validate SWB. In addition, SWB was calibrated for a wide range of vegetables as well as peach trees, using data from the field trials carried out during the project. This allowed the inclusion of several crops in the SWB crop parameter database. Table 5.1 summarizes crops for which data sets were available, and simulations ran. Table 5.1 also includes crops for which the validation was carried out in previous work (Barnard et al., 1998; Annandale et al., 1996).

Data sets were not obtained for some important irrigated crops, namely cotton and some fruit tree crops. It was also not possible to set up time-consuming and expensive field trials. Specific crop growth parameters are therefore not available for these crops, but FAO crop factors were included in SWB. The user will therefore be able to schedule irrigations by making use of the FAO-based model.

In the following Sections, simulations of crop growth and soil water balance are presented. The following output graphs are shown for each simulation (Figures 5.1 to 5.101):

i) Soil water balance summary graph;
ii) Root depth (RD);
iii) Leaf area index (LAI);
iv) Total above ground dry matter and harvestable dry matter (TDM & HDM); and
v) Soil water deficit to field capacity.

The soil water balance graph of SWB includes the following information:

i) Irrigation and rainfall input data in the top part of the graph (histograms).

ii) Simulated soil water deficit to field capacity in the bottom part of the graph.

iii) The horizontal line on the graph indicates the field capacity level (FC).

iv) Simulated profile soil water deficit as well as root zone deficit to field capacity at the end of the simulation in the top right corner of the graph.

v) The output summary below the graph shows: planting date, irrigation system, crop, irrigation timing and amount, type of model, seasonal rainfall, irrigation, transpiration, evaporation, drainage, canopy interception and runoff, saturated profile soil water content, profile soil water content at field capacity, allowable depletion at the end of the simulation, and mass balance error.

TABLE 5.1
CROPS FOR WHICH DATA SETS FOR CALIBRATION/VALIDATION OF SWB WERE OBTAINED

Crop	Source of data	Type of model	Purpose of simulation with SWB
Agronomic crops:			
Babala	Barnard et al. (1998)	Crop growth	Validation
Cowpeas	Barnard et al. (1998)	Crop growth	Validation
Maize	Bennie et al. (1996);	Crop growth and FAO	Validation
"	Hensley et al. (1994);	Crop growth and FAO	Validation
"	Barnard et al. (1998)	Crop growth	Validation
Oats	Barnard et al. (1998)	Crop growth	Validation
Peanuts	Bennie et al. (1996)	Crop growth and FAO	Validation
Peas (dry)	Bennie et al. (1996)	Crop growth and FAO	Validation
Peas (green)	Annandale et al. (1996)	Crop growth	Validation
Potato	Bennie et al. (1996)	Crop growth and FAO	Validation
Rye	Barnard et al. (1998)	Crop growth	Validation
Ryegrass	Barnard et al. (1998)	Crop growth	Validation
Soybean	Mason et al. (1980);	Crop growth and FAO	Validation
"	Barnard et al. (1998)	Crop growth	Validation
Sorghum	Barnard et al. (1998)	Crop growth	Validation
Sugarcane	Thompson (1991)	Crop growth and FAO	Validation
Sunflower	A. Nel (personal communication)	Crop growth and FAO	Validation
Tobacco	J.J.B. Pretorius (personal communication)	Crop growth and FAO	Calibration
Triticale	Barnard et al. (1998)	Crop growth	Validation
Wheat	Bennie et al. (1996);	Crop growth and FAO	Validation
"	Walker et al. (1995);	Crop growth and FAO	Validation
"	Barnard et al. (1998)	Crop growth	Validation
Forage crops:			
Cocksfoot	Barnard et al. (1998)	Crop growth	Validation
Crownvetch	Barnard et al. (1998)	Crop growth	Validation
Fescue	Barnard et al. (1998)	Crop growth	Validation
Kikuyu	Barnard et al. (1998)	Crop growth	Validation
Lucerne	Barnard et al. (1998)	Crop growth	Validation
Milkvetch	Barnard et al. (1998)	Crop growth	Validation
Panicum	Barnard et al. (1998)	Crop growth	Validation
Rhodes grass	Barnard et al. (1998)	Crop growth	Validation
Smuts finger grass	Barnard et al. (1998)	Crop growth	Validation
Weeping love-grass	Barnard et al. (1998)	Crop growth	Validation

TABLE 5.1
CROPS FOR WHICH DATA SETS FOR CALIBRATION/VALIDATION OF SWB WERE OBTAINED (Continued)

Crop	Source of data	Type of model	Purpose of simulation with SWB
Vegetable crops:			
Beans (bush)	Roodeplaat field trial	Crop growth and FAO	Calibration
Beans (runner)	Roodeplaat field trial	Crop growth and FAO	Calibration
Beetroot	Roodeplaat field trial	Crop growth and FAO	Calibration
Cabbage	Roodeplaat field trial	Crop growth and FAO	Calibration
Carrots	Roodeplaat field trial	Crop growth and FAO	Calibration
Eggplant	Roodeplaat field trial	Crop growth and FAO	Calibration
Lettuce	Roodeplaat field trial	Crop growth and FAO	Calibration
Marrow	Roodeplaat field trial	Crop growth and FAO	Calibration
Onions	Roodeplaat field trial	Crop growth and FAO	Calibration
Pepper (chilli)	Roodeplaat field trial	Crop growth and FAO	Calibration
Pepper (green)	Roodeplaat field trial	Crop growth and FAO	Calibration
Pumpkin	Roodeplaat field trial	Crop growth and FAO	Calibration
Squash	Roodeplaat field trial	Crop growth and FAO	Calibration
Sweet corn	Roodeplaat field trial	Crop growth and FAO	Calibration
Swisschard	Roodeplaat field trial	Crop growth and FAO	Calibration
Tomato	Roodeplaat field trial	Crop growth and FAO	Calibration
Tree crops:			
Apple	T. Volschenk (personal communication)	FAO	Calibration
Citrus	G.C. Green and H.M. du Plessis (personal communication)	FAO	Validation
Peach	Hatfield field trial	FAO	Calibration

Note that in most of the soil water balance graphs shown in this Chapter, the vertical bars in the top part of the graph represent the sum of rainfall and irrigation. For these simulations, the output parameter "Precip" shown in the summary below the soil water balance graphs, represents the sum of seasonal rainfall and irrigation. In many data sets obtained for this study, rainfall plus irrigation was measured with rain gauges read by operators at certain time intervals. It was, therefore, not always possible to differentiate rainfall and irrigation amounts.

Root depth, leaf area index, top and harvestable dry matter, as well as the soil water deficit graph include simulated (solid line) and measured (symbols) data points (Figures 5.1 to 5.101).

A visual fit was used as rough estimation of how the model performs compared to measured data. Standard errors of measurements, if available, are displayed in the output graphs as vertical bars. SWB also calculates parameters of the statistical analysis between measured and simulated data, and outputs them in the top right corner of each graph. This allows quick, efficient and quantitative evaluation of model performance. The parameters of the statistical analysis are:

i) Number of observations (N);
ii) Coefficient of determination (r^2);
iii) Index of agreement of Willmott (D);
iv) Root mean square error (RMSE); and
v) Mean absolute error (MAE).

These were recommended by de Jager (1994) to assess model accuracy. He also recommended as model prediction reliability criteria that r^2 and D should be > 0.8, whilst MAE should be < 20%.

The statistical analysis shown in the TDM & HDM graph is only for measured and simulated total above ground dry matter production.

Note that the FAO model does not simulate leaf area index and dry matter production. Final yield is estimated and output if the potential yield is entered as input (Appendix A).

All data used for calibration and validation are available in the SWB database. Specific crop growth parameters and FAO crop factors are summarized in Tables B1 and B2 (Appendix B).

5.1 Agronomic crops

5.1.1 Maize

Complete data sets were obtained from Prof ATP Bennie (University of the Orange Free State, Bloemfontein). Bennie, van Rensburg, Strydom and du Preez (1996) carried out an experiment to test the response of several crops to different water management options. During this trial, maize (*Zea mays* cv. PNR 6552) was grown at the experimental station of the University of the Orange Free State, 13 km from Bloemfontein. The crop was irrigated with a pivot system. The soil is Bainsvlei Amalia (Soil Classification Working Group, 1991).

Several treatments were differentiated:

i) Two target yields: high (H) and low (L);

ii) Three irrigation schedules: irrigations every week (1), two weeks (2) and three weeks (3); and

iii) Four water management options:

- Start with wet soil profile and end with dry soil profile (VL);
- Start with dry soil profile and end with wet soil profile (LV);
- Start and end with wet soil profile (VV); and
- Start and end with dry soil profile (LL).

In this work, the soil water balance and crop growth was simulated with SWB for the following treatments:

i) High target yield, weekly irrigations, start with wet soil profile and end with dry soil profile (H1VL) (examples of model output are in Figure 5.1); and

ii) Low target yield, weekly irrigations, start with wet soil profile and end with dry soil profile (L1VL) (examples of model output are in Figure 5.2).

The independent data sets were used to validate the soil water balance and crop growth subroutines of SWB. Crop growth parameters for maize calibrated at Kromdraai (Barnard et al., 1998), were used as basis. The trial at Kromdraai was set up on a sandy acid soil and the crop was irrigated with lime-treated acid mine drainage. Both crop growth and root development were poor. Water and radiation use efficiency, canopy extinction coefficient, maximum root depth and the fraction of total dry matter partitioned to roots had therefore to be increased for the simulations shown in Figures 5.1 and 5.2. Thermal time requirements for crop developmental stages were also modified to account for the difference in cultivar (Table B1, Appendix B).

The soil water balance was also simulated with the FAO model for H1VL (examples of model output are in Figure 5.3) and L1VL (examples of model output are in Figure 5.4). The crop factors recommended by the FAO for maize, were used in these simulations. Only root depth for mid-season and late-season stage was modified (Table B2, Appendix B).

Soil water deficit predicted with the FAO-type model for the L1VL treatment at the end of the growing season (Figure 5.4), was higher than that calculated with the crop growth model (Figure 5.2), as the FAO model does not account for smaller canopy size under water stress conditions. The FAO crop factors are set for well-watered conditions, and they should be modified when water stress occurs in order to simulate accurately smaller canopy size and partitioning of PET. The strength of the growth model is that reduction in both canopy size and amount of energy used for transpiration is simulated under water stress. This makes it suitable for deficit irrigation simulations.

The statistical output parameters indicated that predictions with both crop growth and FAO model were inside, or marginally outside the reliability criteria. In practice, refinement of specific crop growth parameters and FAO crop factors is recommended for maize to account for differences in cultivars and specific environmental conditions.

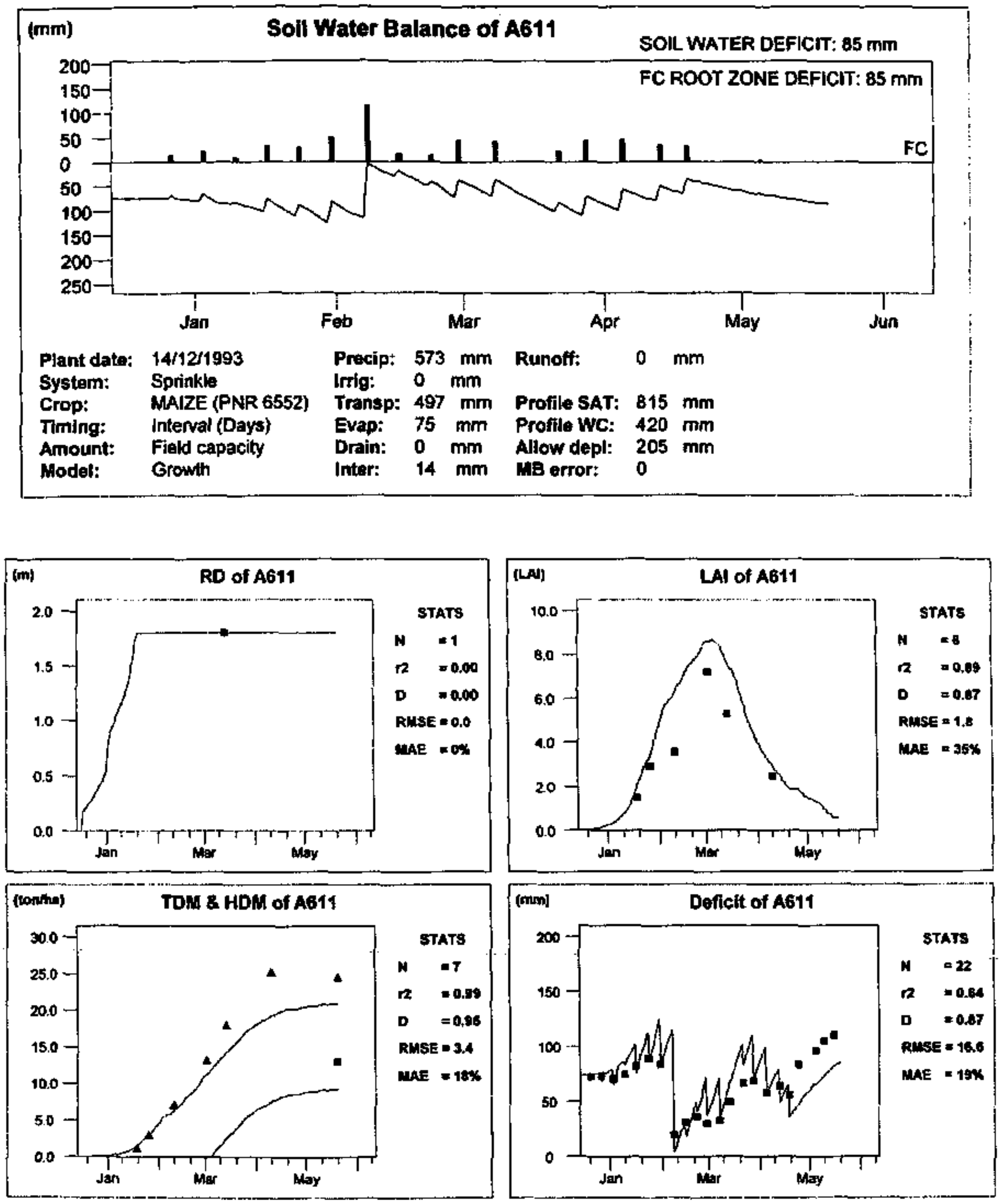


Figure 5.1

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Maize

Input and measured data sets: Bloemfontein, treatment H1VL (Bennie et al., 1996)

Model type: Crop growth

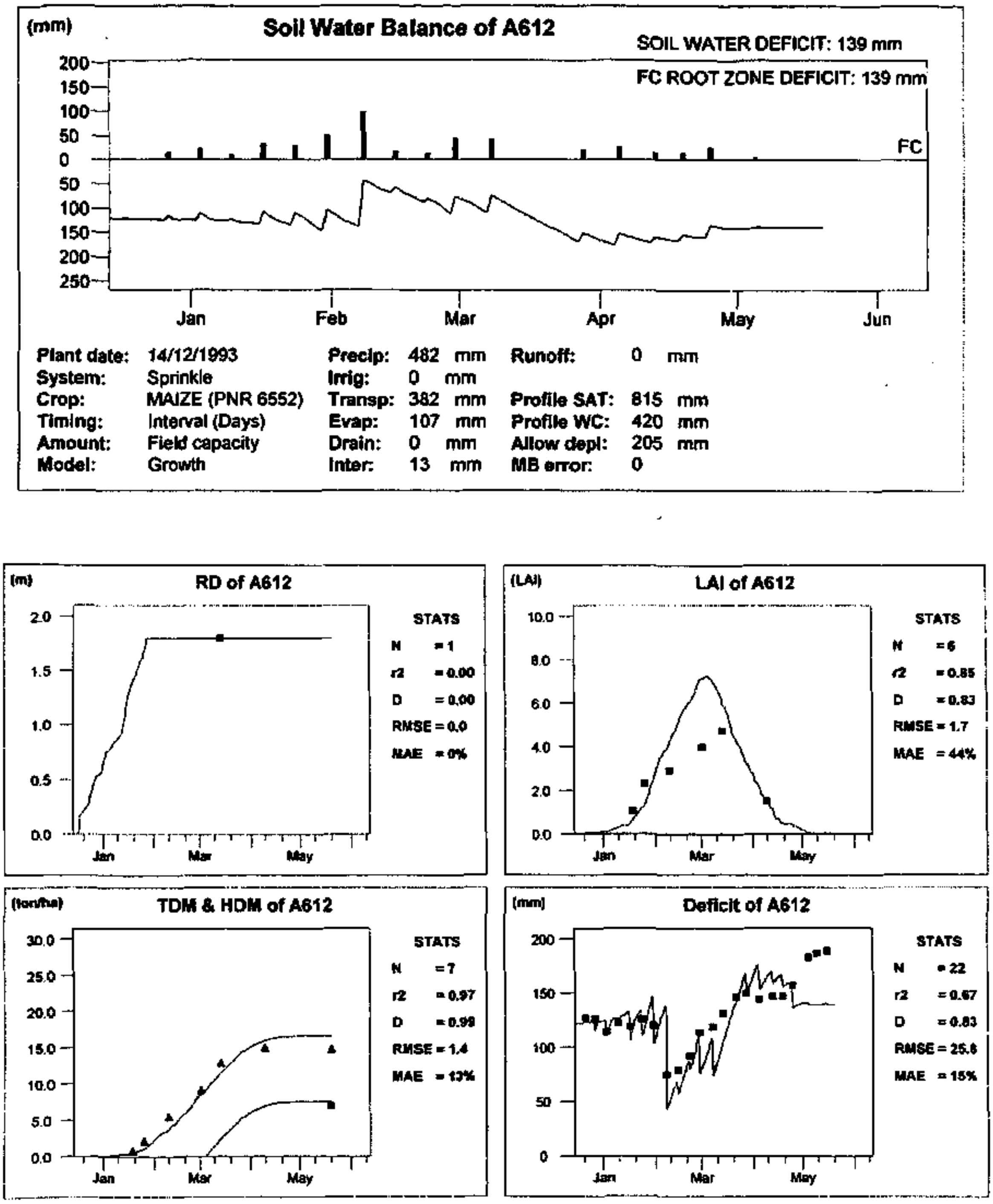


Figure 5.2

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Maize
Input and measured data sets: Bloemfontein, treatment L1VL (Bennie et al., 1996)
Model type: Crop growth

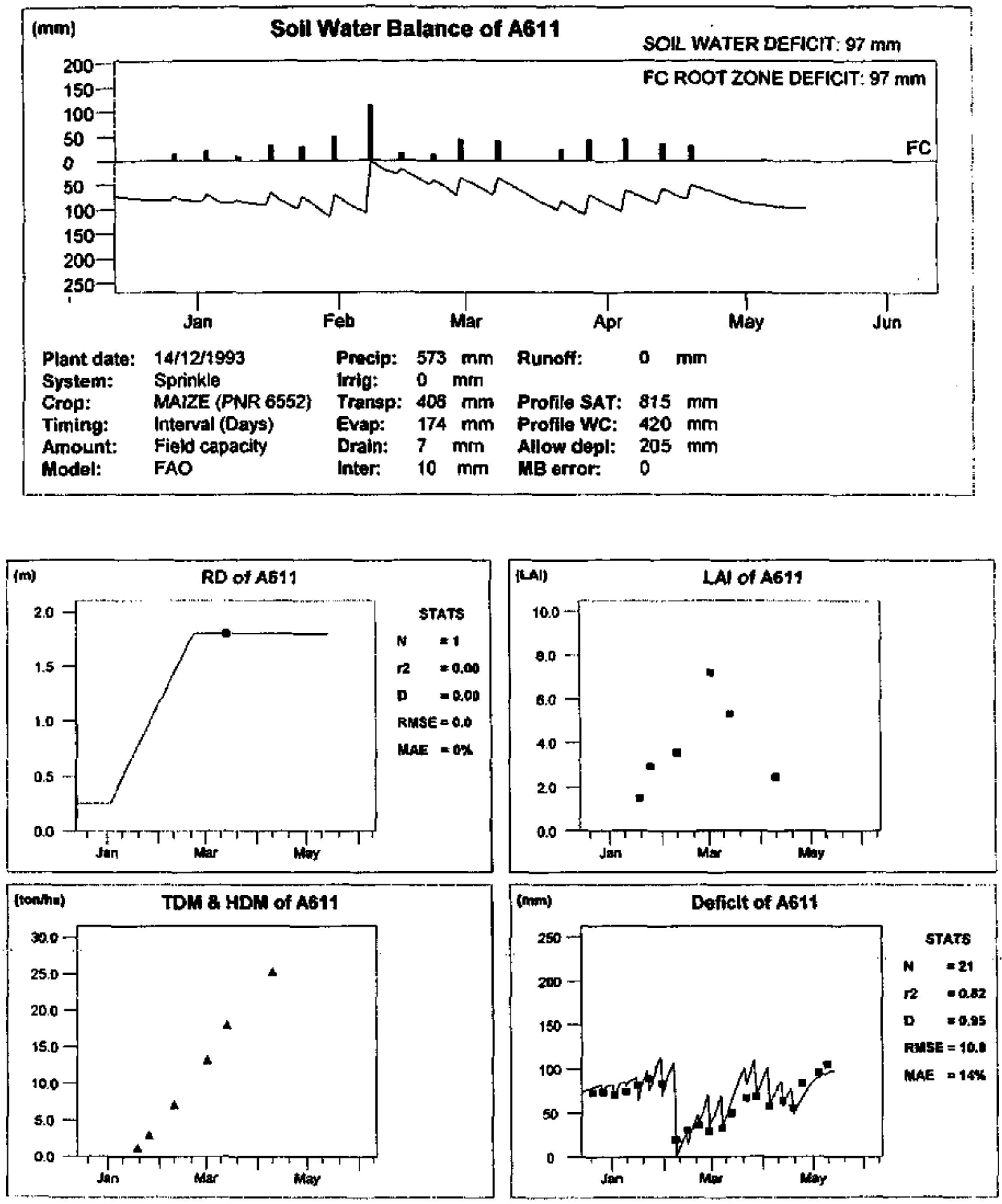


Figure 5.3

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Maize

Input and measured data sets: Bloemfontein, treatment H1VL (Bennie et al., 1996)

Model type: FAO

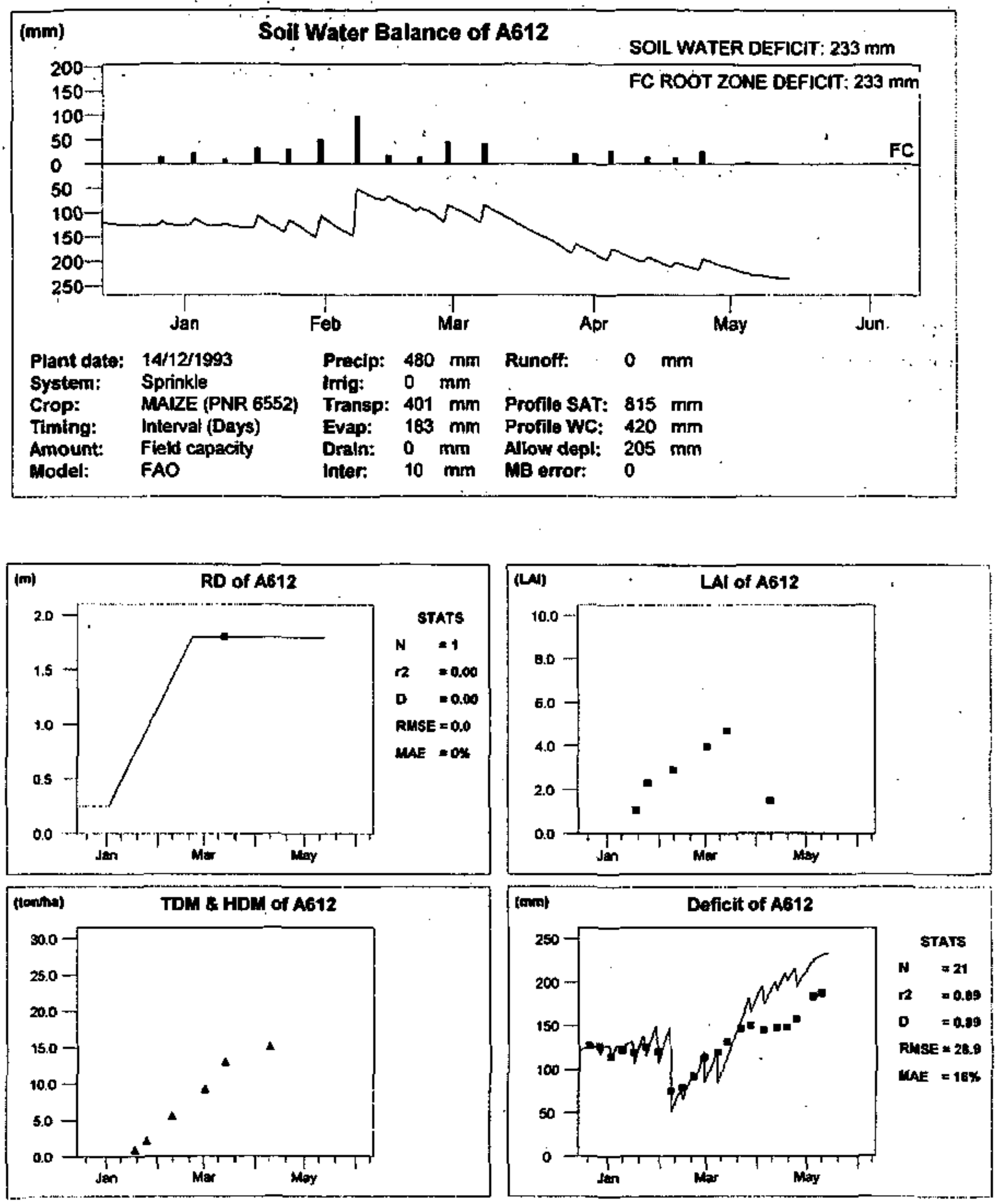


Figure 5.4

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Maize
Input and measured data sets: Bloemfontein, treatment L1VL (Bennie et al., 1996)
Model type: FAO

Data sets were also obtained from Dr M Hensley (Institute for Soil, Climate and Water - Agricultural Research Council, Glen). Dry land maize was grown on several ecotopes (Hensley, van den Berg, Anderson, Oberholzer, du Toit, Berry and de Jager, 1994). In this study, SWB simulations were carried out both with the crop growth and FAO model for the Setlagole/Clovelly (cv. PNR 473, Figures 5.5 and 5.6), Ermelo/Longlands (cv. PNR 6479, Figures 5.7 and 5.8) and Kroonstad/Avalon ecotopes (cv. PNR 6479, Figures 5.9 and 5.10).

The independent data sets were used to validate the soil water balance subroutine of SWB. Crop growth parameters for maize calibrated at Kromdraai (Barnard et al., 1998), were used as basis. Water and radiation use efficiency, canopy extinction coefficient, maximum root depth and the fraction of total dry matter partitioned to roots were increased for the simulations with the crop growth model (Table B1, Appendix B). Growth analysis data were available only for the end of the season, so it was not possible to validate the crop growth subroutine.

Crop factors recommended by the FAO were used to simulate the soil water balance with the FAO model. Root depth for mid-season and late-season stage was modified (Table B2, Appendix B).

The growth model predicted TDM for Setlagole (Figure 5.5) and Kroonstad (Figure 5.9) reasonably well. It is very difficult to indicate the exact reason for the poor prediction of soil water deficit, as measurements of canopy development were not available. Initial soil water content per soil layer was not available, and had therefore to be estimated. This could have caused discrepancies between measured and simulated values of soil water deficit.

Simulated soil water deficit to field capacity was occasionally negative (Figures 5.5 to 5.8), as SWB simulates non-instantaneous drainage (Appendix A). Waterlogging suppressed maize growth at the Ermelo/Longlands ecotope (Hensley et al., 1994). Measured soil water content was between saturation and field capacity during large part of the growing season. SWB does not simulate the effect of waterlogging on the crop, and it therefore overestimated total above ground and harvestable dry matter production (Figure 5.7). Hensley et al. (1994) used the same input settings to simulate yield with CERES. CERES predicted a yield of 9.093 t ha^{-1} and total biomass production of 14.869 t ha^{-1}.

The unsuccessful validation of these data sets underlines the importance of field measurements to be used as model input or for checking purposes.

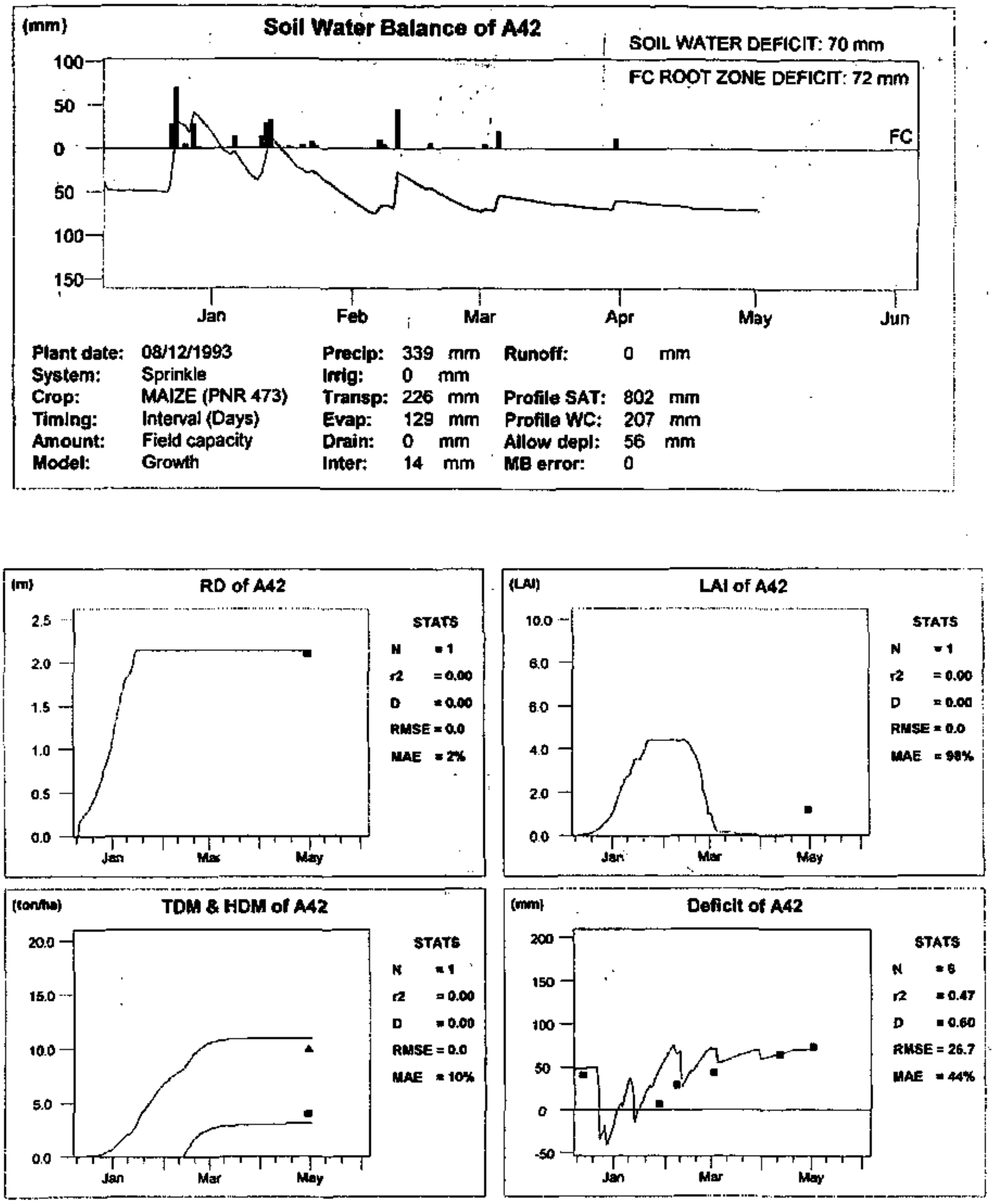


Figure 5.5

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Dry land maize

Input and measured data sets: Setlagole/Clovelly ecotope (Hensley et al., 1994)

Model type: Crop growth

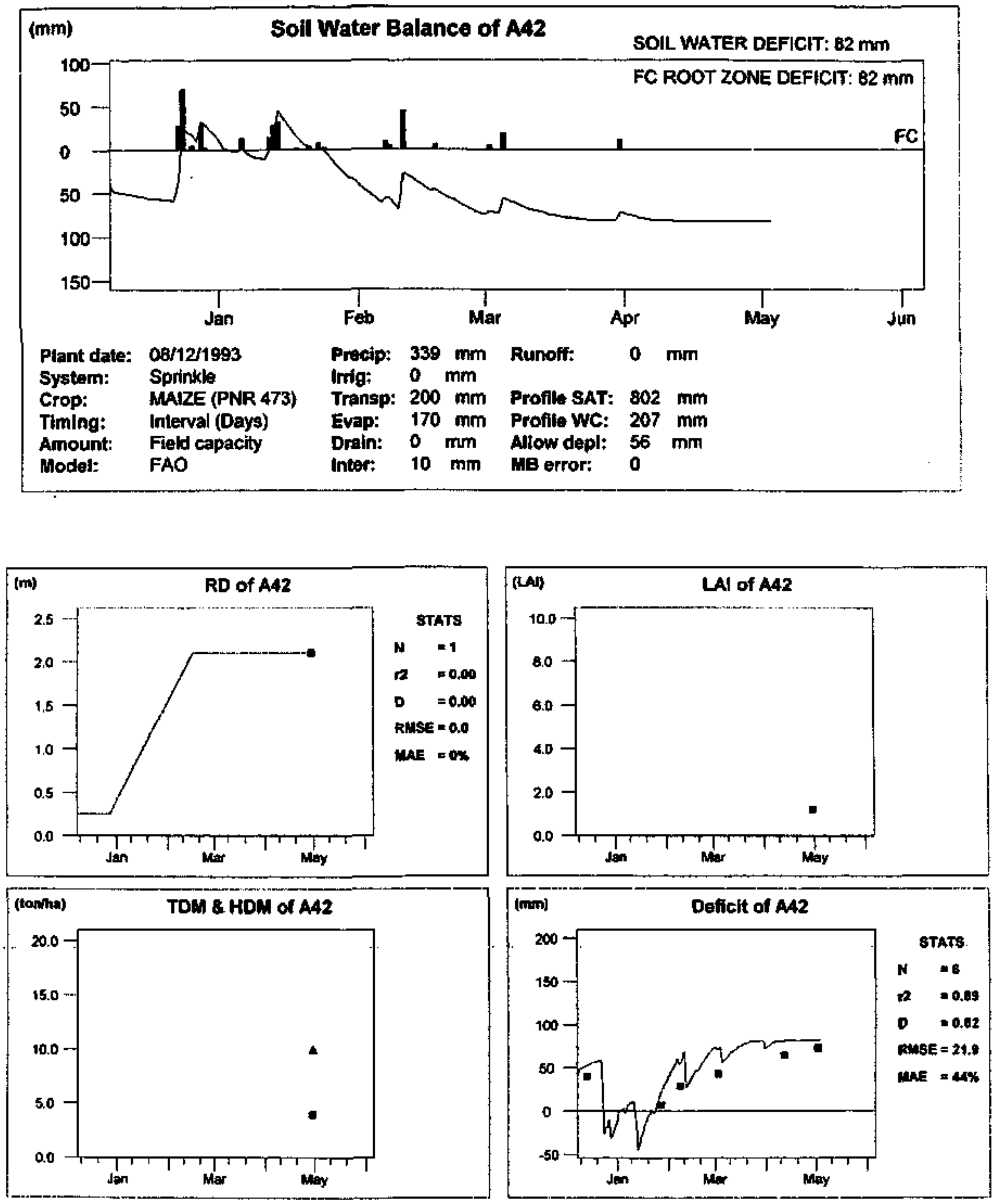


Figure 5.6

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Dry land maize

Input and measured data sets: Setlagole/Clovelly ecotope (Hensley et al., 1994)

Model type: FAO

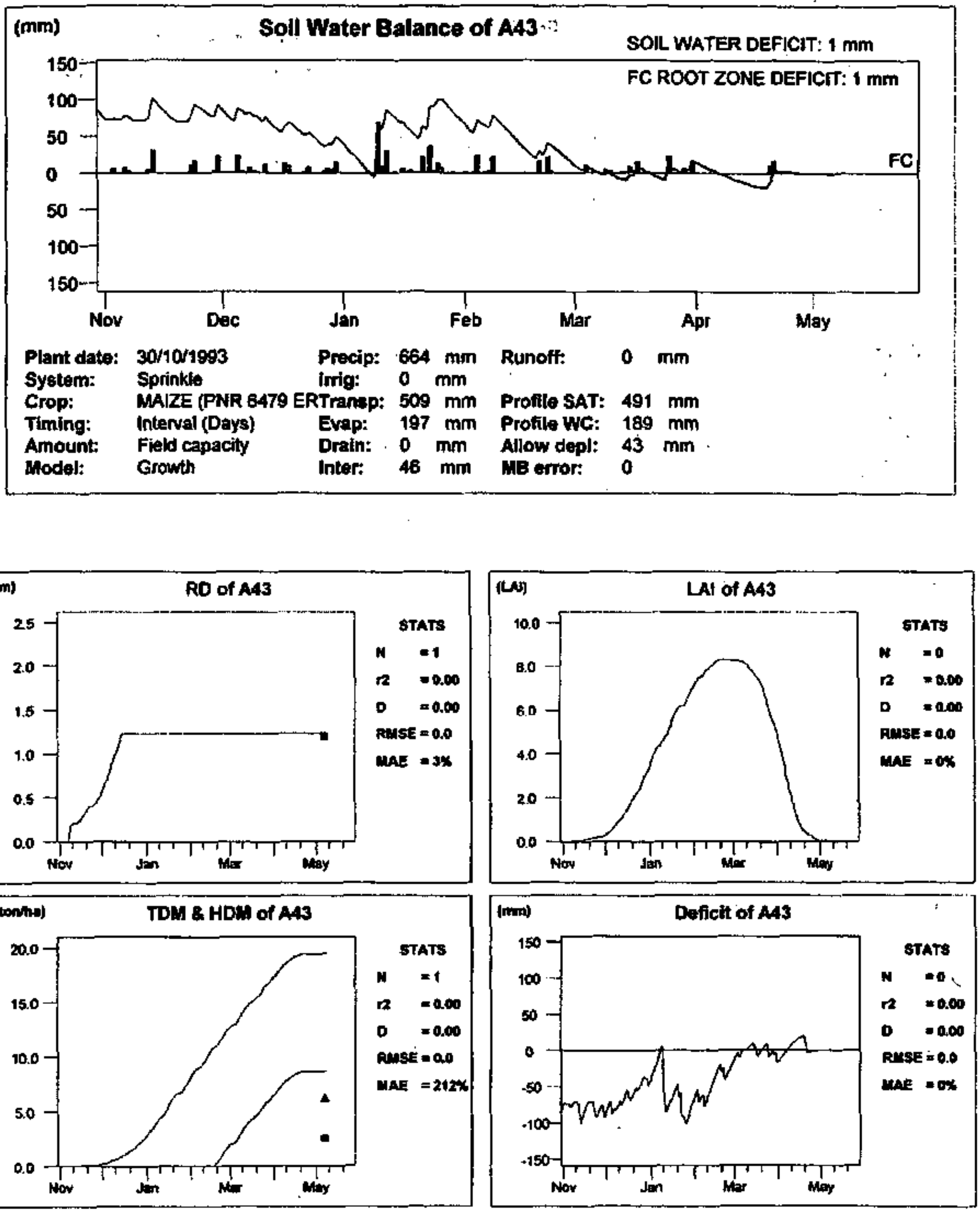


Figure 5.7

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Dry land maize
Input and measured data sets: Ermelo/Longlands ecotope (Hensley et al., 1994)
Model type: Crop growth

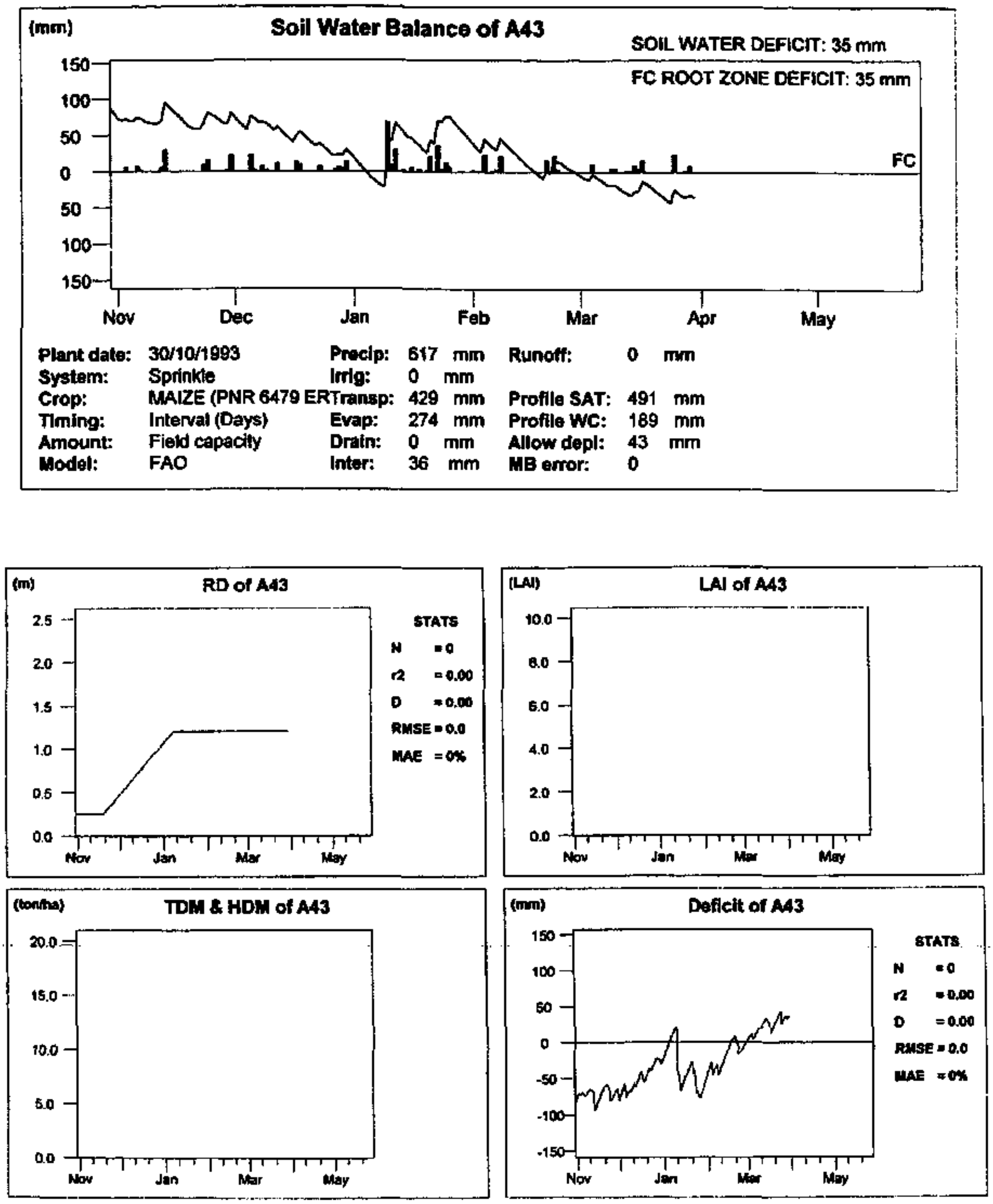


Figure 5.8

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Dry land maize

Input and measured data sets: Ermelo/Longlands ecotope (Hensley et al., 1994)

Model type: FAO

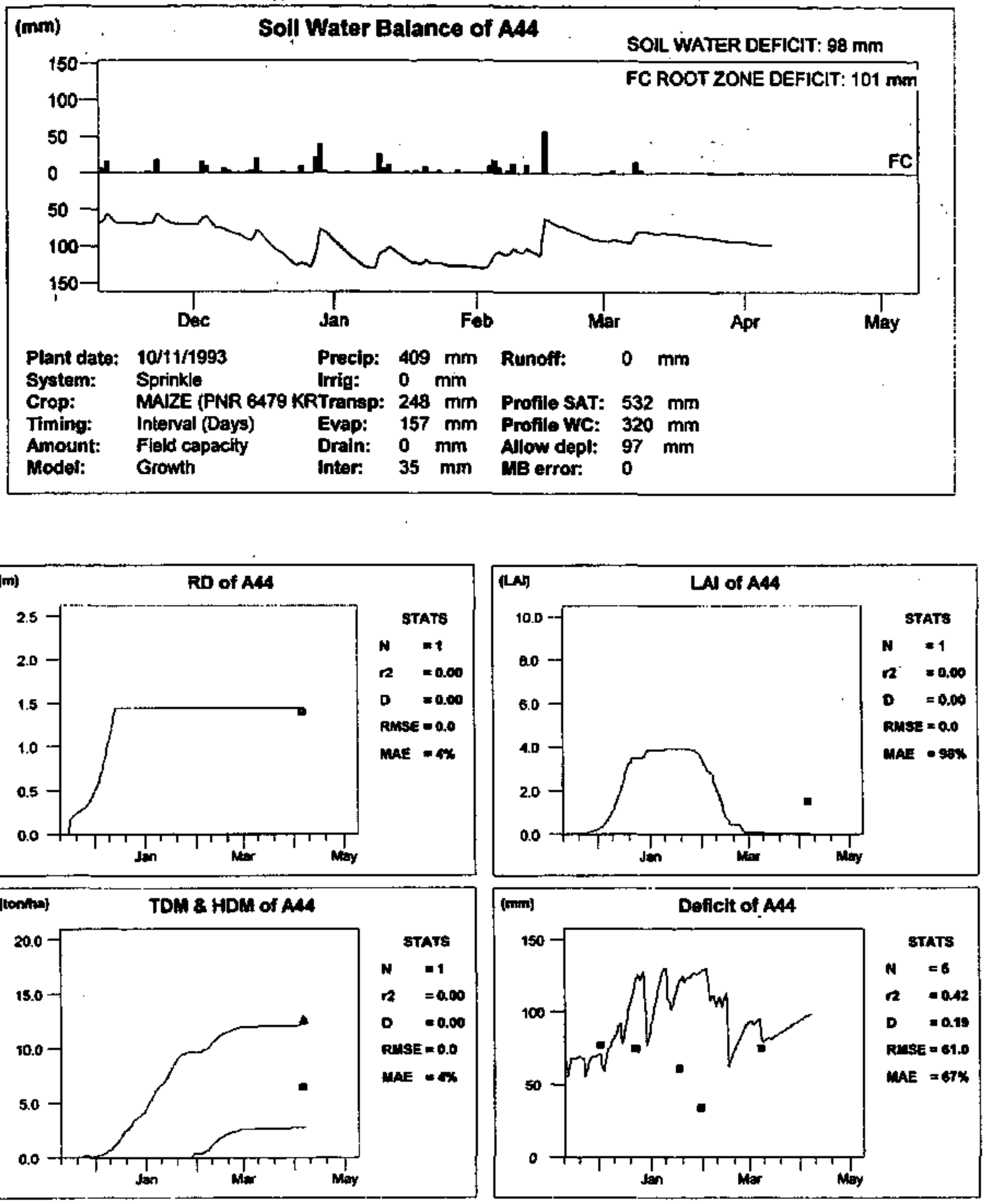


Figure 5.9

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Dry land maize

Input and measured data sets: Kroonstad/Avalon ecotope (Hensley et al., 1994)

Model type: Crop growth

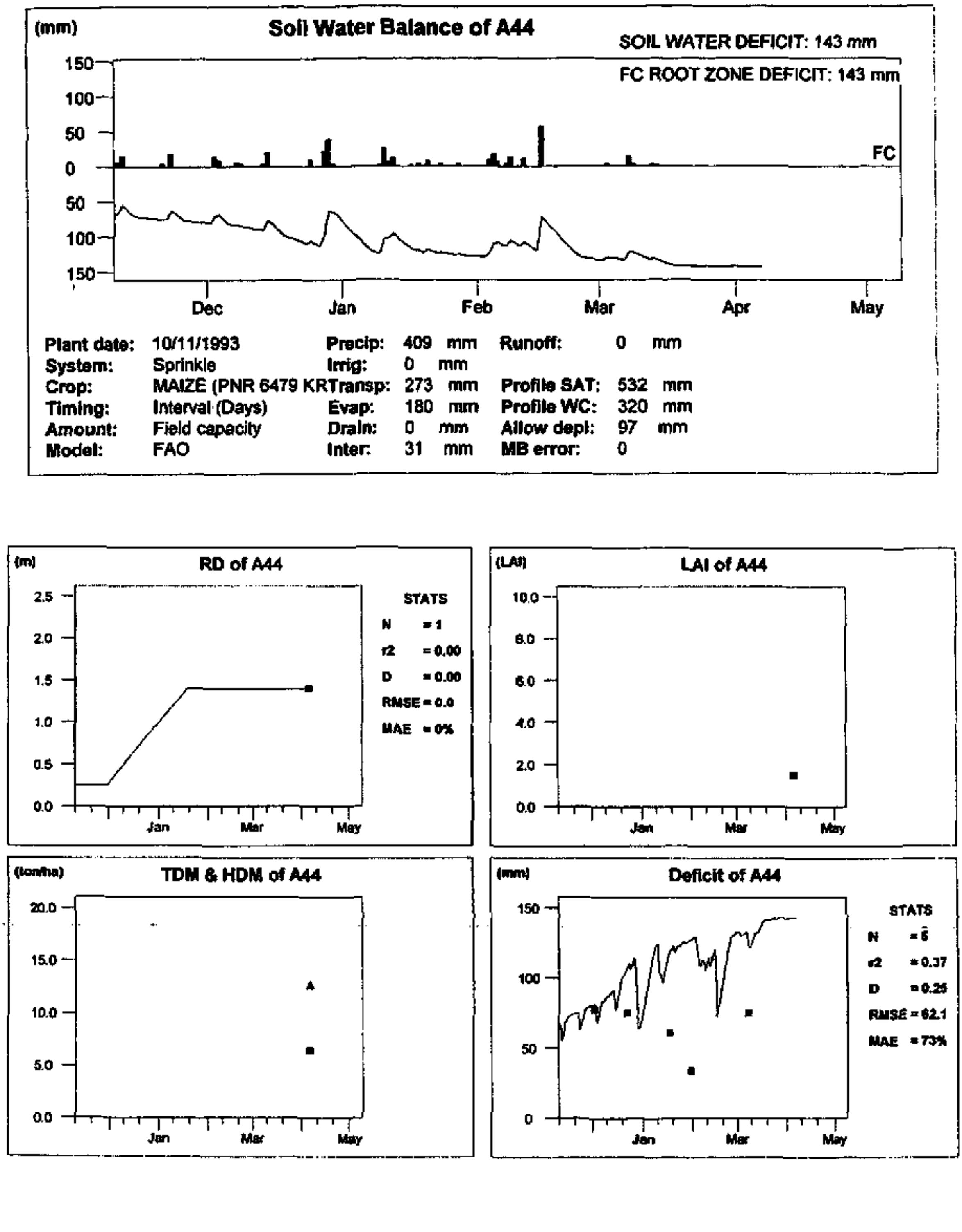


Figure 5.10

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Dry land maize

Input and measured data sets: Kroonstad/Avalon ecotope (Hensley et al., 1994)

Model type: FAO

5.1.2 Peanuts

Complete data sets were obtained from Prof ATP Bennie. Peanuts (*Arachis hypogea* cv. Harts) were grown at the experimental station of the University of the Orange Free State, 13 km from Bloemfontein (Bennie et al., 1996). See Section 5.1.1 for a more detailed description of the trial.

In this work, the soil water balance and crop growth was simulated with SWB for the following treatments:

i) High target yield, weekly irrigations, start with wet soil profile and end with dry soil profile (H1VL) (examples of model output are in Figure 5.11); and

ii) Low target yield, weekly irrigations, start with wet soil profile and end with dry soil profile (L1VL) (examples of model output are in Figure 5.12).

The H1VL treatment was used to calibrate the model, whilst the L1VL treatment was used to validate the soil water balance and crop growth subroutines of SWB.

In addition, the soil water balance was simulated with the FAO model for H1VL (Figure 5.13) and L1VL (Figure 5.14). Crop factors recommended by the FAO were used in these simulations. Root depth for mid-season and late-season stage was modified (Table B2, Appendix B).

Difficulties were experienced in modelling the crop growth of peanuts (Figures 5.11 and 5.12). The soil water balance predictions were acceptable for the H1VL treatment. The model, however, overestimated crop water use for treatment L1VL at the end of the growing season (Figures 5.12 and 5.14). The reason is most likely a specific physiological response of the crop to water stress, which is not accounted for adequately in SWB.

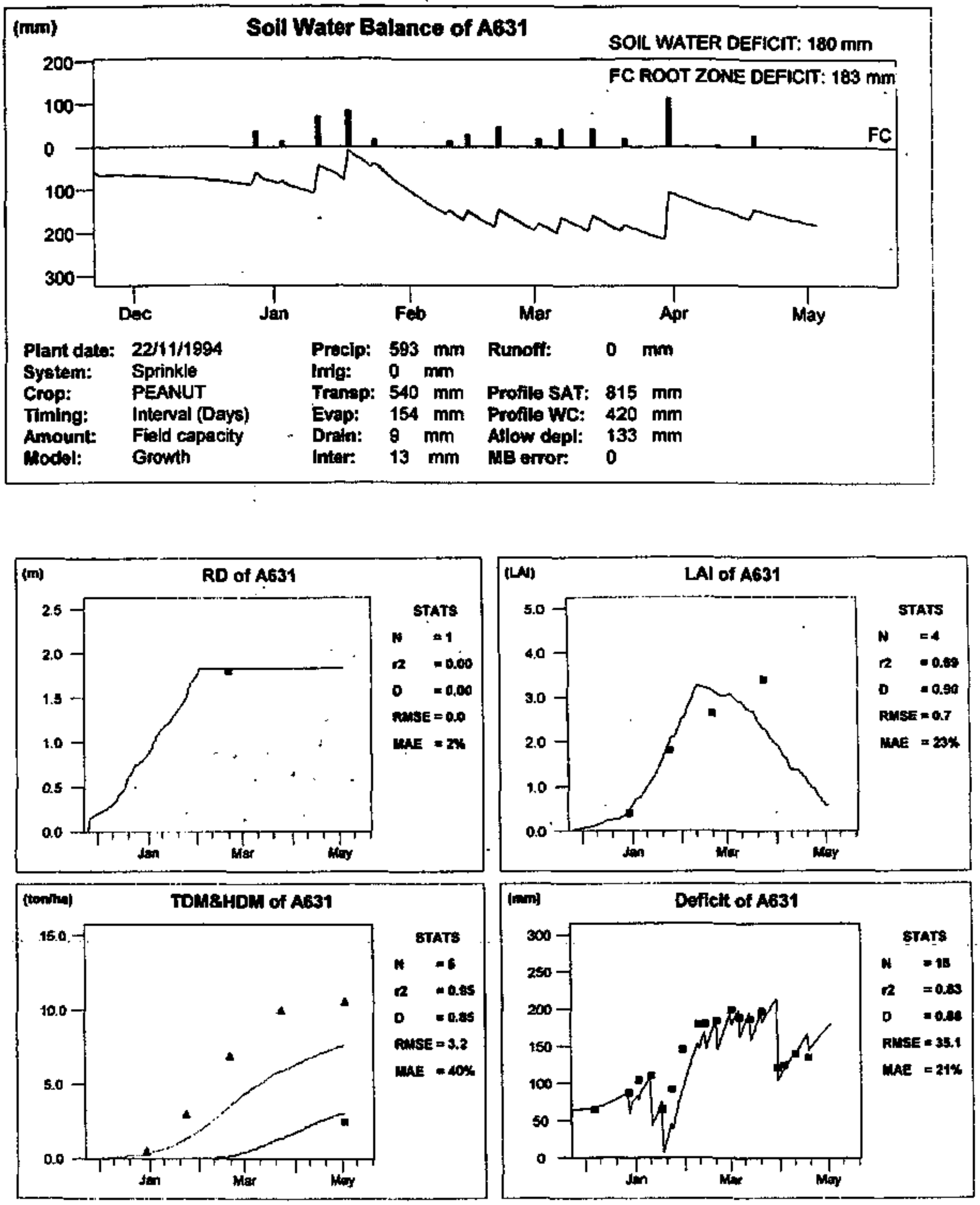


Figure 5.11

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Peanuts

Input and measured data sets: Bloemfontein, treatment H1VL (Bennie et al., 1996)

Model type: Crop growth

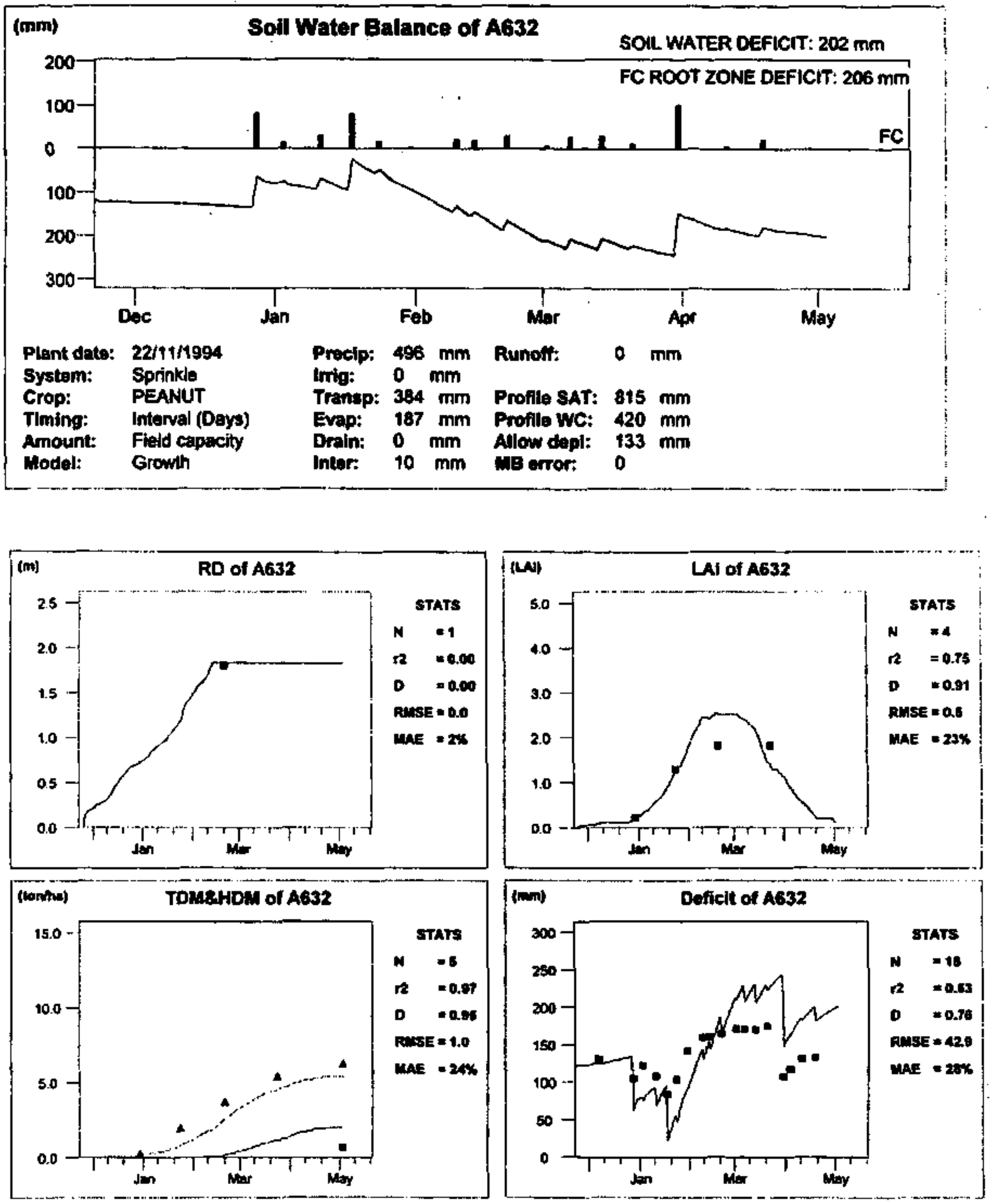


Figure 5.12

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Peanuts

Input and measured data sets: Bloemfontein, treatment L1VL (Bennie et al., 1996)

Model type: Crop growth

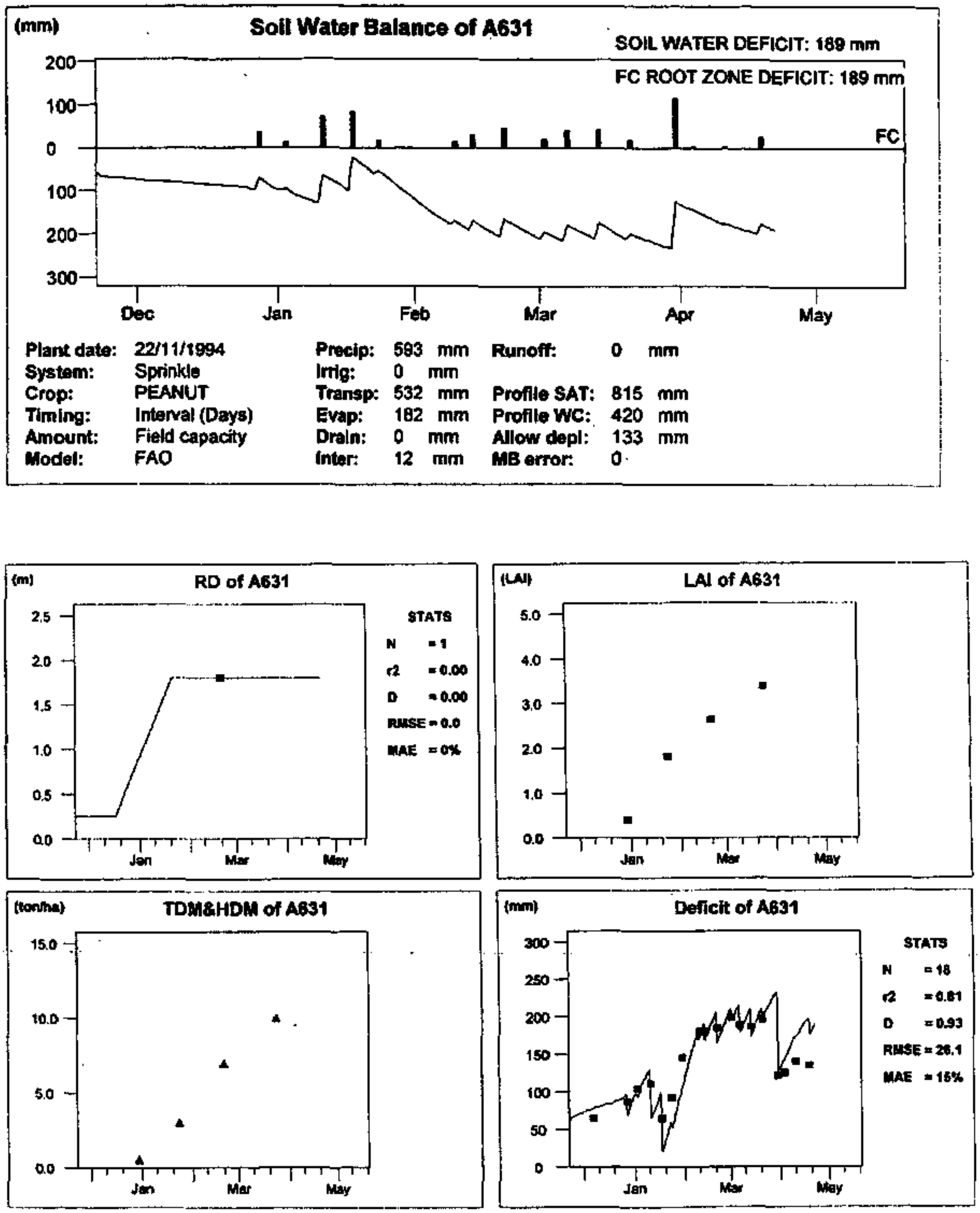


Figure 5.13

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Peanuts

Input and measured data sets: Bloemfontein, treatment H1VL (Bennie et al., 1996)

Model type: FAO

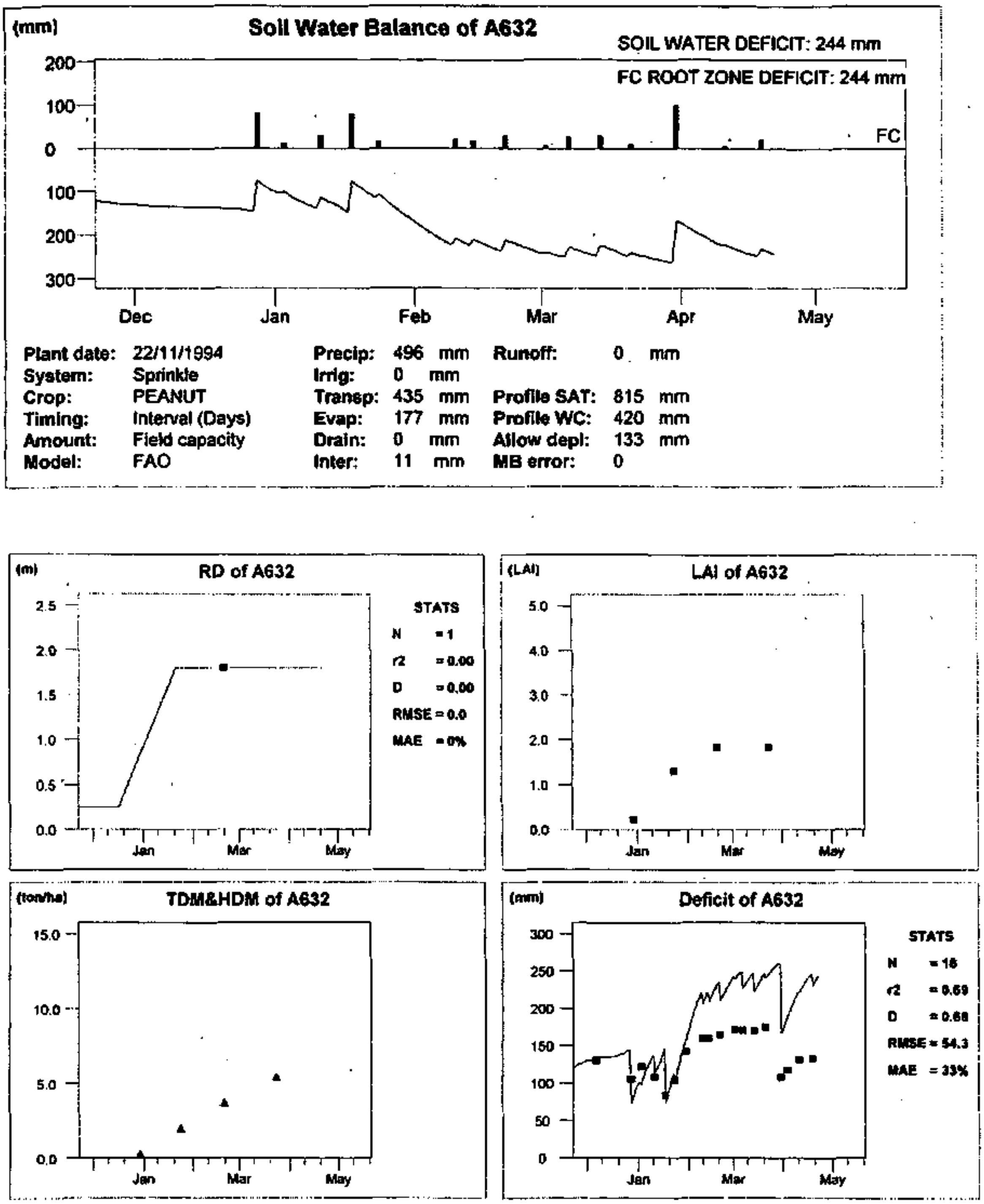


Figure 5.14

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Peanuts

Input and measured data sets: Bloemfontein, treatment L1VL (Bennie et al., 1996)

Model type: FAO

5.1.3 Peas (dry)

Complete data sets were obtained from Prof ATP Bennie. Dry peas (*Pisum sativum* cv. Orb) were grown at the experimental station of the University of the Orange Free State, 13 km from Bloemfontein (Bennie et al., 1996). See Section 5.1.1 for a more detailed description of the trial.

In this work, the soil water balance and crop growth was simulated with SWB for the following treatments:

i) High target yield, weekly irrigations, start with wet soil profile and end with dry soil profile (H1VL) (examples of model output are in Figure 5.15); and

ii) Low target yield, weekly irrigations, start with wet soil profile and end with dry soil profile (L1VL) (examples of model output are in Figure 5.16).

The independent data sets were used to validate the soil water balance and crop growth subroutines of SWB. Crop growth parameters for green peas (Annandale et al., 1996), were used as basis. Some of the parameters, namely DWR, leaf-stem partition parameter, maximum root depth and thermal time requirements, had to be modified as a different cultivar of peas was grown in Bloemfontein.

The soil water balance was also simulated with the FAO model for H1VL (examples of model output are in Figure 5.17) and L1VL (examples of model output are in Figure 5.18). Crop factors recommended by the FAO were used for these simulations. Root depth for mid-season and late-season stage was modified.

Bennie et al. (1996) recommended a maximum root depth of 1.5 m for peas. They also reported, however, that 90% of the roots occurs in the top 1.2 m soil layer. Maximum root depth of 1.2 m was therefore used as input in the simulations shown in Figures 5.15 to 5.18.

Both the crop growth and the FAO model predicted soil water deficit well. The poor prediction of crop growth parameters (Figures 5.15 and 5.16) could have been caused by spatial variability in TDM, HDM and LAI. SWB underestimated final yield for the L1VL treatment (Figure 5.16), possibly due to early flowering under water stress conditions.

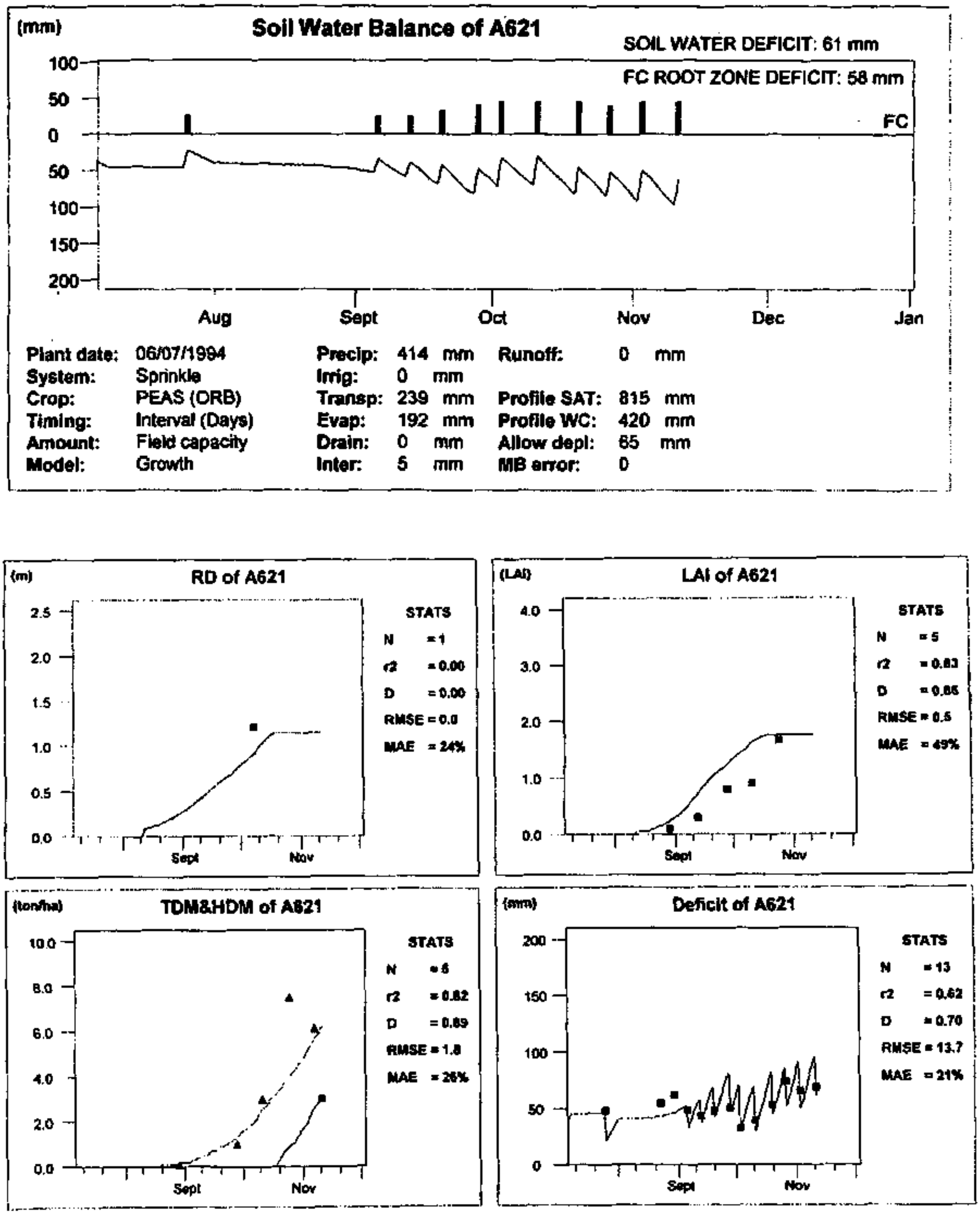


Figure 5.15

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Peas

Input and measured data sets: Bloemfontein, treatment H1VL (Bennie et al., 1996)

Model type: Crop growth

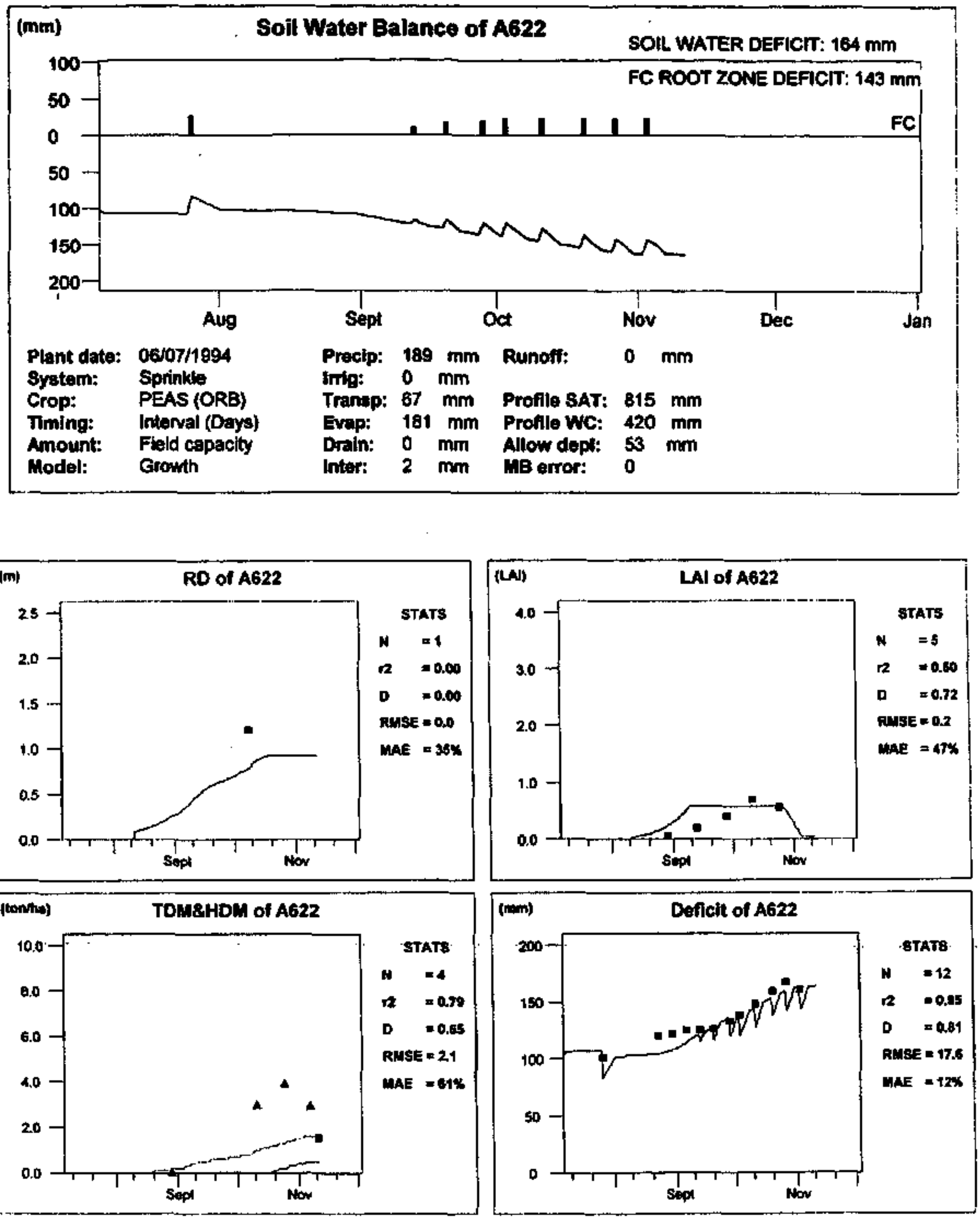


Figure 5.16

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Peas

Input and measured data sets: Bloemfontein, treatment L1VL (Bennie et al., 1996)

Model type: Crop growth

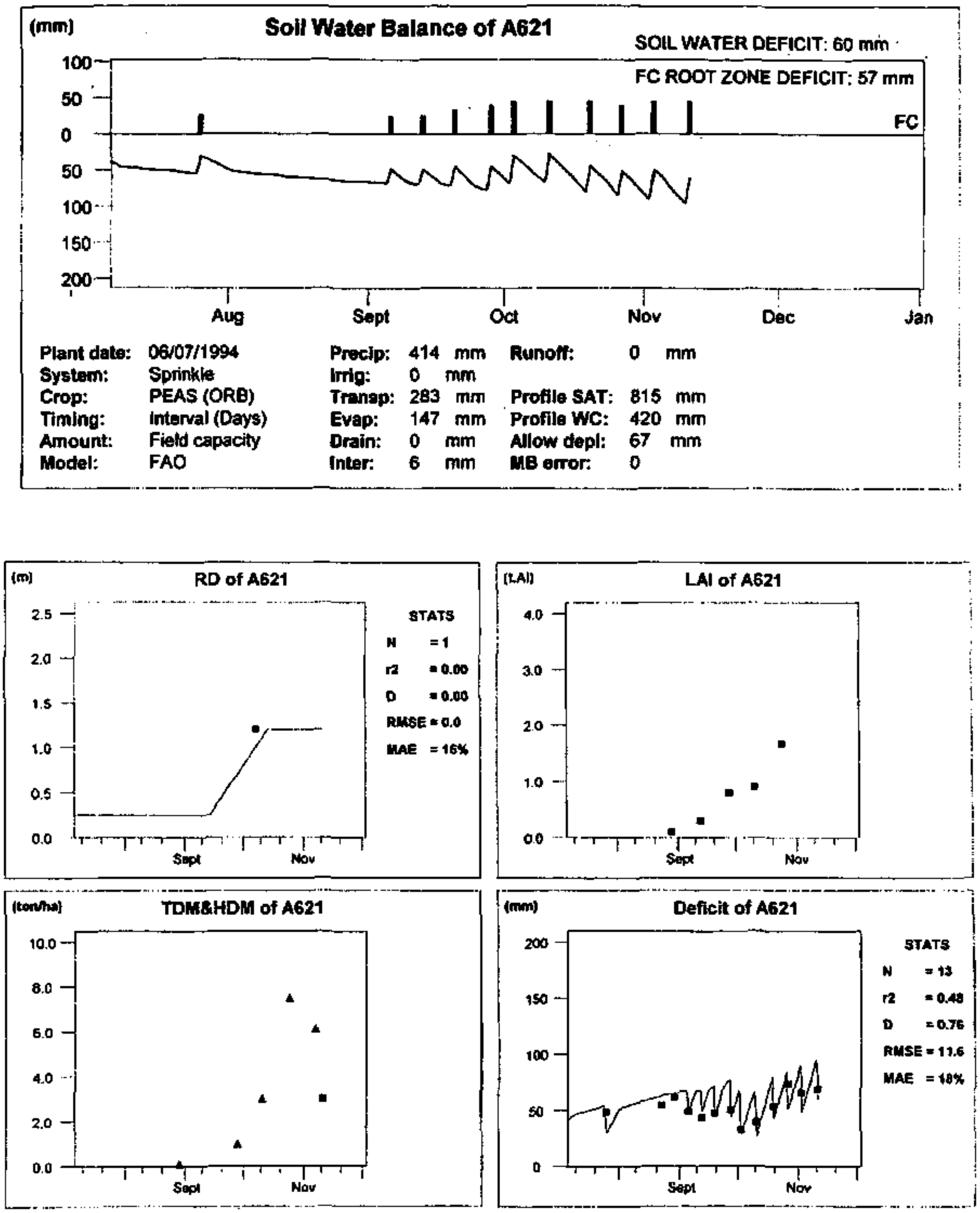


Figure 5.17

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Peas

Input and measured data sets: Bloemfontein, treatment H1VL (Bennie et al., 1996)

Model type: FAO

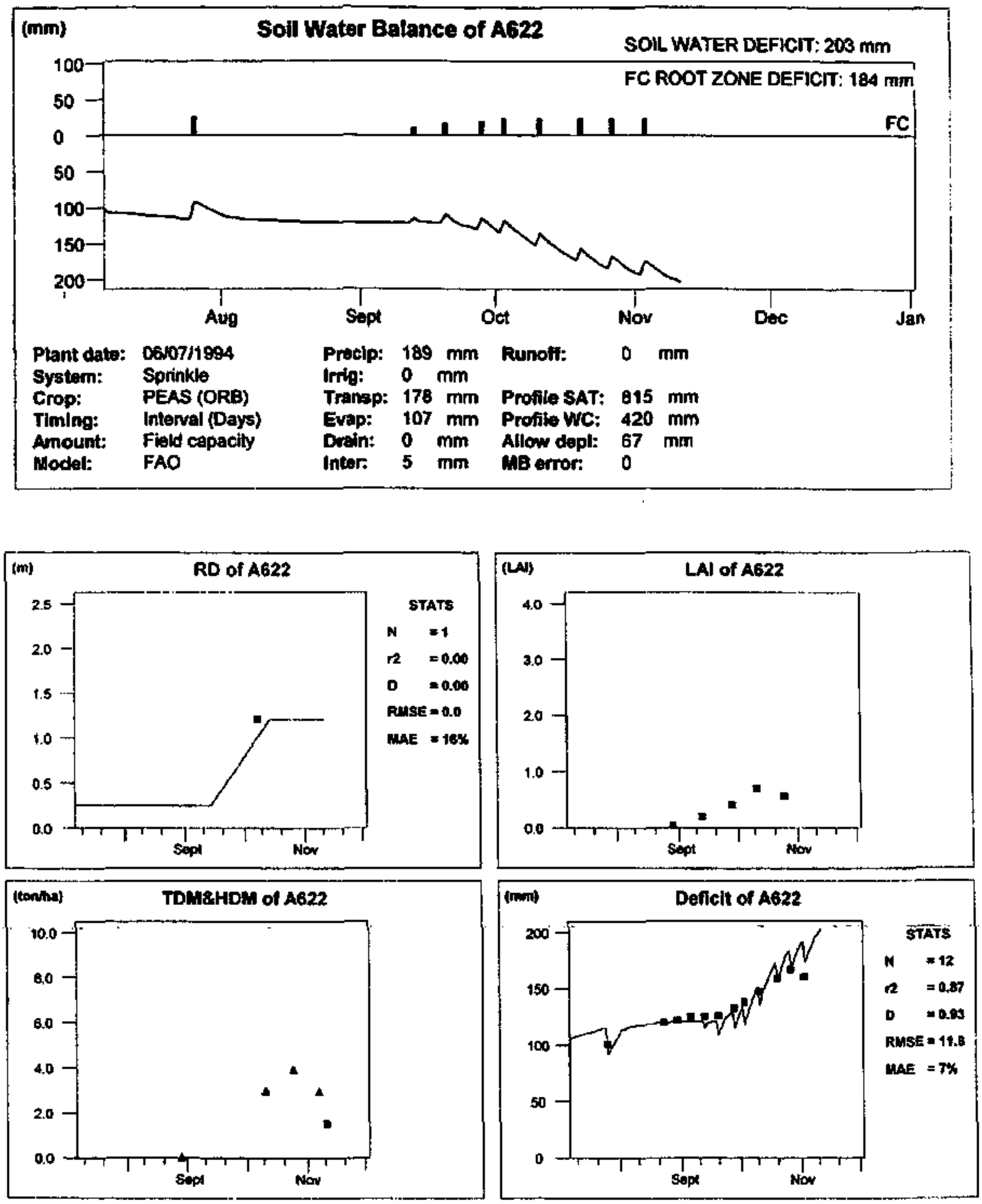


Figure 5.18

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Peas

Input and measured data sets: Bloemfontein, treatment L1VL (Bennie et al., 1996)

Model type: FAO

5.1.4 Potato

Data sets were obtained from Prof ATP Bennie. Spring potato (*Solanum tuberosum* cv. Buffelspoort BP13) was grown at the experimental station of the University of the Orange Free State, 13 km from Bloemfontein (Bennie et al., 1996). See Section 5.1.1 for a more detailed description of the trial.

In this work, the soil water balance and crop growth was simulated with SWB for the following treatments:

i) High target yield, weekly irrigations, start with wet soil profile and end with dry soil profile (H1VL) (examples of model output are in Figure 5.19); and

ii) Low target yield, weekly irrigations, start with wet soil profile and end with dry soil profile (L1VL) (examples of model output are in Figure 5.20).

The independent data sets were used to validate the soil water balance subroutine of SWB. Crop growth parameters for autumn potato recommended by Steyn, du Plessis and Fourie (1998), were used as basis. Thermal time requirements for crop developmental stages were modified to account for the difference in cultivar. No growth analysis data were available for the validation of the crop growth subroutine of the model.

The soil water balance was also simulated with the FAO model for H1VL (examples of model output are in Figure 5.21) and L1VL (examples of model output are in Figure 5.22). The crop factors recommended by the FAO for potato, were used in these simulations. Root depth for mid-season and late-season stage was modified.

Bennie et al. (1996) recommended a maximum root depth of 1.8 m for potato. They also reported, however, that 90% of the roots occurs in the top 1.2 m soil layer. Maximum root depth of 1.2 m was therefore used as input for the simulations shown in Figures 5.19 to 5.22.

The crop growth model underestimated both final yield and crop water use (Figures 5.19 and 5.20). The onset of tuber initiation, which change the priority of assimilate translocation, is influenced by day length or photoperiod in potatoes. Crop growth parameters for autumn potato should not be used for spring cultivars.

Soil water deficit was better predicted with the FAO-type model, compared to the crop growth model.

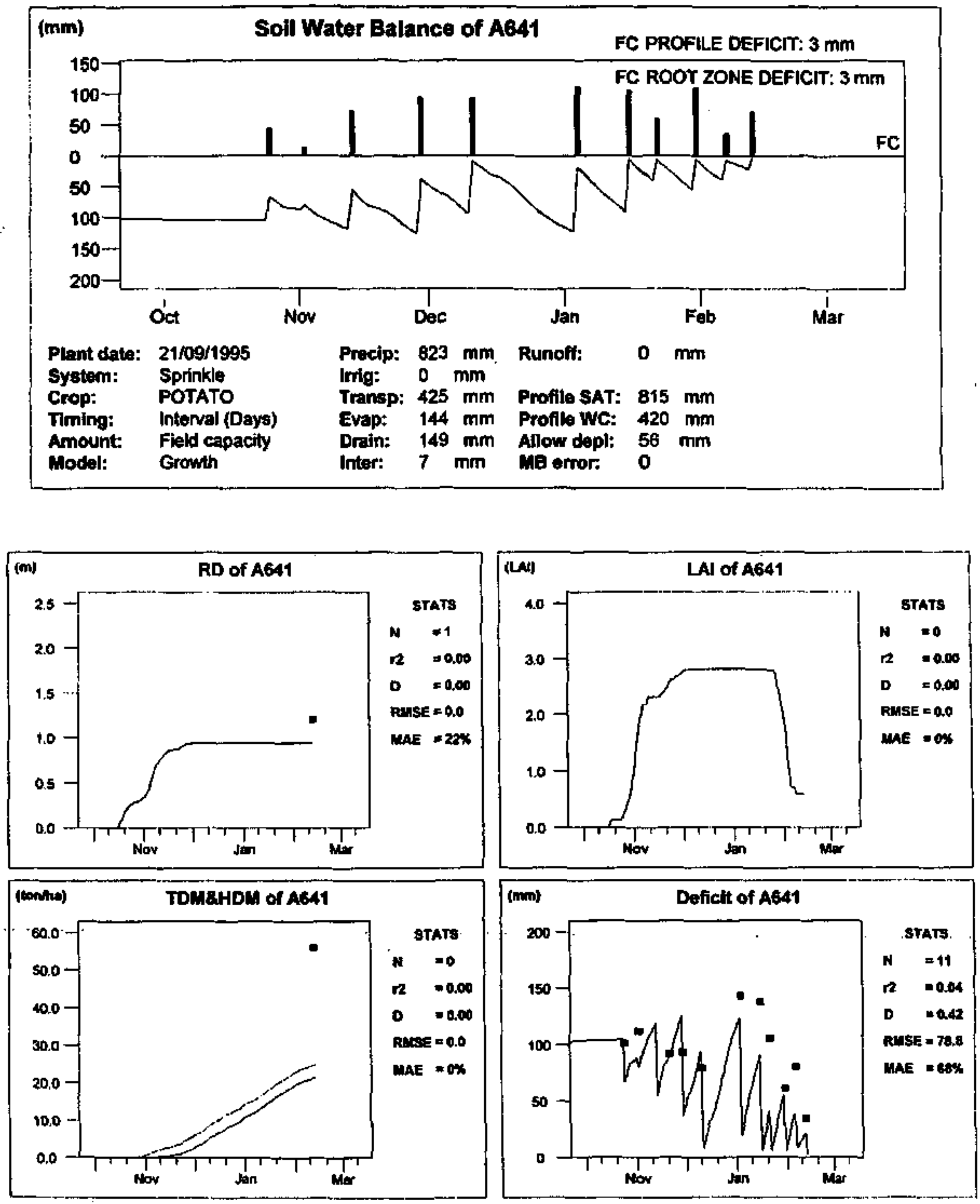


Figure 5.19

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Potato

Input and measured data sets: Bloemfontein, treatment H1VL (Bennie et al., 1996)

Model type: Crop growth

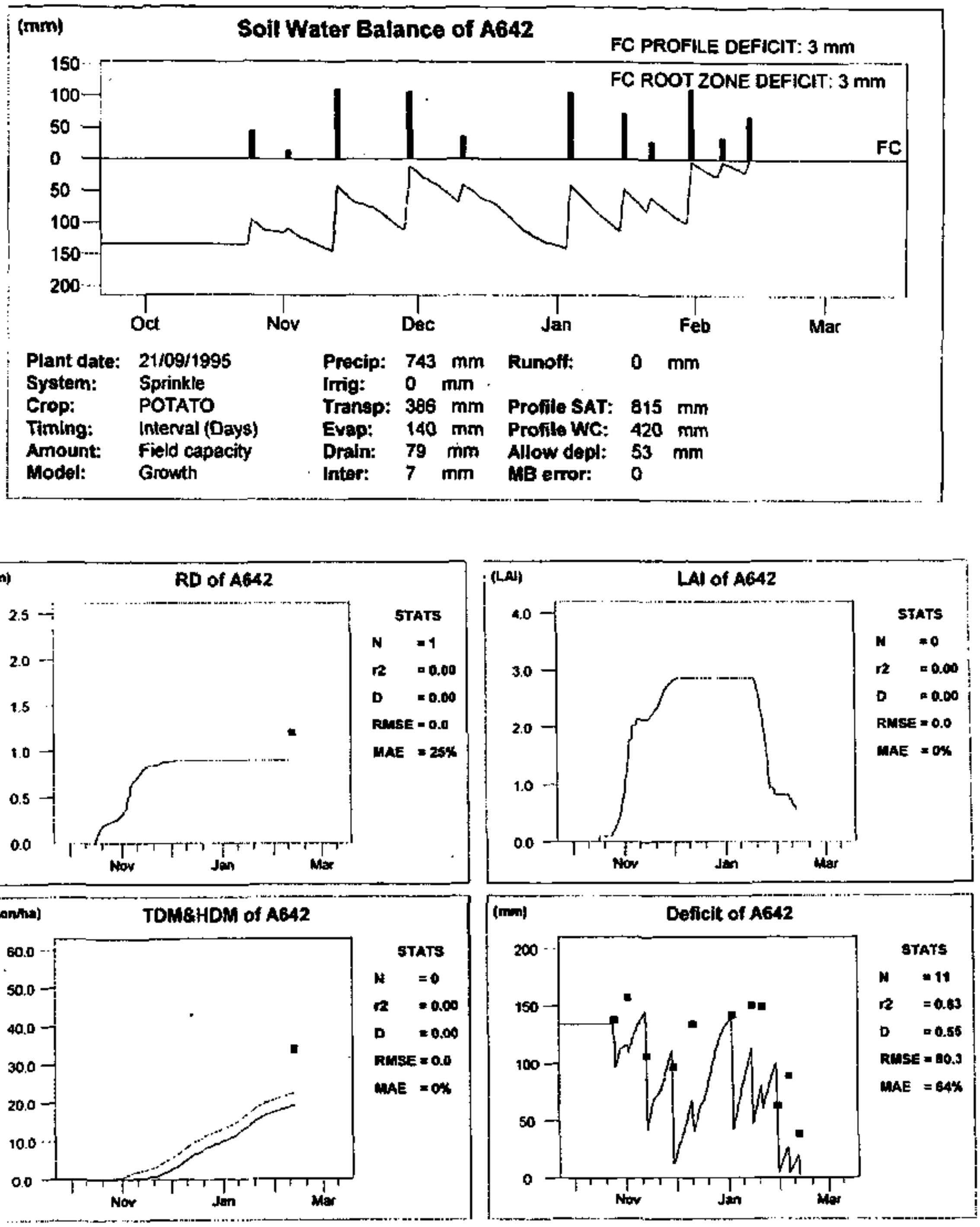


Figure 5.20

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Potato

Input and measured data sets: Bloemfontein, treatment L1VL (Bennie et al., 1996)

Model type: Crop growth

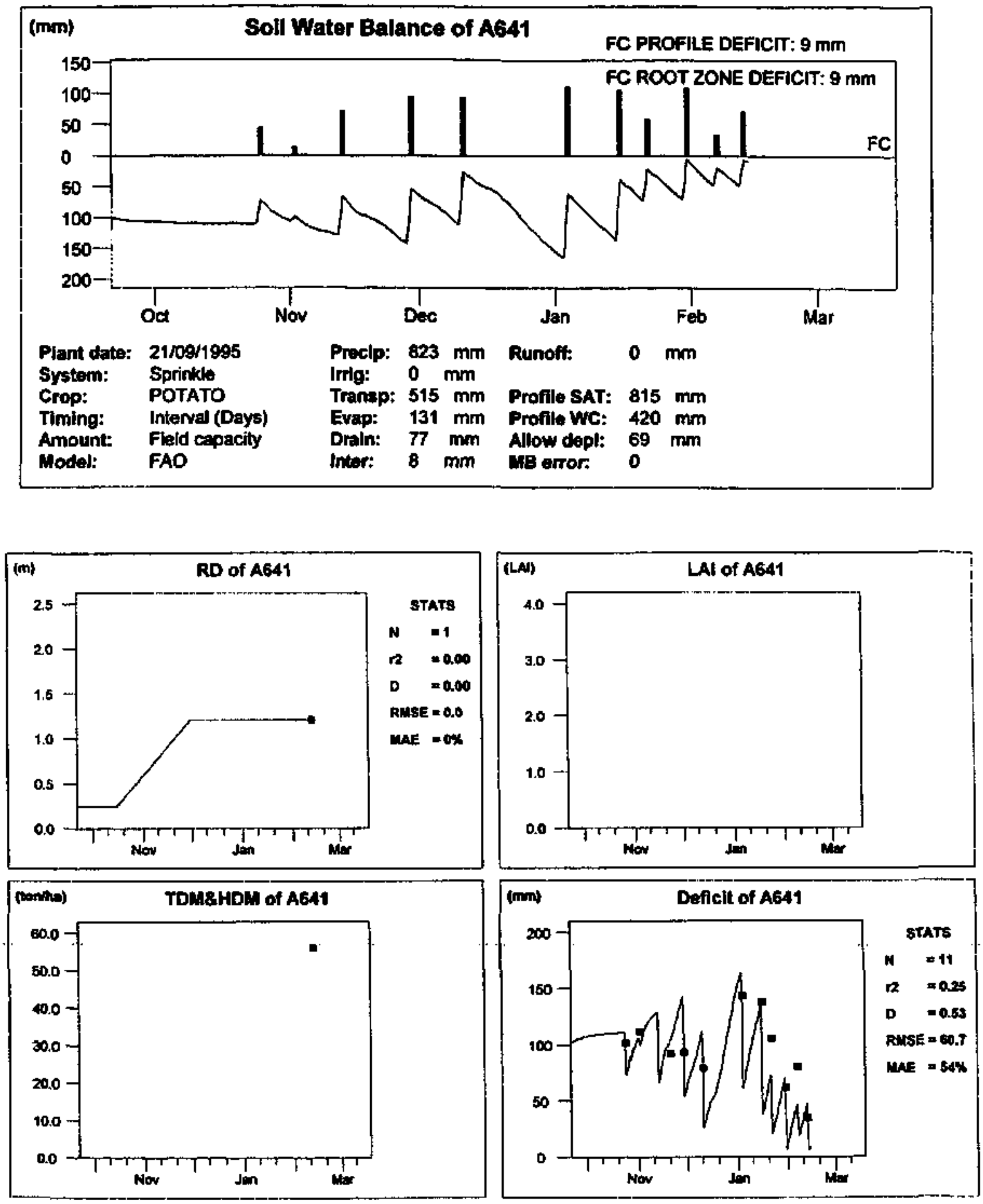


Figure 5.21

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Potato

Input and measured data sets: Bloemfontein, treatment H1VL (Bennie et al., 1996)

Model type: FAO

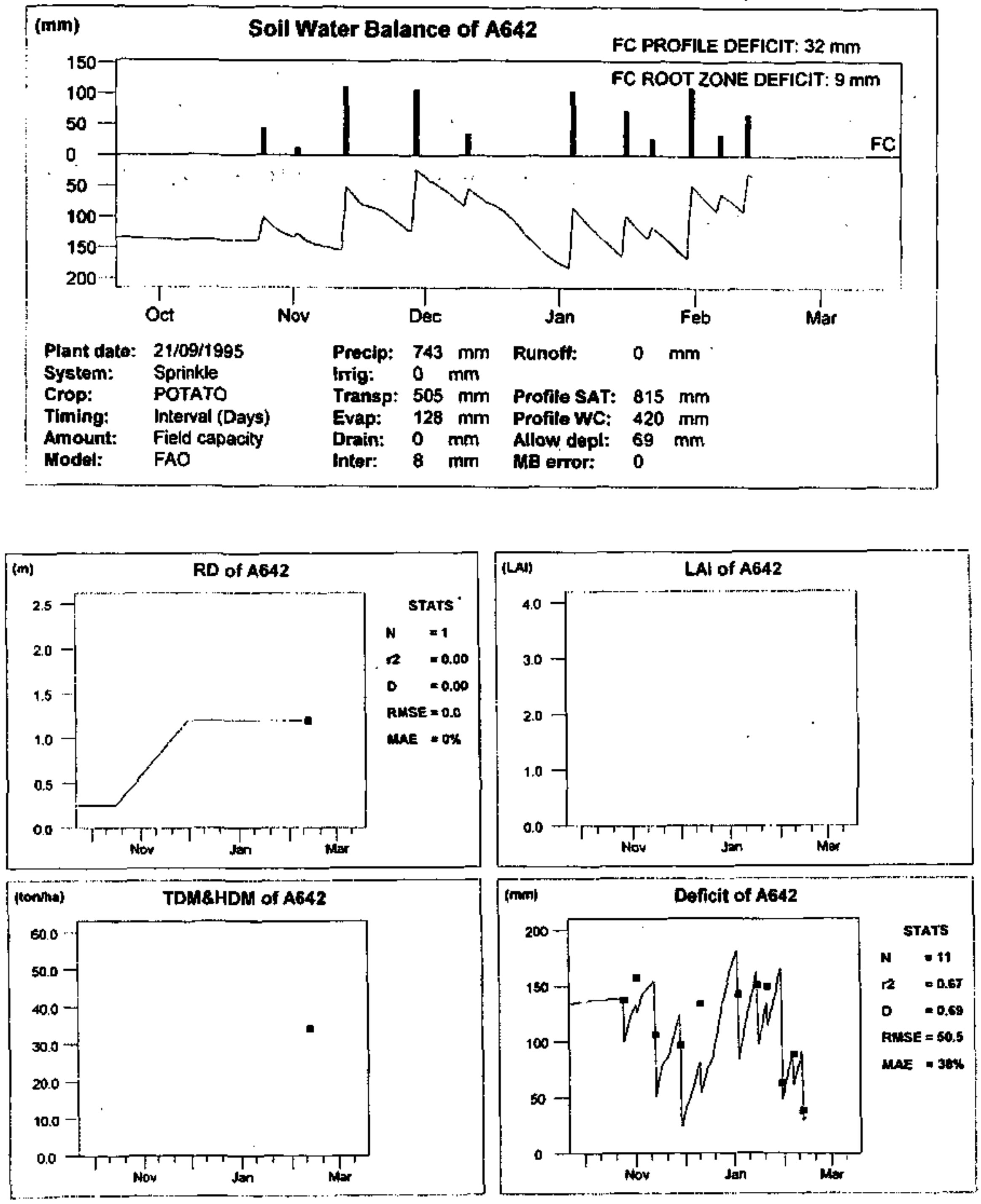


Figure 5.22

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Potato

Input and measured data sets: Bloemfontein, treatment L1VL (Bennie et al., 1996)

Model type: FAO

5.1.5 Soybean

A complete data set for soybean (*Glycine max.* cv. Wayne, maturity group 3) was obtained from Prof ATP Bennie. Soybean data refer to a study on crop response to different row spacings and soil water levels (Bennie, Mason and Taylor, 1982; Mason, Rowse, Bennie, Kaspar and Taylor, 1982; Taylor, Mason, Bennie and Rowse, 1982). The experiment was conducted in 1979 at the Western Iowa Experimental Farm (Castana, Iowa), on an Ida silt loam. Four treatments of soybean were differentiated:

i) Irrigated, planted in rows 1 m apart (I100);

ii) Non-irrigated, planted in rows 1 m apart (N100);

iii) Irrigated, planted in rows 0.25 m apart (I25); and

iv) Non-irrigated, planted in rows 0.25 m apart (N25).

Specific crop growth parameters were determined for each treatment according to the procedure described in Section 4.1.3, using detailed crop growth, soil and weather data made available by Mason, Taylor, Bennie, Rowse, Reicosky, Jung, Righes, Yang, Kaspar and Stone (1980). These parameters are summarized in Table 5.2. Specific leaf area and the leaf-stem partition parameter were determined using growth analysis data before leaf senescence occurred. Root growth rate and the fraction of total dry matter partitioned to roots were obtained using data before maximum root depth was reached. The values obtained for treatment I100 and N100 were averaged to generate a database of crop parameters for soybean planted in rows 1.0 m apart (Table B1, Appendix B). The values obtained for treatment I25 and N25 were also averaged to generate a database for soybean planted in rows 0.25 m apart (Table B1, Appendix B).

Simulations of soil water balance and crop growth were carried out for each treatment, and are shown in Figures 5.23-5.26. The I100 and I25 treatments were used to calibrate the model for soybean planted at 1 m and 0.25 m row spacing. The N100 and N25 were used to validate the soil water balance and crop growth subroutines of SWB. Initial volumetric soil water content was estimated. Water and radiation use efficiency were taken from Barnard et al. (1998). The crop growth model underestimated LAI and crop water use in the second half of the growing season for the non-irrigated treatments. The vertical error bars indicated large variability in the measurement of LAI. Possible source of error is also seasonal variability in SLA and leaf-stem partitioning factor.

The soil water balance was also simulated with the FAO model for all treatments (Figures 5.27-5.30). The crop factors recommended by the FAO for soybean were used in these simulations. Length of stages was modified.

The statistical output parameters indicated that predictions with both crop growth and FAO model were inside, or marginally outside the reliability criteria. MAE > 20% was calculated for soil water deficit to field capacity for all irrigated treatments (Figures 5.23, 5.25, 5.27 and 5.29), as this parameter was generally close to 0 throughout the season.

TABLE 5.2
SPECIFIC CROP GROWTH PARAMETERS FOR SOYBEAN (CV. WAYNE, MATURITY GROUP 3)[1]

Specific crop growth parameter	Treatment			
	Irrigated, planted in rows 1 m apart (I100)	**Non-irrigated, planted in rows 1 m apart (N100)**	**Irrigated, planted in rows 0.25 m apart (I25)**	**Non-irrigated, planted in rows 0.25 m apart (N25)**
Canopy radiation extinction coefficient	0.35 (r^2 = 0.88)		0.42 (r^2 = 0.61)	
Specific leaf area (m^2 kg^{-1})	25.8 ± 4.6	26.1 ± 4.1	28.0 ± 6.3	26.5 ± 4.1
Leaf-stem partition parameter (m^2 kg^{-1})	3.5 (r^2 = 0.83)	3.9 (r^2 = 0.67)	4.1 (r^2 = 0.72)	4.1 (r^2 = 0.68)
Root growth rate (m^2 $kg^{-0.5}$)	7.7 ± 1.5	7.4 ± 1.1	6.5 ± 1.4	6.1 ± 1.2
Fraction of total dry matter partitioned to roots	0.13 ± 0.04	0.15 ± 0.01	0.16 ± 0.08	0.19 ± 0.04
Maximum crop height (m)	≈ 1.1	≈ 0.9	≈ 1.2	≈ 0.85
Maximum root depth (m)	1.8	1.8	1.8	1.8
Leaf water potential at maximum transpiration (kPa)	≈ -1200	≈ -1200	≈ -1200	≈ -1200

[1] Source data obtained from Mason et al. (1980)

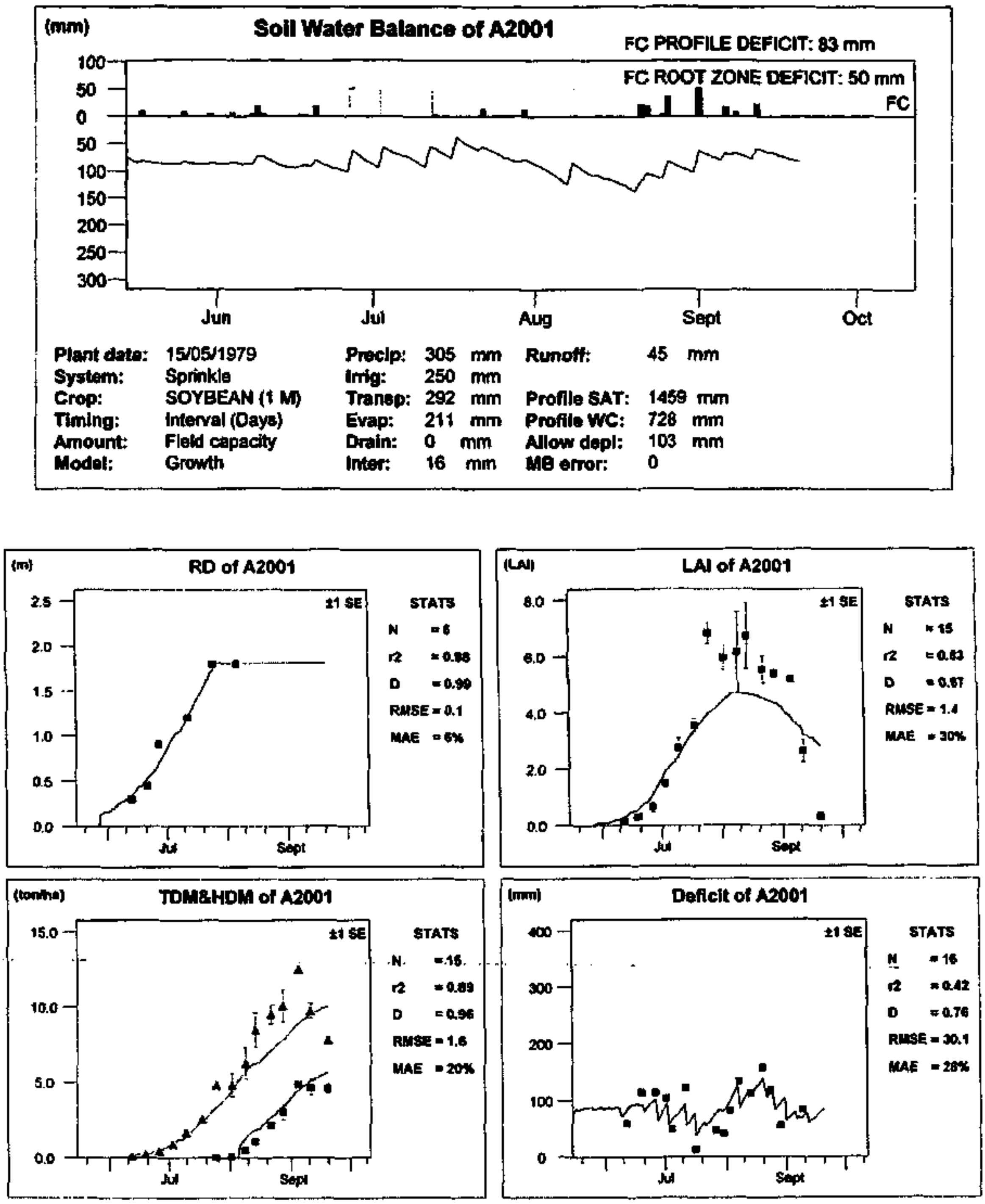


Figure 5.23

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Soybean

Input and measured data sets: Castana, Iowa, USA, treatment I100 (Mason et al., 1980)

Model type: Crop growth

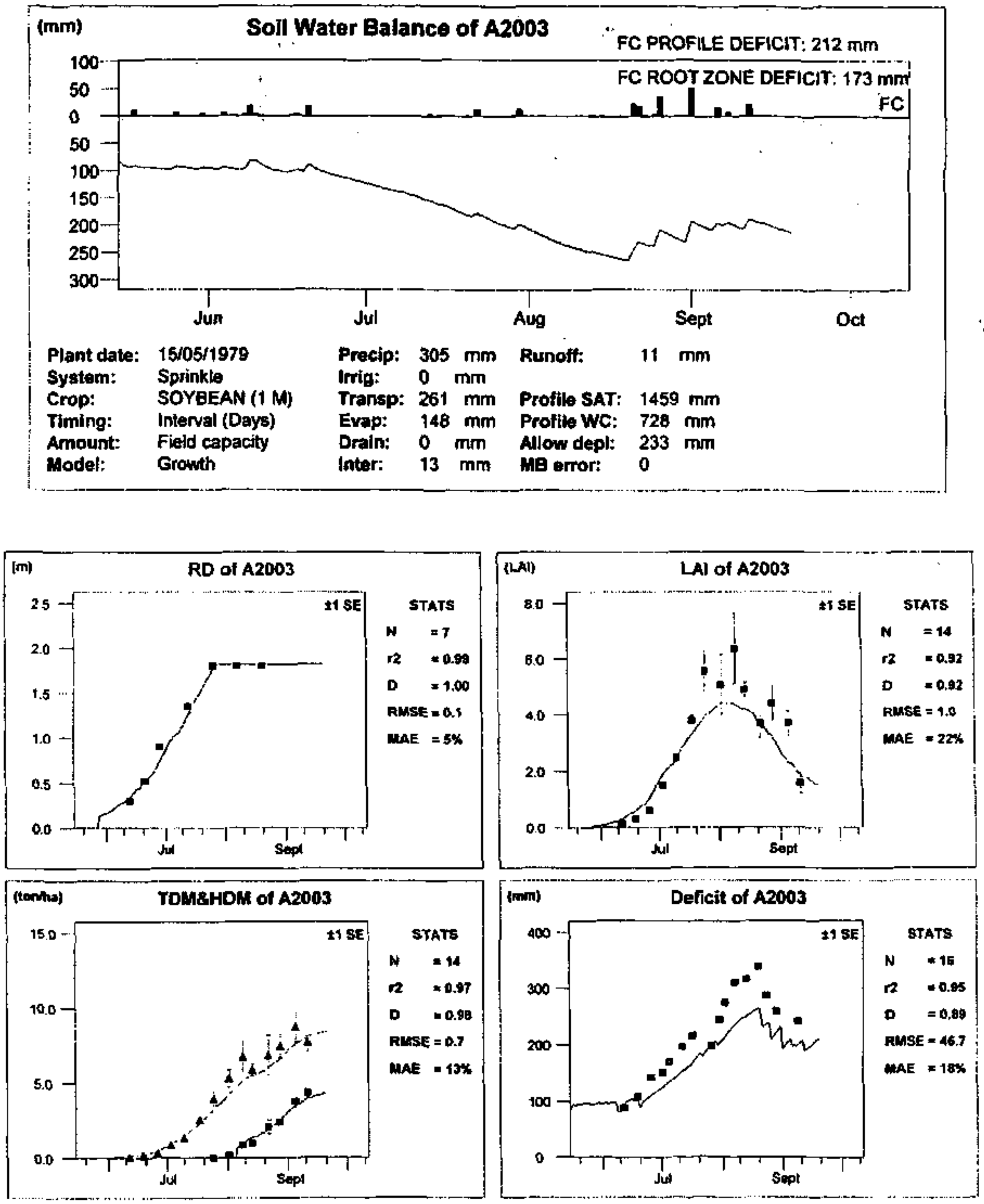


Figure 5.24

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), to.al above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Soybean

Input and measured data sets: Castana, Iowa, USA, treatment N100 (Mason et al., 1980)

Model type: Crop growth

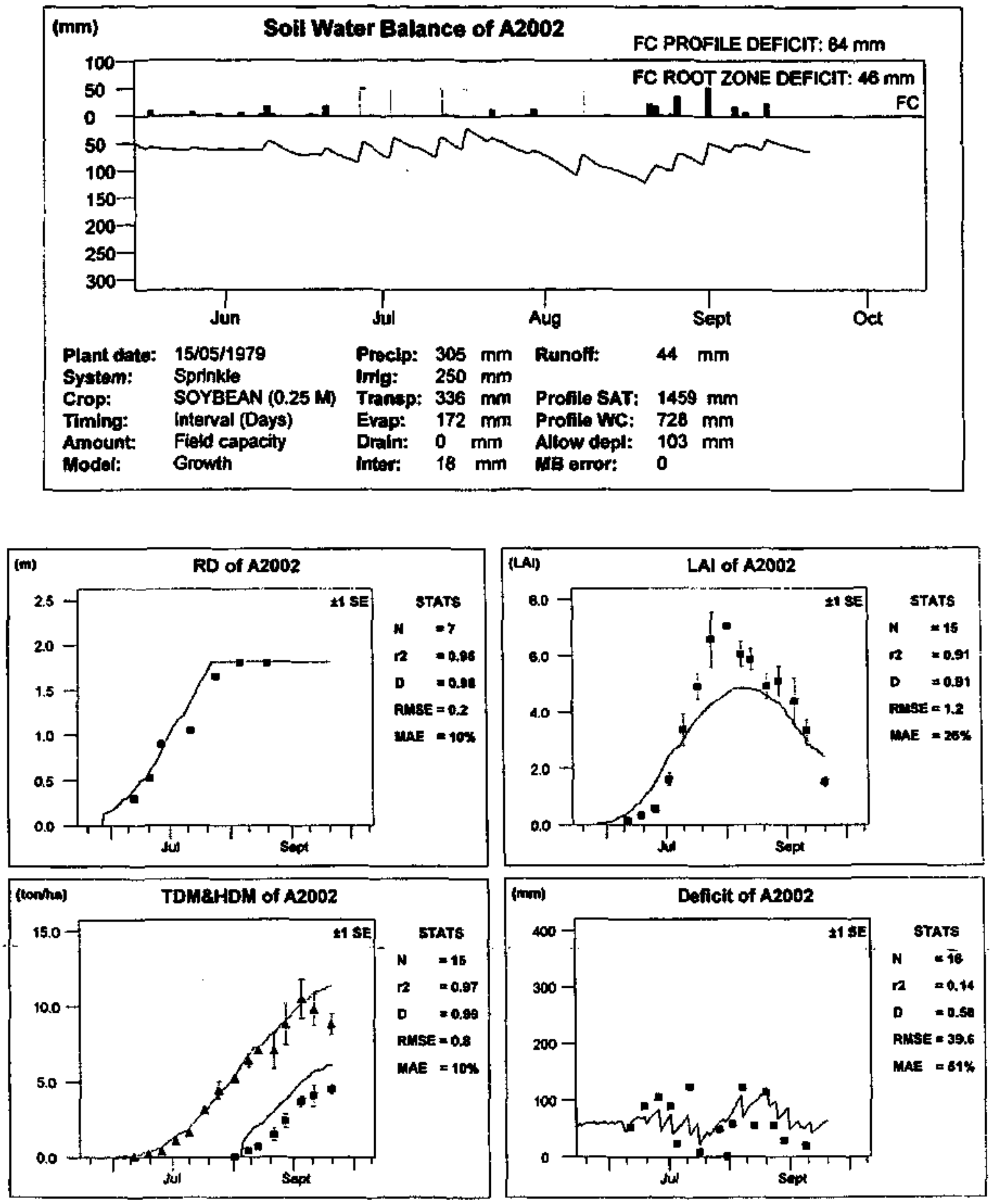


Figure 5.25

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Soybean

Input and measured data sets: Castana, Iowa, USA, treatment I25 (Mason et al., 1980)

Model type: Crop growth

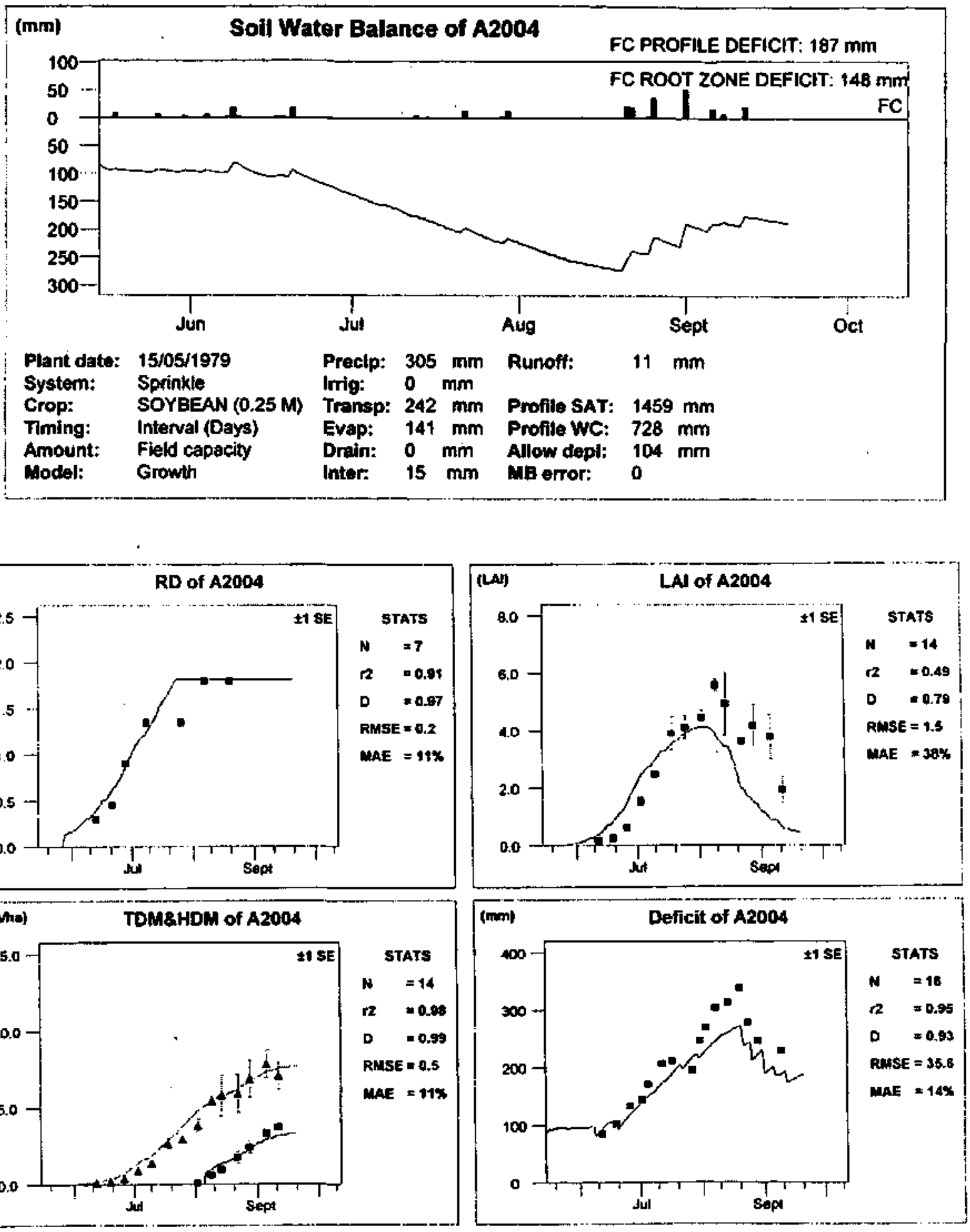


Figure 5.26

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Soybean

Input and measured data sets: Castana, Iowa, USA, treatment N25 (Mason et al., 1980)

Model type: Crop growth

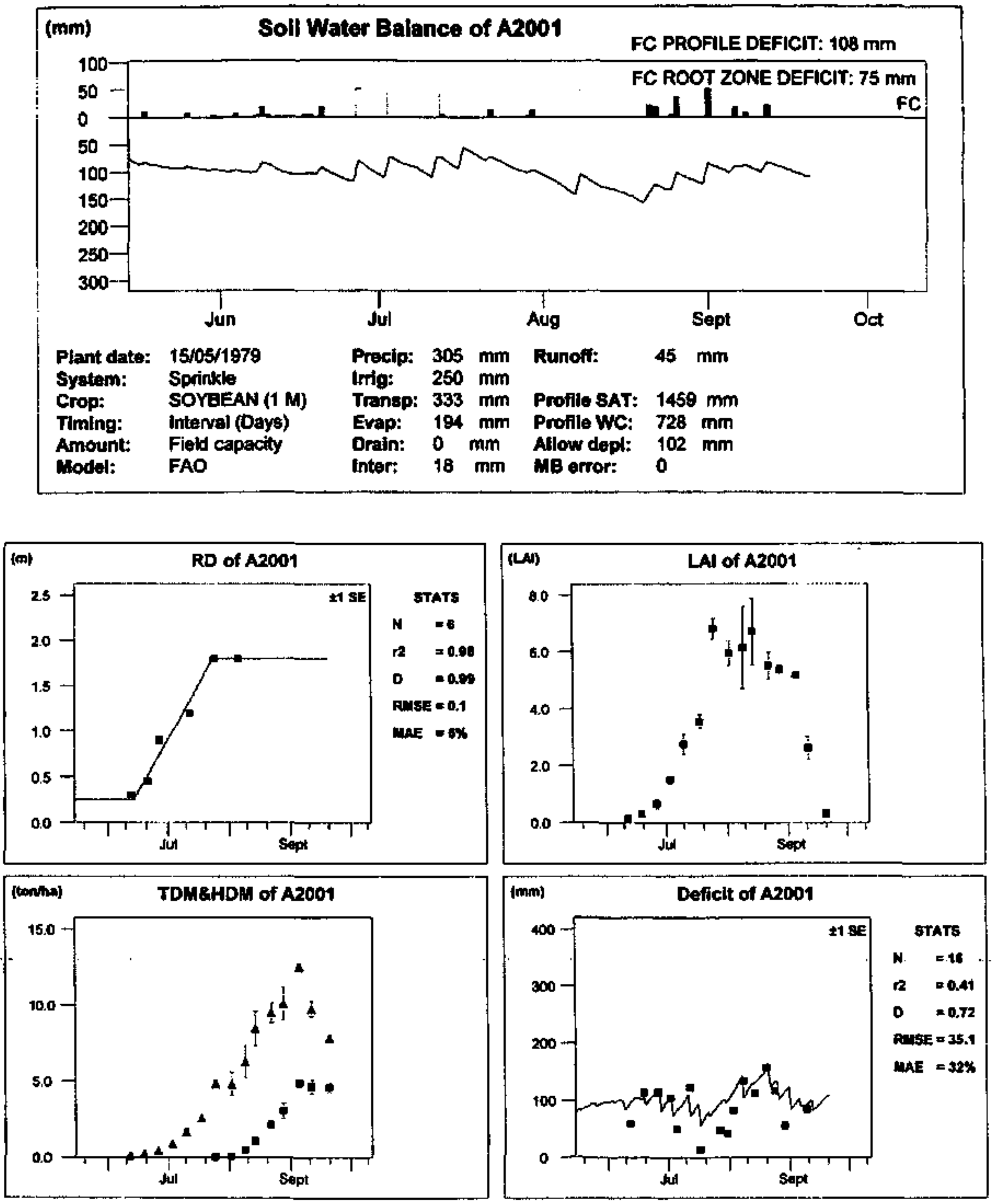


Figure 5.27

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Soybean

Input and measured data sets: Castana, Iowa, USA, treatment I100 (Mason et al., 1980)

Model type: FAO

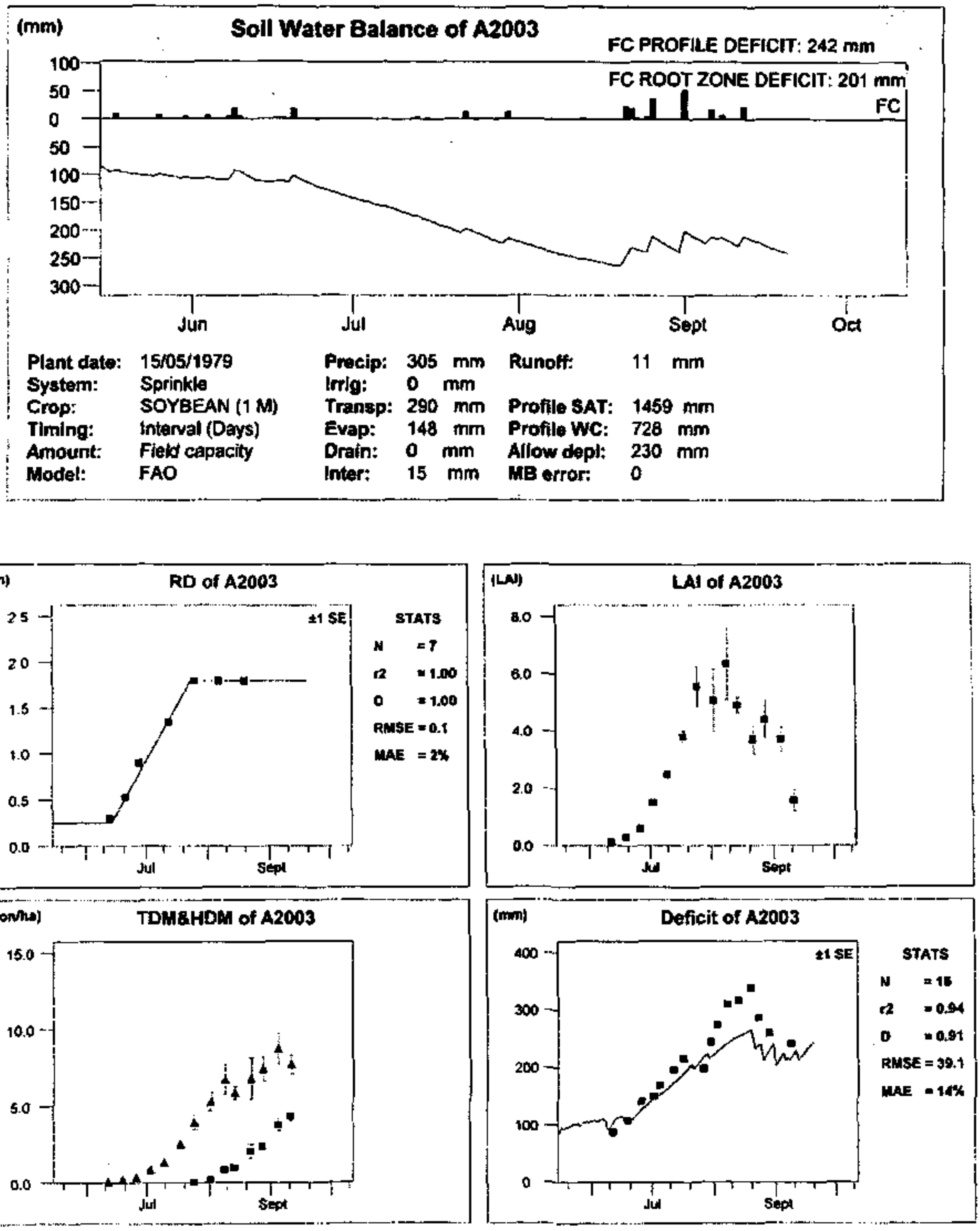


Figure 5.28

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Soybean

Input and measured data sets: Castana, Iowa, USA, treatment N100 (Mason et al., 1980)

Model type: FAO

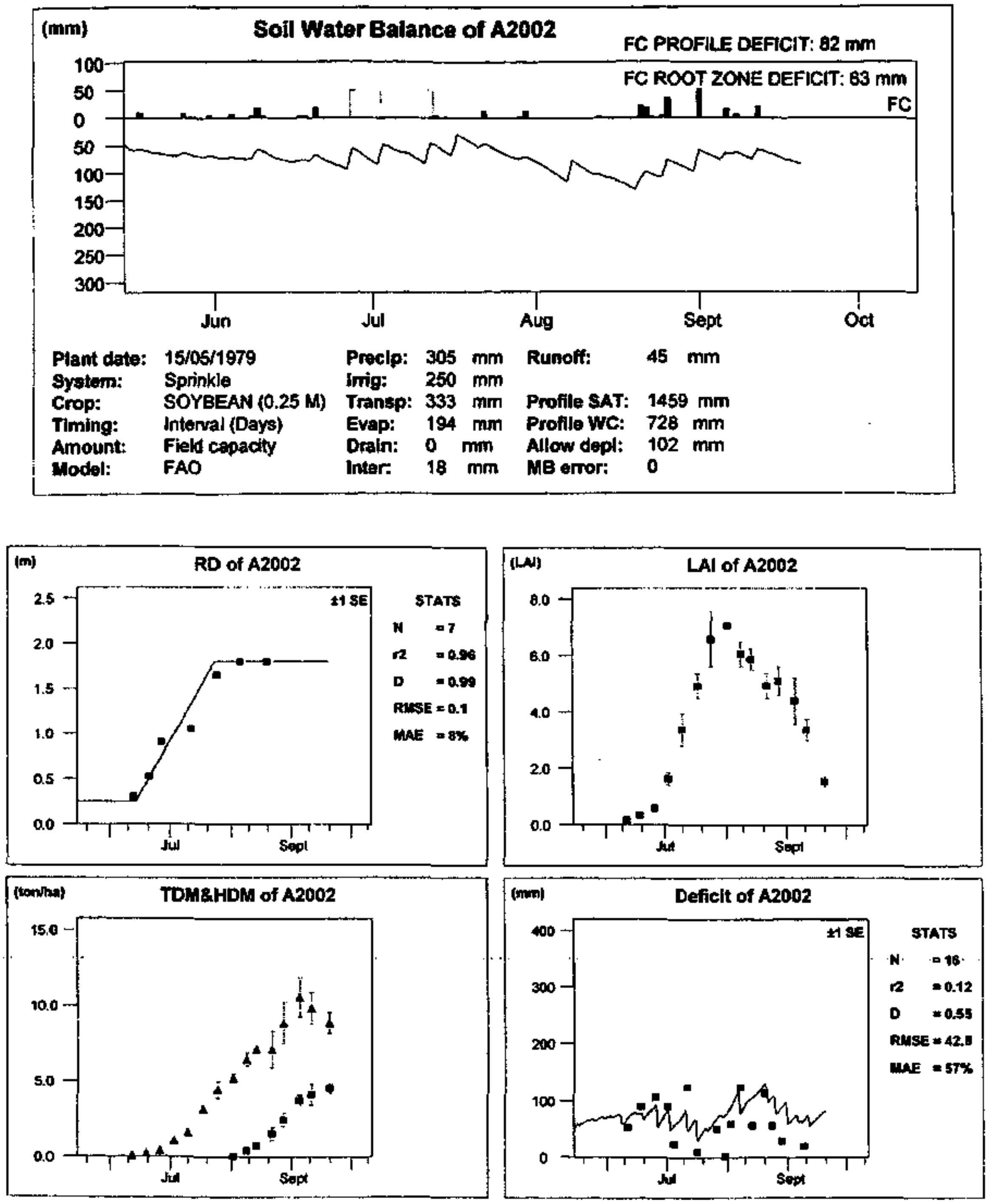


Figure 5.29

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Soybean

Input and measured data sets: Castana, Iowa, USA, treatment I25 (Mason et al., 1980)

Model type: FAO

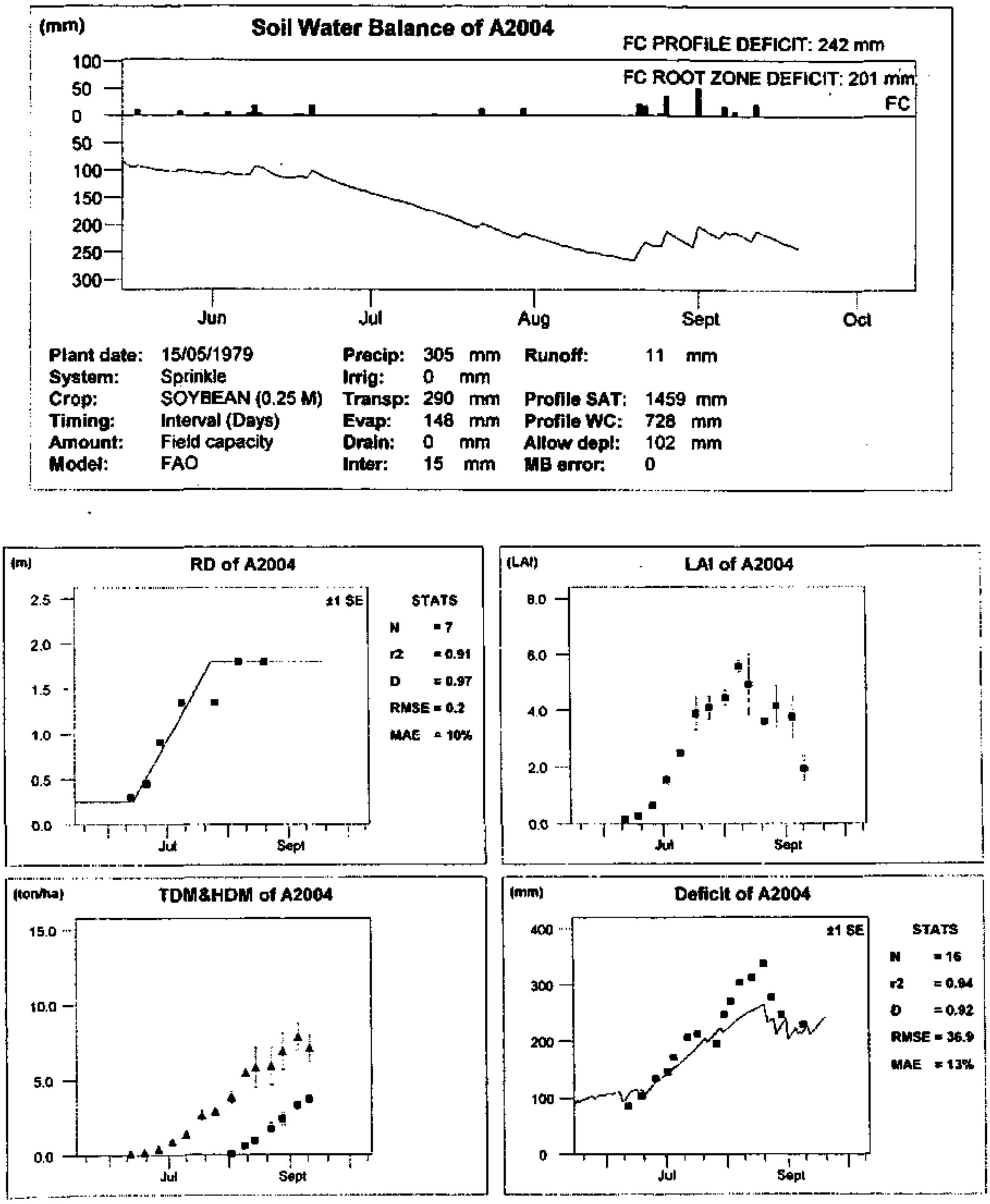


Figure 5.30

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Soybean

Input and measured data sets: Castana, Iowa, USA, treatment N25 (Mason et al., 1980)

Model type: FAO

5.1.6 Sugarcane

A complete data set for sugarcane (*Saccharum officinalis* var. N14) was obtained from Dr MG Inman-Bamber (formerly South African Sugar Association Experiment Station, Mount Edgecombe; presently CSIRO, Townsville, Australia). Sugarcane data refer to a lysimeter study carried out at Pongola (Thompson, 1991).

The independent data set was used to validate the soil water balance and crop growth subroutines of SWB.

SWB simulations were carried out both with the generic crop growth (Figure 5.31) and FAO model (Figure 5.32). Specific crop growth parameters were obtained from Dr Inman-Bamber (personal communication) and they are shown in Table B1 (Appendix B). Crop factors recommended by the FAO, were used in the simulation with the FAO model. Maximum root depth was assumed to be 1.3 m (depth of the lysimeter at Pongola).

LAI, TDM and HDM was predicted well with the crop growth model (Figure 5.31). High MAE values were calculated for soil water deficit to field capacity with both crop growth and FAO model, as this parameter was generally close to 0 throughout the season.

The parameters used in these simulations are for plant cane. Different parameters are required for ratoons. Mr J Kennedy (South African Sugar Association Experiment Station, Mount Edgecombe) will work further on the validation of SWB for sugarcane.

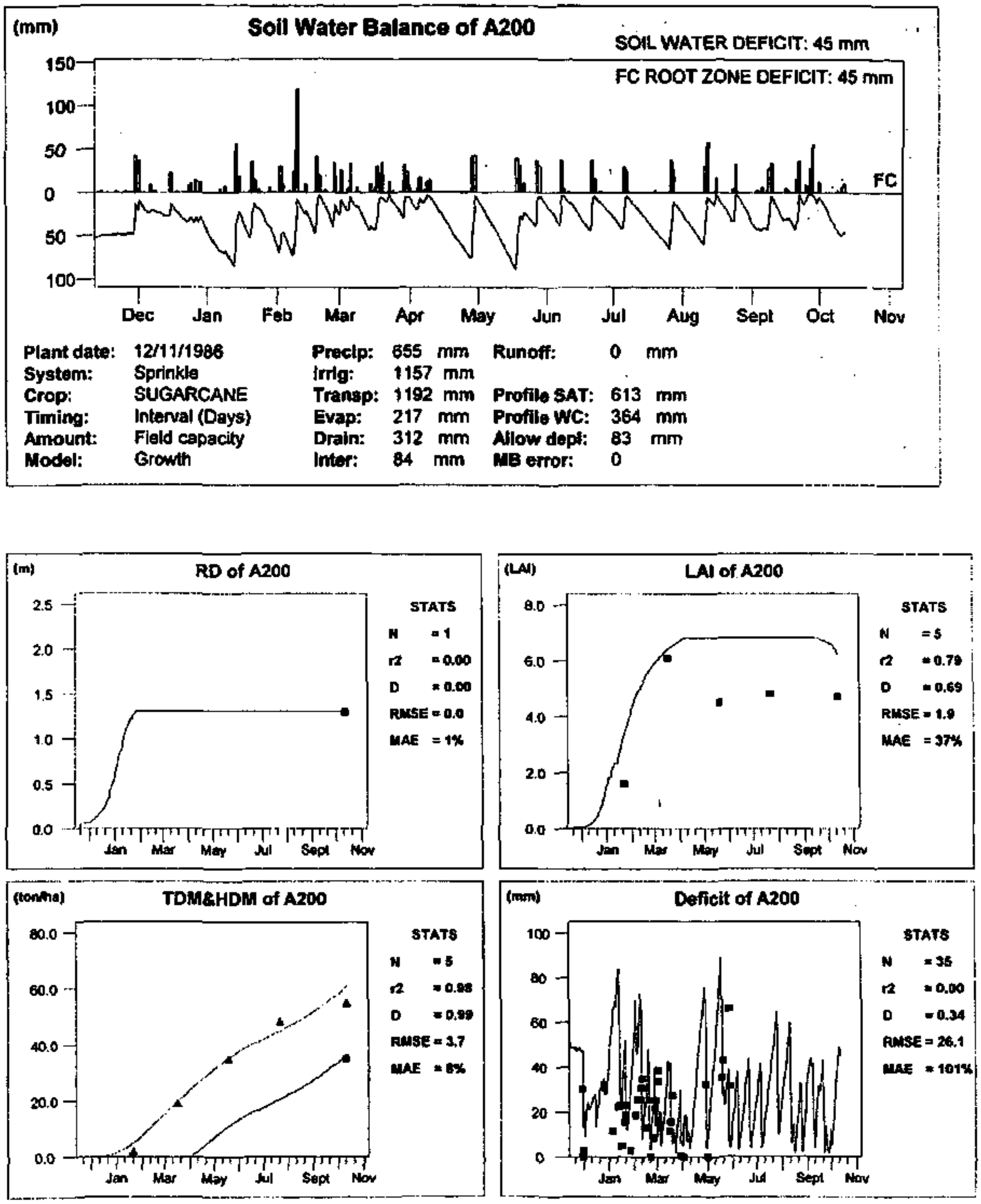


Figure 5.31

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Sugarcane

Input data set: Lysimeter study, Pongola (Thompson, 1991)

Model type: Crop growth

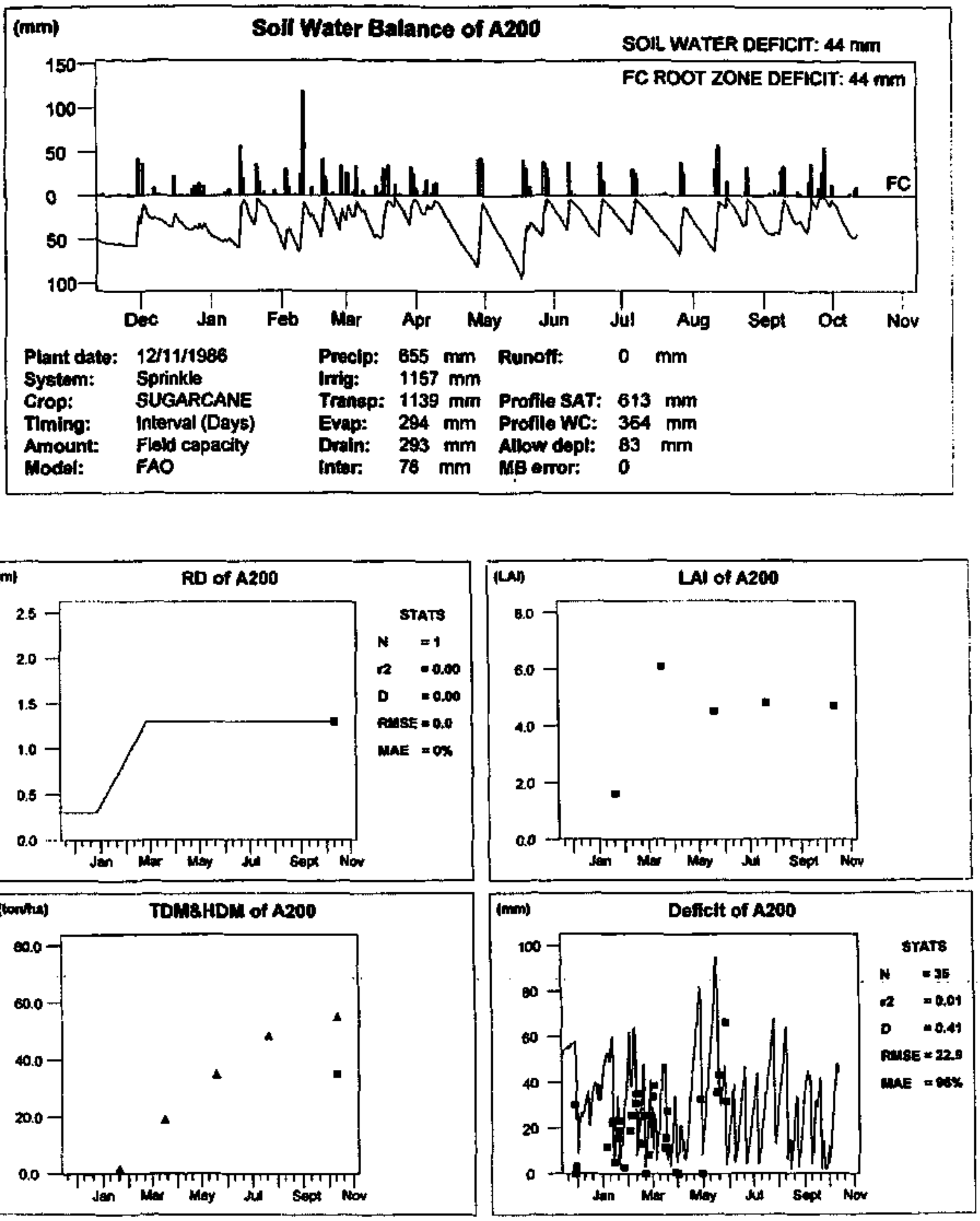


Figure 5.32

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Sugarcane
Input data set: Lysimeter study, Pongola (Thompson, 1991)
Model type: FAO

5.1.7 Sunflower

Data sets for sunflower (*Helyanthus annuum* cv. CAR1199 and SO306) were obtained from Mr A Nel (Grain Crops Research Institute - Agricultural Research Council - Potchefstroom). Data refer to an irrigation trial carried out at Potchefstroom. The crops were planted on 19 January 1993 at 40,000 plants ha^{-1}. Emergence occurred after 7 d. Flowering was 64 d after planting for SO306 and 61 d after planting for CAR1199. Several irrigation treatments were differentiated. Irrigations were scheduled for each treatment on the basis of relative water content in the leaf. In this work, the following treatments were considered:

i) P8 (cv. CAR1199, seasonal irrigation 300 mm);

ii) P11 (cv. CAR1199, seasonal irrigation 100 mm);

iii) P1 (cv. SO306, seasonal irrigation 360 mm); and

iv) P21 (cv. SO306, no irrigation).

Treatments P8 and P1 were used to calibrate the crop growth model, whilst treatments P11 and P21 were used to validate the soil water balance and crop growth subroutines of SWB. The output results are shown in Figures 5.33 and 5.34 for cv. CAR1199, and Figures 5.35 and 5.36 for cv. SO306.

Day degrees for emergence, flowering and maturity were determined using daily temperature records (Section 4.1.3). Base temperature, temperature for optimum growth, cutoff temperature, specific leaf area, radiation use efficiency, the fraction of total dry matter translocated to grains, and the fraction of total dry matter partitioned to roots were taken from Villalobos, Hall, Ritchie and Orgaz (1996). Bange, Hammer and Rickert (1997) recommended a canopy extinction coefficient for total solar radiation of 1.06 before anthesis and 0.56 after anthesis. In this work, K_s was assumed to be 0.8 throughout the season. The specific crop growth parameters for sunflower are summarized in Appendix B (Table B1).

The soil water balance was simulated with the FAO model for cv. CAR1199 (Figures 5.37 and 5.38) and SO306 (Figures 5.39 and 5.40). The crop factors recommended by the FAO for sunflower, were used in these simulations. Length of stages was modified (Table B2, Appendix B).

The statistical output parameters indicated that predictions with both crop growth and FAO model were inside, or marginally outside the reliability criteria. No measurement of TDM was available.

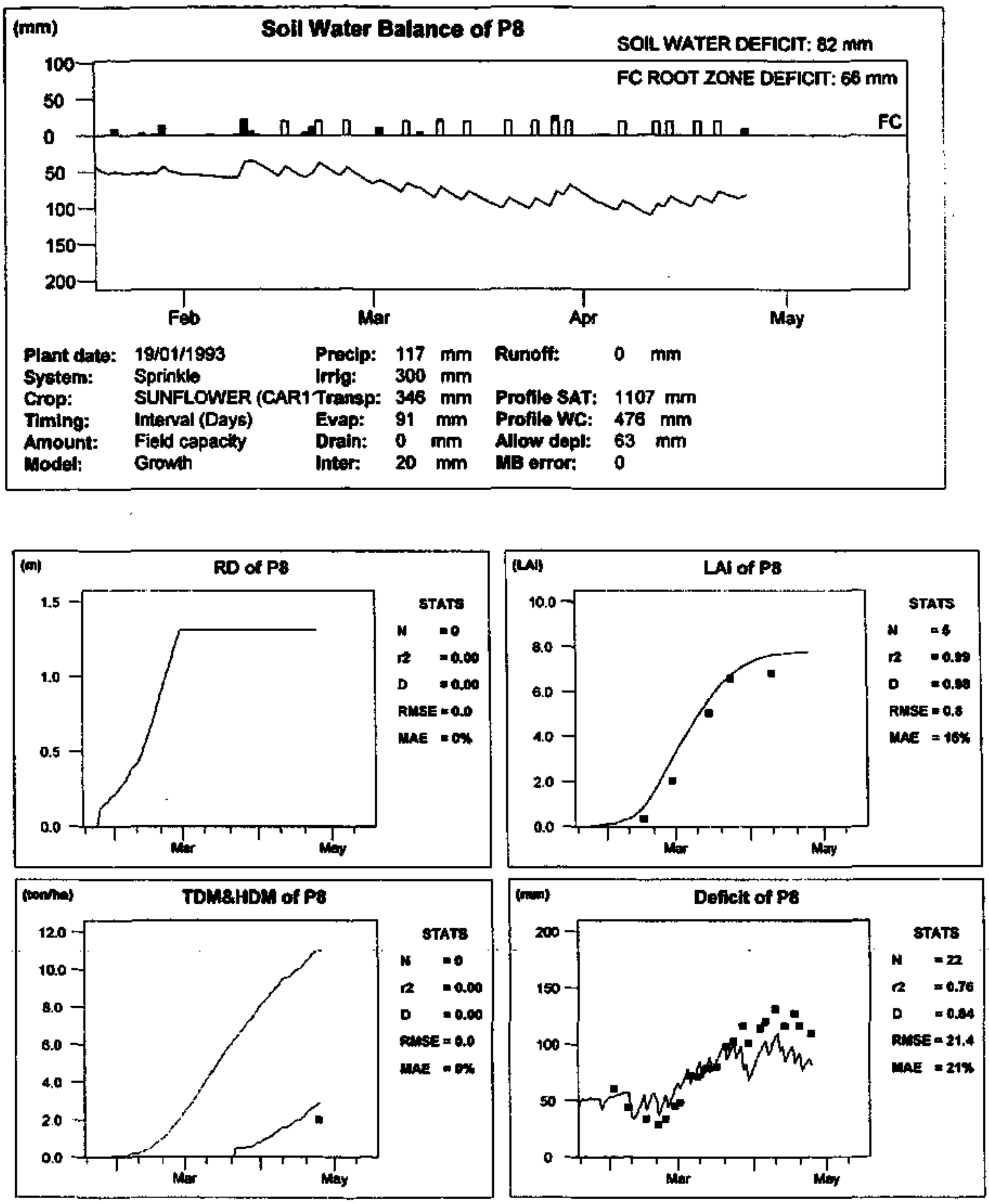


Figure 5.33

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Sunflower (cv. CAR1199)

Input data set: Potchefstroom, treatment P8 (A. Nel, personal communication)

Model type: Crop growth

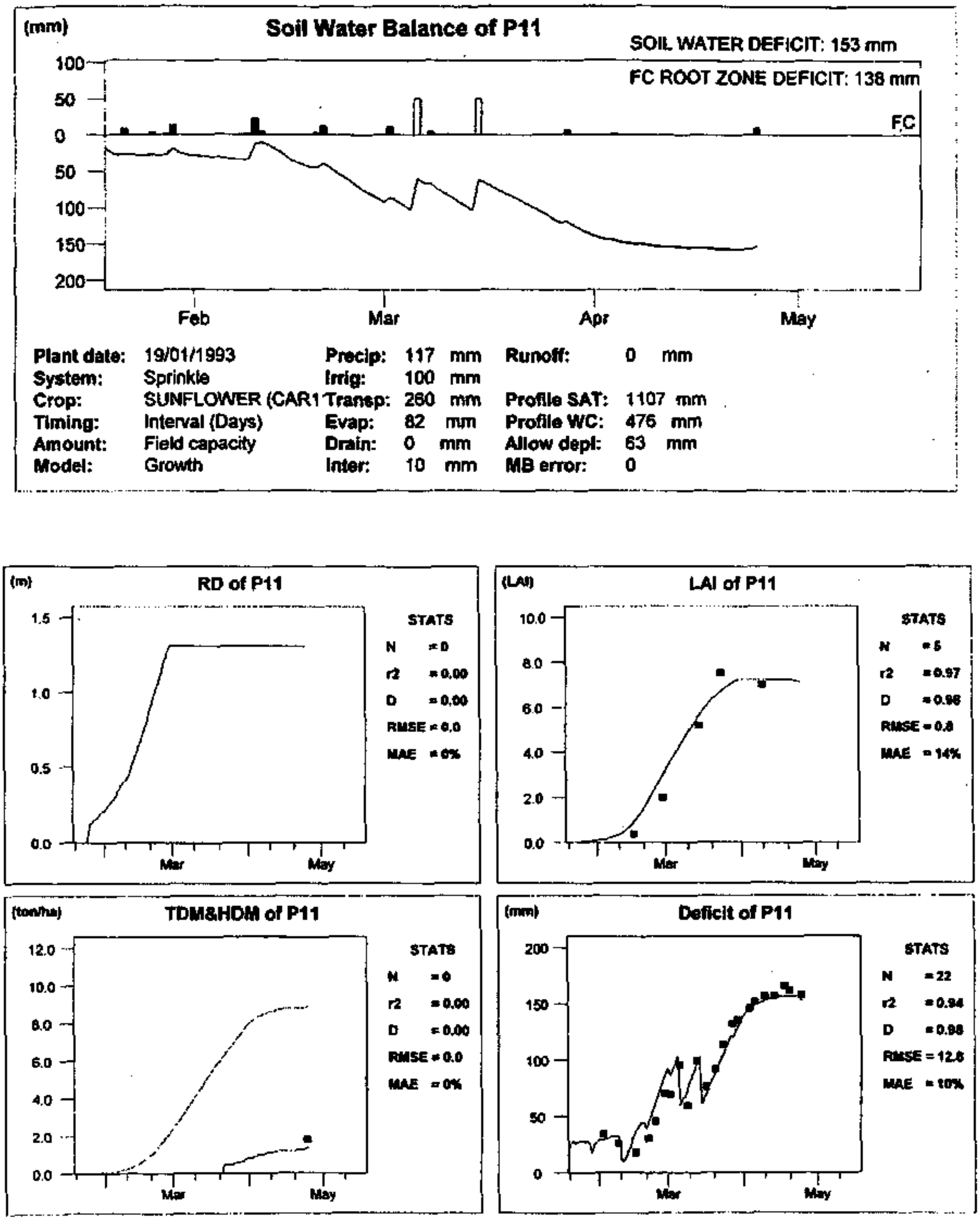


Figure 5.34

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Sunflower (cv. CAR1199)

Input data set: Potchefstroom, treatment P11 (A. Nel, personal communication)

Model type: Crop growth

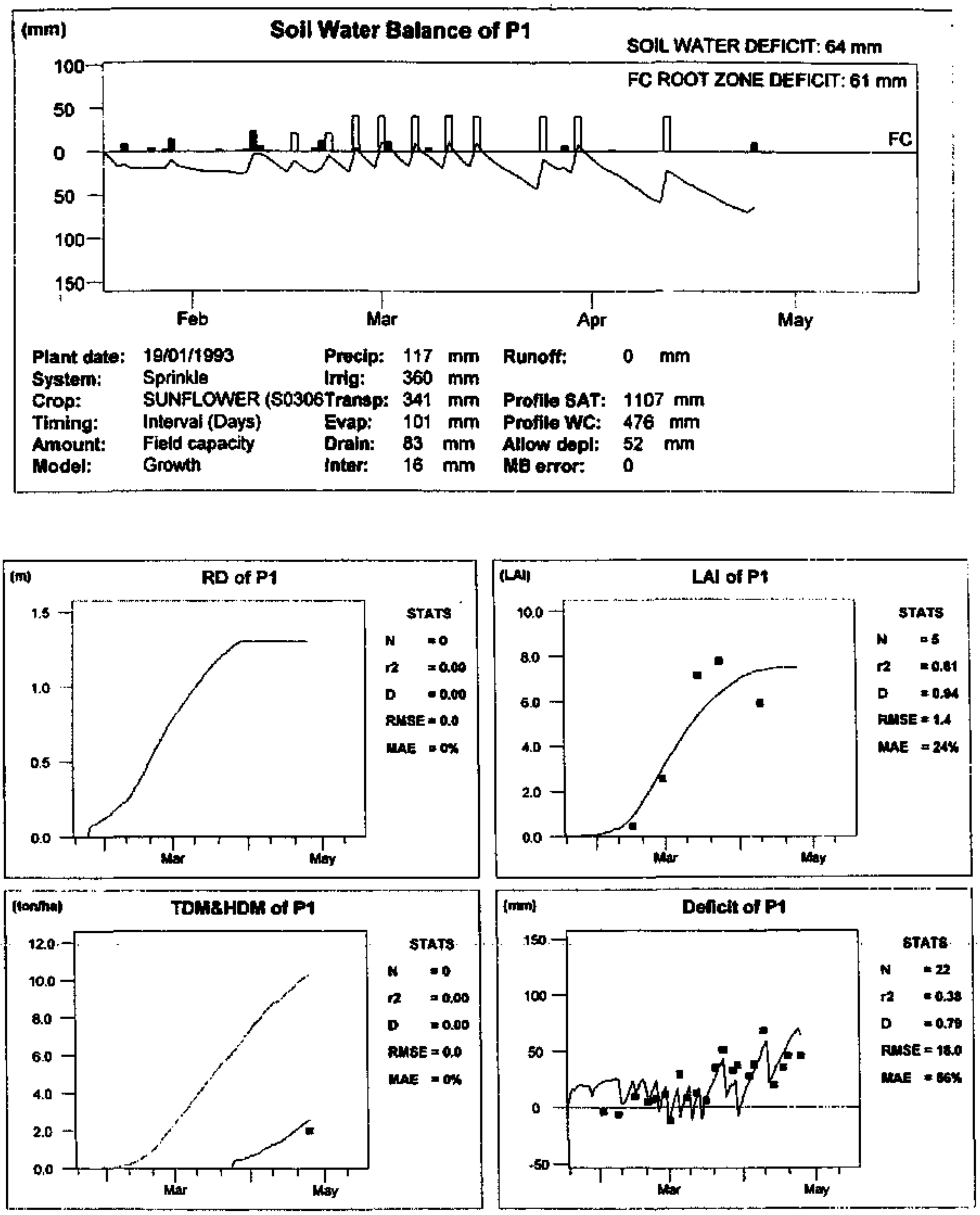


Figure 5.35

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Sunflower (cv. SO306)

Input data set: Potchefstroom, treatment P1 (A. Nel, personal communication)

Model type: Crop growth

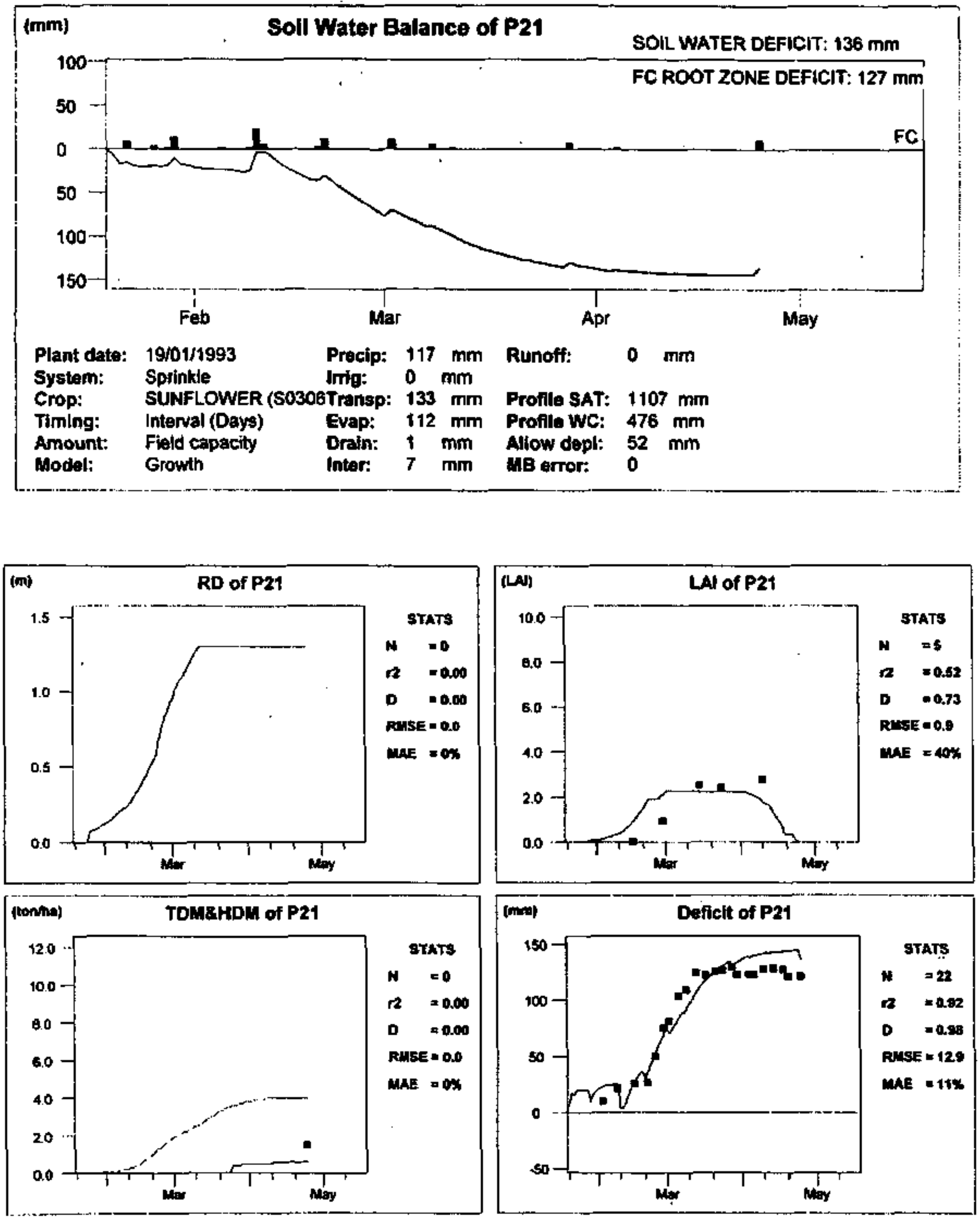


Figure 5.36

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Sunflower (cv. SO306)

Input data set: Potchefstroom, treatment P21 (A. Nel, personal communication)

Model type: Crop growth

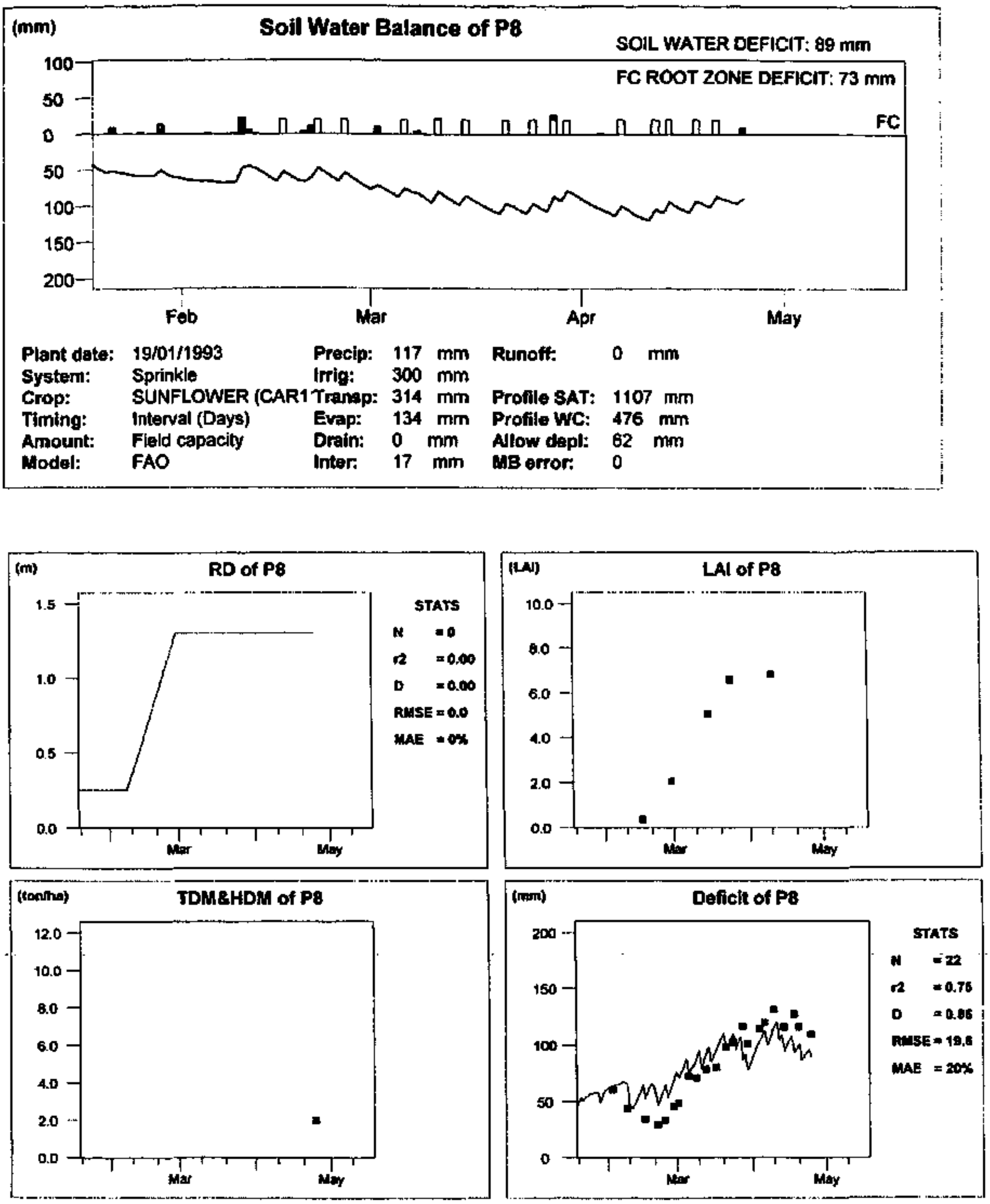


Figure 5.37

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Sunflower (cv. CAR1199)

Input data set: Potchefstroom, treatment P8 (A. Nel, personal communication)

Model type: FAO

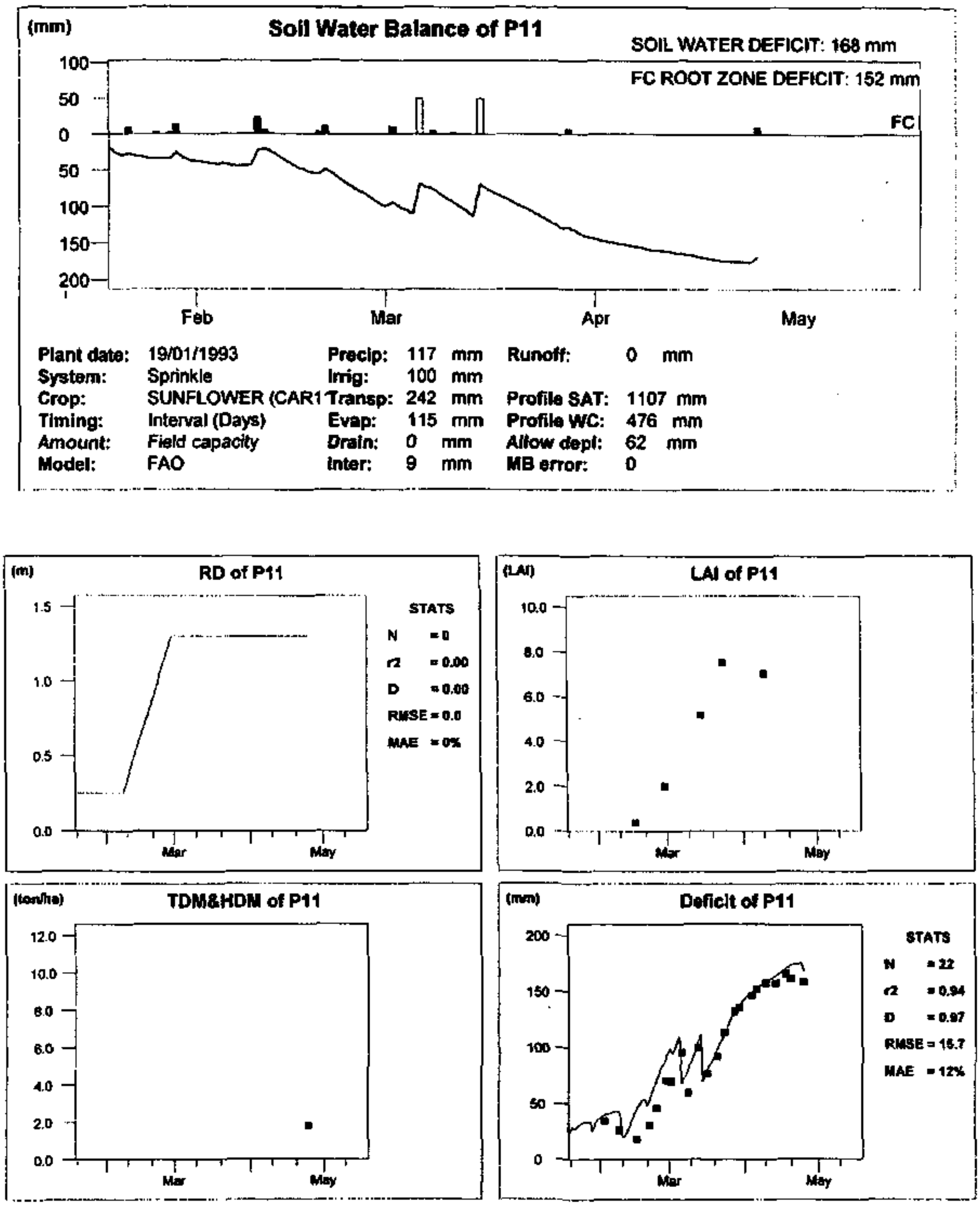


Figure 5.38

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Sunflower (cv. CAR1199)

Input data set: Potchefstroom, treatment P11 (A. Nel, personal communication)

Model type: FAO

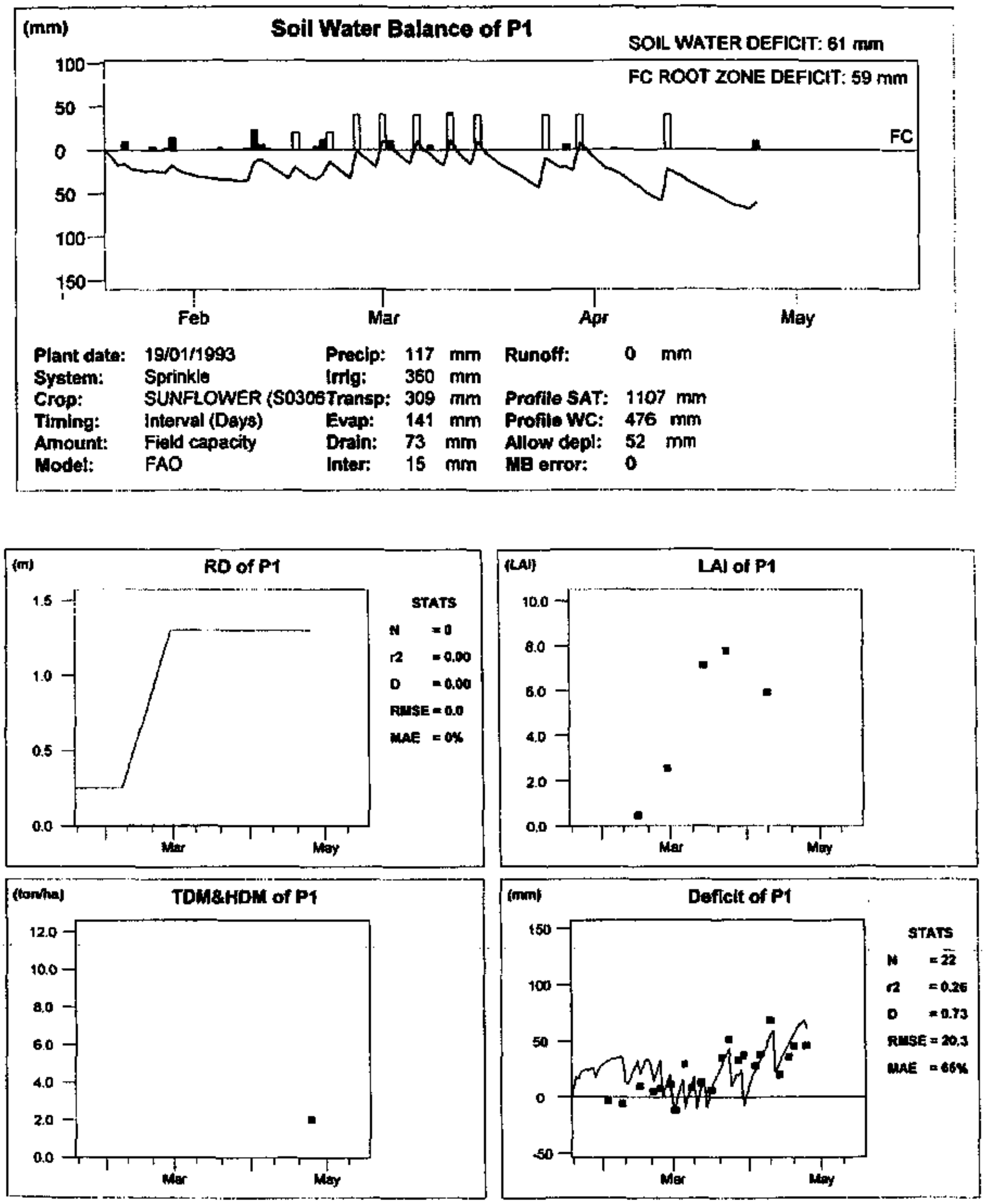


Figure 5.39

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Sunflower (cv. SO306)

Input data set: Potchefstroom, treatment P1 (A. Nel, personal communication)

Model type: FAO

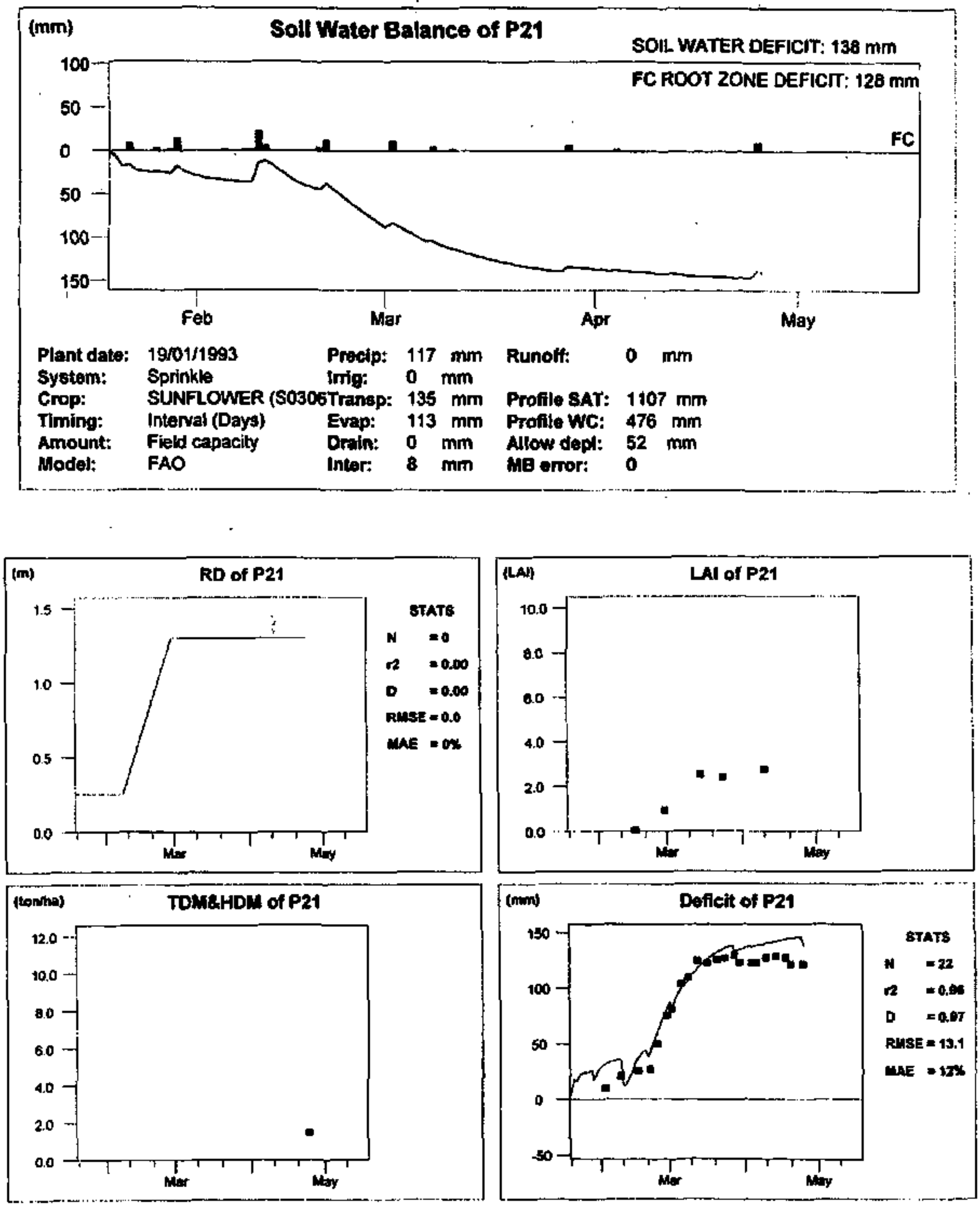


Figure 5.40

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Sunflower (cv. SO306)

Input data set: Potchefstroom, treatment P21 (A. Nel, personal communication)

Model type: FAO

5.1.8 Tobacco

A data set for tobacco was obtained from a commercial planting in the Brits area (North-West Province). Air-dried tobacco was planted on 17/01/1997. Weather data were collected with an automatic weather station and plant samples were taken regularly for growth analyses. Canopy cover was also measured. These data sets were then used to calculate the following growth parameters for tobacco:

- radiation conversion efficiency,
- specific leaf area,
- leaf-stem partitioning parameter, and
- canopy radiation extinction coefficient.

Thermal time requirements were determined from field observations and temperature data. The other growth parameters for tobacco were estimated by calibration against measurements. According to the field managers, irrigations were estimated to be 25 mm twice per week. Figure 5.41 presents the soil water balance graph, simulated and measured root depth (RD), leaf area index (LAI), above-ground dry matter (TDM) and harvestable dry matter (HDM), as well as soil water deficit to field capacity.

Data sets were also obtained from Besproeiings Bestuurs Dienste for flue-cured tobacco grown in the Alma region (Northern Province). No growth analysis data were available. Soil water content was measured with a neutron water meter. Soil water deficit to field capacity was then calculated and used to determine FAO crop factors. Figure 5.42 shows an example of a simulation with the soil water balance graph, as well as the simulated and measured soil water deficit to field capacity.

Specific crop growth parameters and FAO crop factors for tobacco are summarized in Appendix B (Tables B1 and B2).

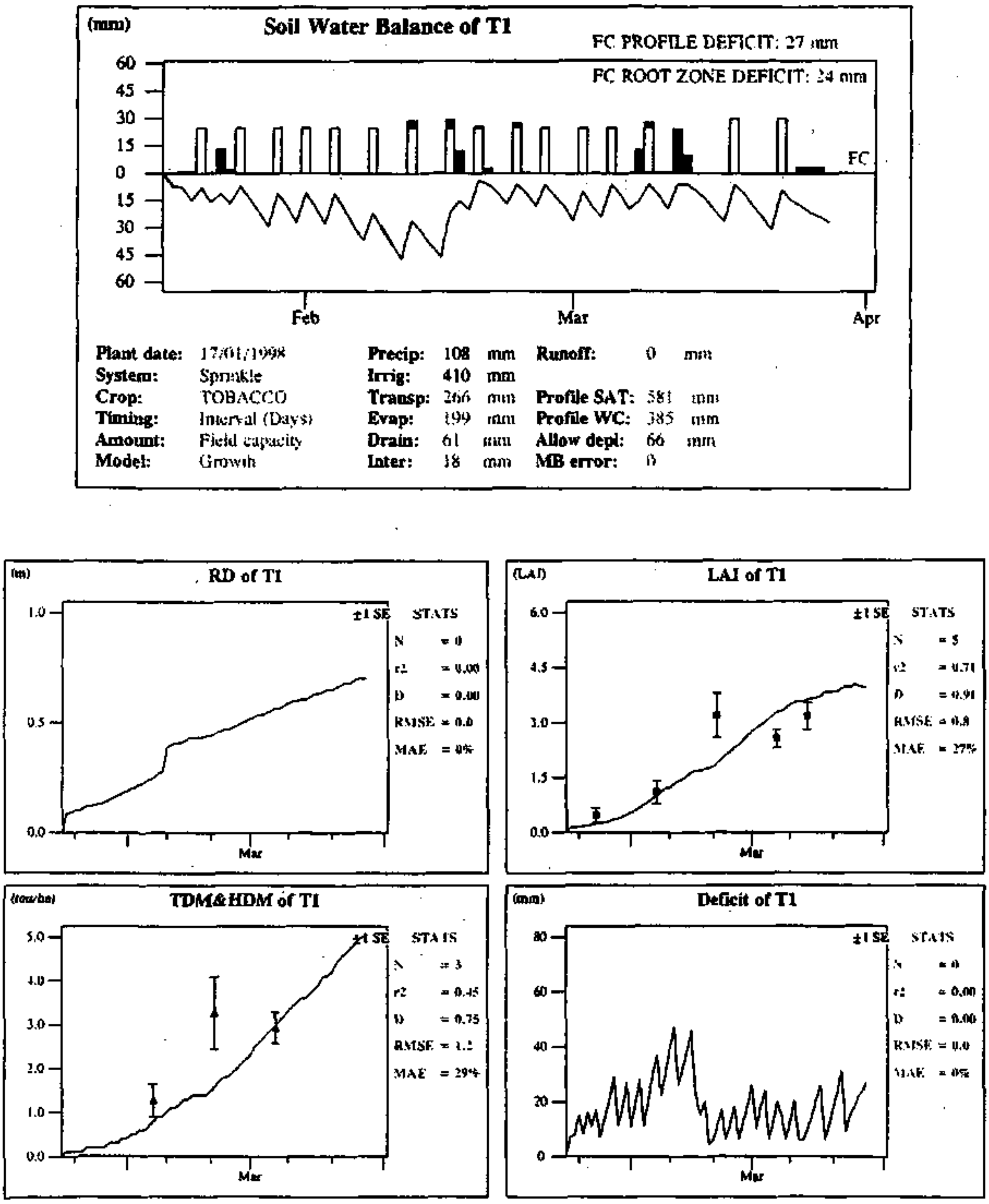
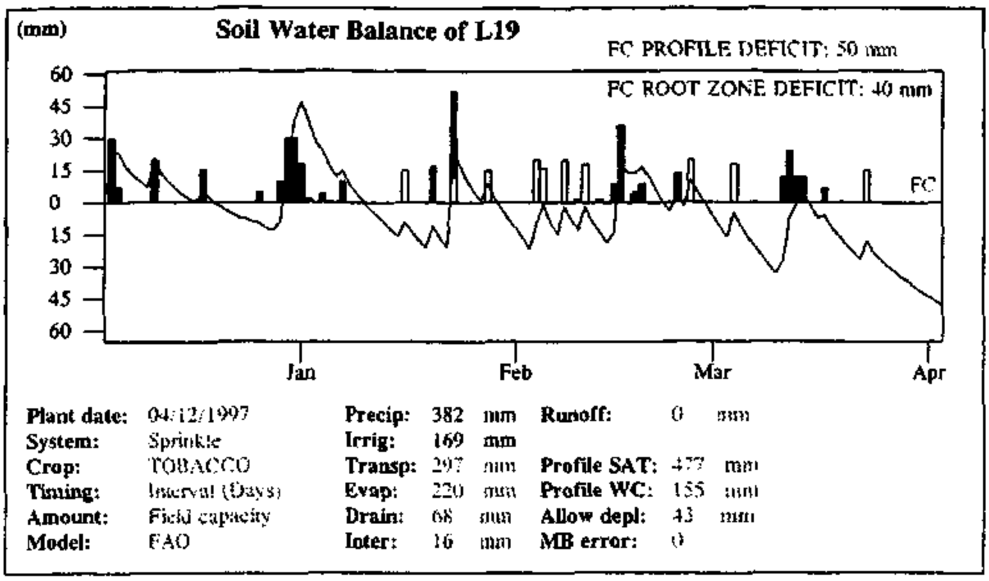


Figure 5.41

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above-ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit to field capacity.

Crop: Air-dried tobacco
Input data set: Brits commercial trial
Model type: Crop growth



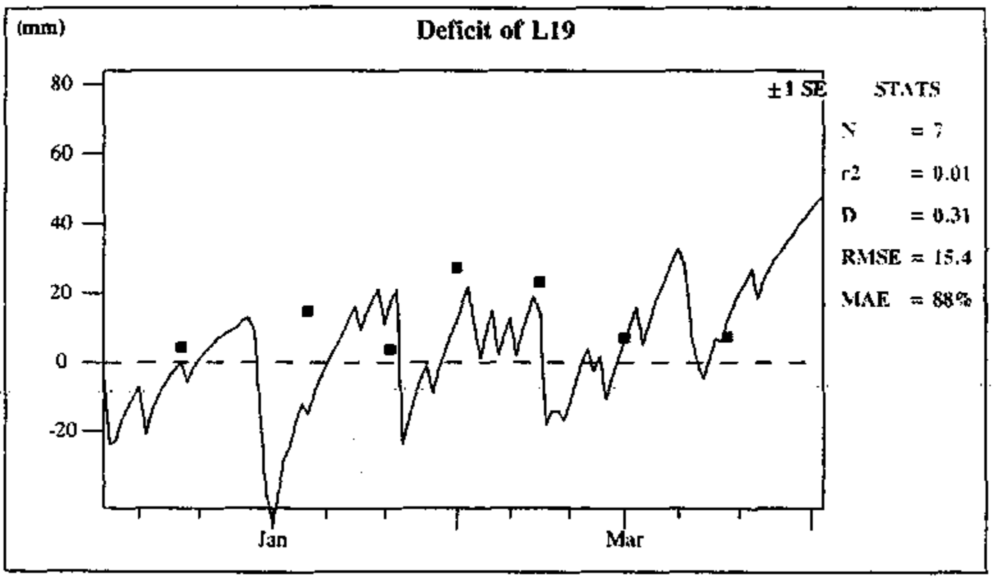


Figure 5.42

Soil water balance output graph, simulated (solid line) and measured (symbols) soil water deficit to field capacity

Crop: Flue-cured tobacco

Input data set: Besproeiings Bestuurs Dienste (Alma region)

Model type: FAO

5.1.9 Wheat

Complete data sets were obtained from Prof ATP Bennie. Wheat (*Triticum aestivum* cv. Gamtoos) was grown at the experimental station of the University of the Orange Free State, 13 km from Bloemfontein (Bennie et al., 1996). See Section 5.1.1 for a more detailed description of the trial.

In this work, the soil water balance and crop growth was simulated with SWB for the following treatments:

i) High target yield, weekly irrigations, start with wet soil profile and end with dry soil profile (H1VL) (examples of model output are in Figure 5.43); and

ii) Low target yield, weekly irrigations, start with wet soil profile and end with dry soil profile (L1VL) (examples of model output are in Figure 5.44).

The H1VL treatment was used to calibrate the model for the particular cultivar, whilst the L1VL treatment was used to validate the soil water balance and crop growth subroutines of SWB.

The soil water balance was simulated with the FAO model for H1VL (examples of model output are in Figure 5.45) and L1VL (examples of model output are in Figure 5.46). The crop factors recommended by the FAO for wheat, were used in these simulations. Length of stages, basal crop coefficient for mid-season stage and maximum root depth were modified.

The statistical output parameters indicated that predictions with both crop growth and FAO model were inside, or marginally outside the reliability criteria. Soil water deficit predicted with the FAO-type model for the L1VL treatment at the end of the growing season (Figure 5.46), was higher than that calculated with the crop growth model (Figure 5.44), as the FAO model does not account for smaller canopy size under water stress conditions. Refinement of specific crop growth parameters and FAO crop factors is recommended for wheat to account for differences in cultivars and specific environmental conditions.

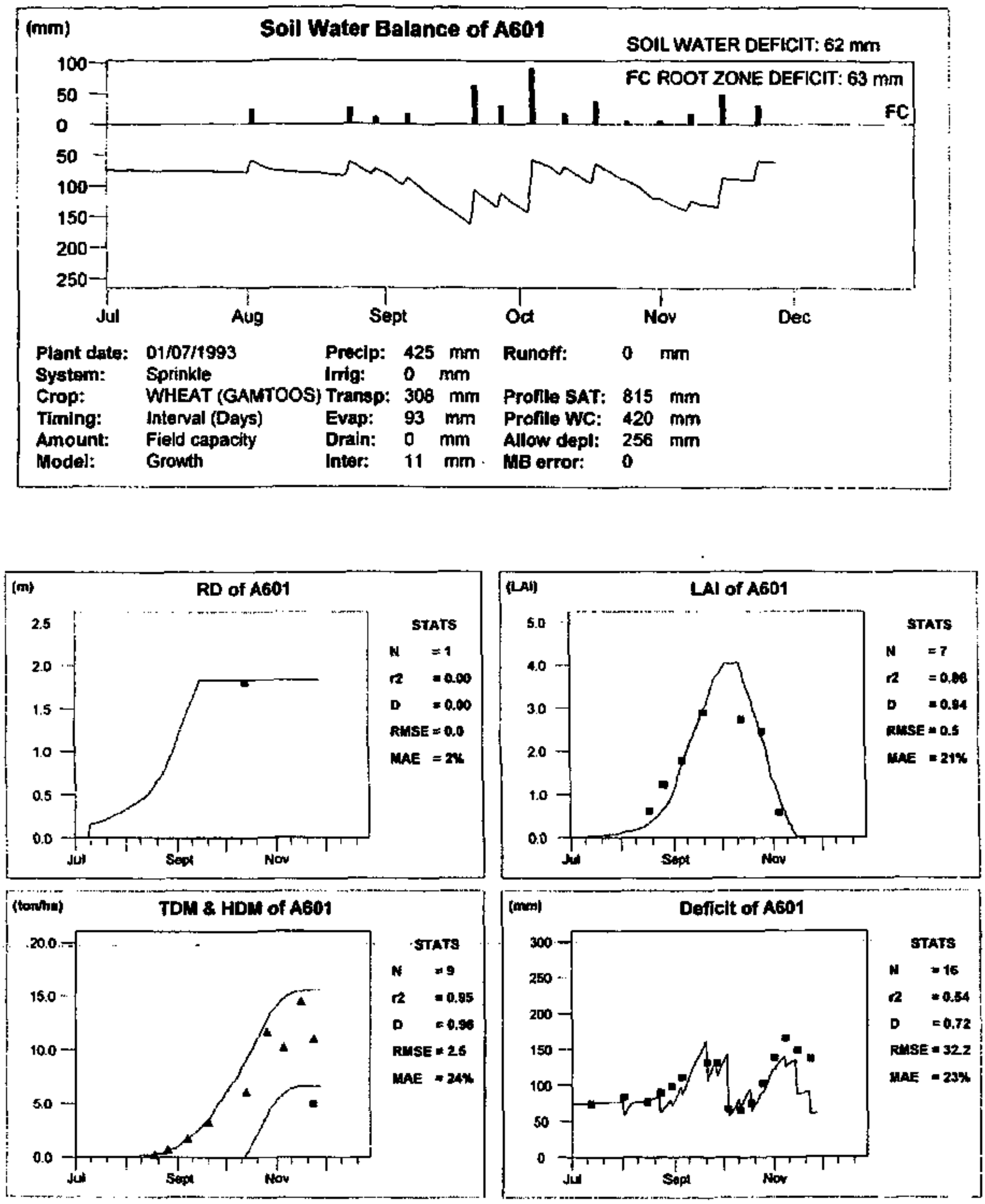


Figure 5.43

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Wheat

Input and measured data sets: Bloemfontein, treatment H1VL (Bennie et al., 1996)

Model type: Crop growth

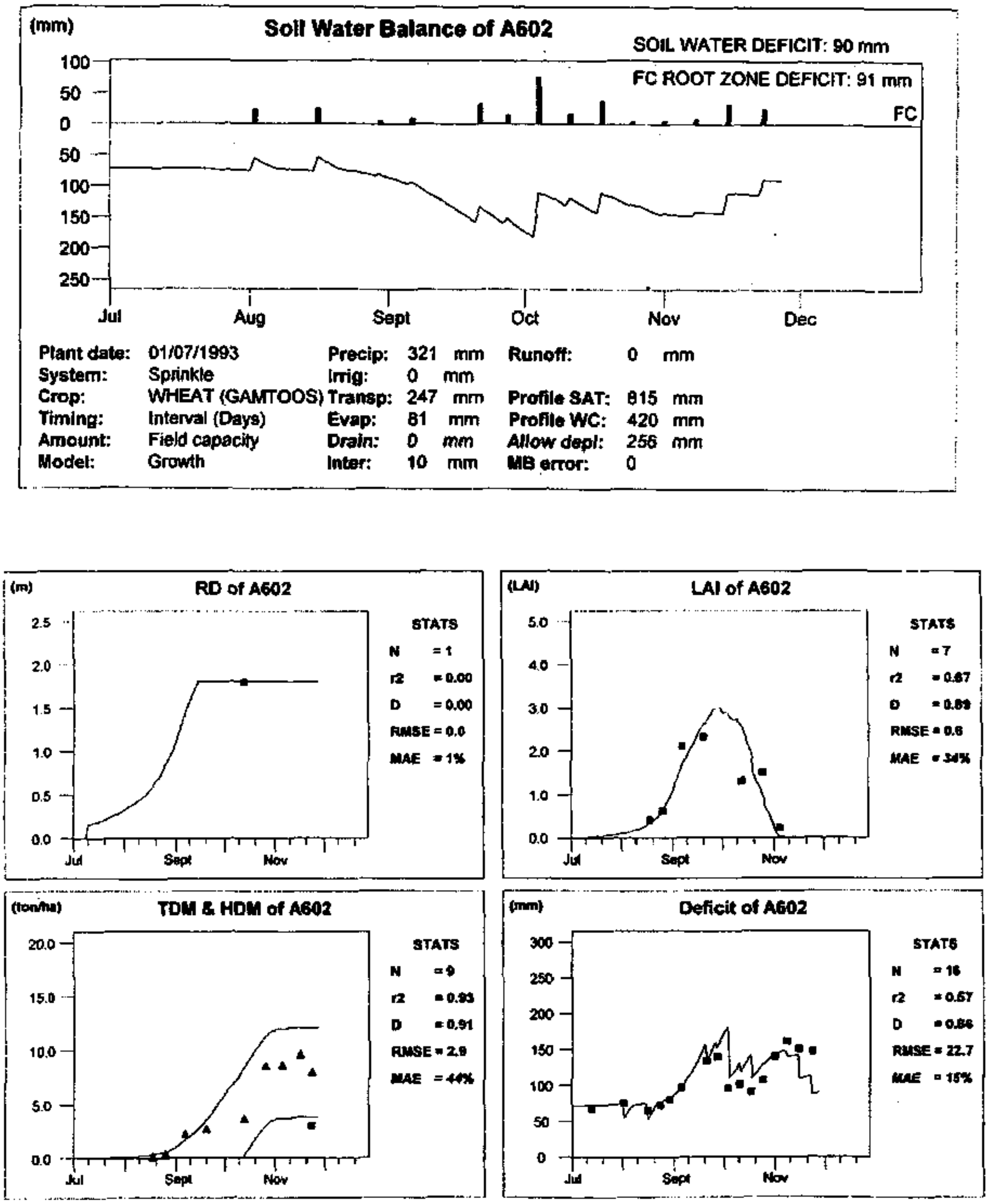


Figure 5.44

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Wheat

Input and measured data sets: Bloemfontein, treatment L1VL (Bennie et al., 1996)

Model type: Crop growth

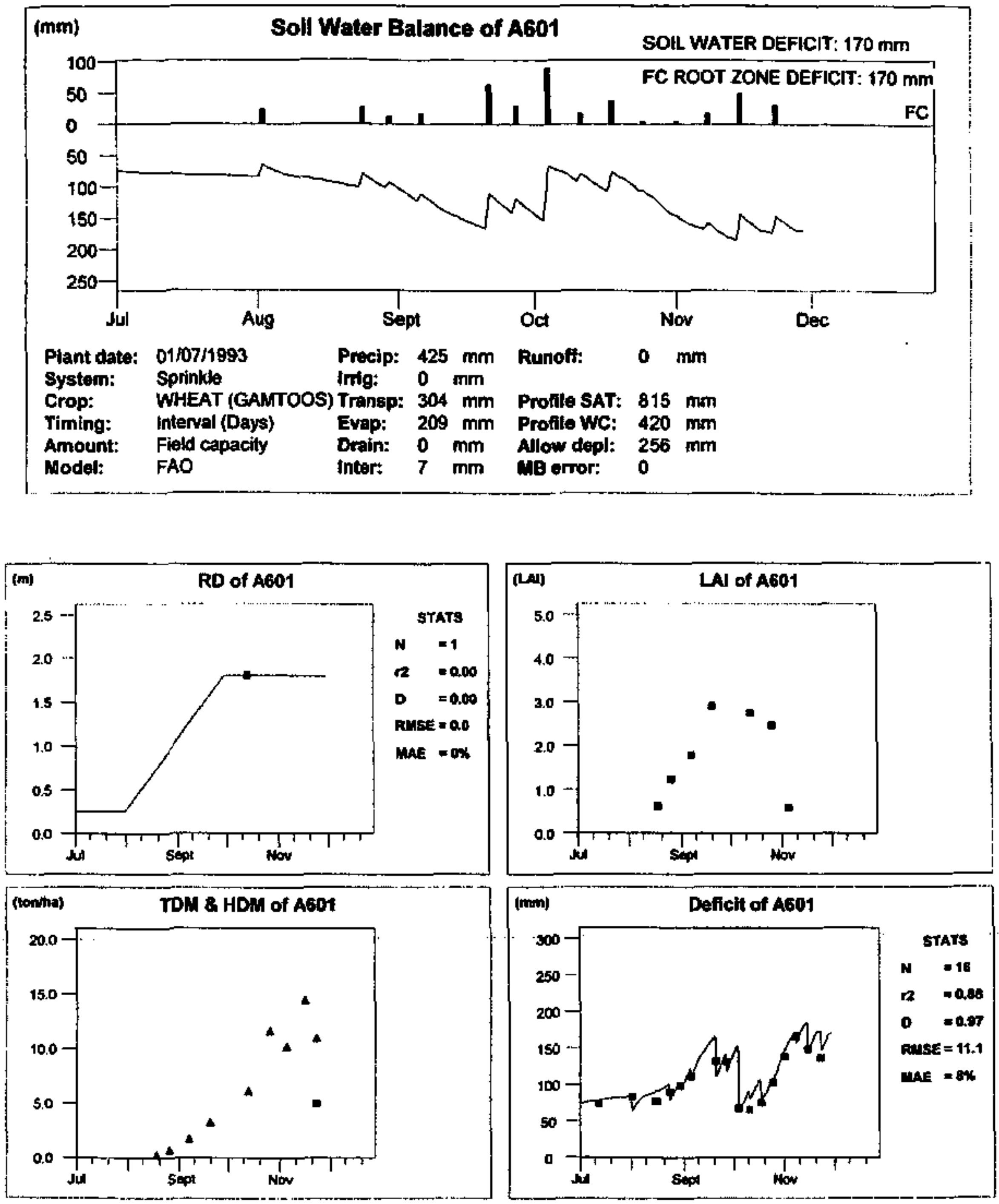


Figure 5.45

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Wheat

Input and measured data sets: Bloemfontein, treatment H1VL (Bennie et al., 1996)

Model type: FAO

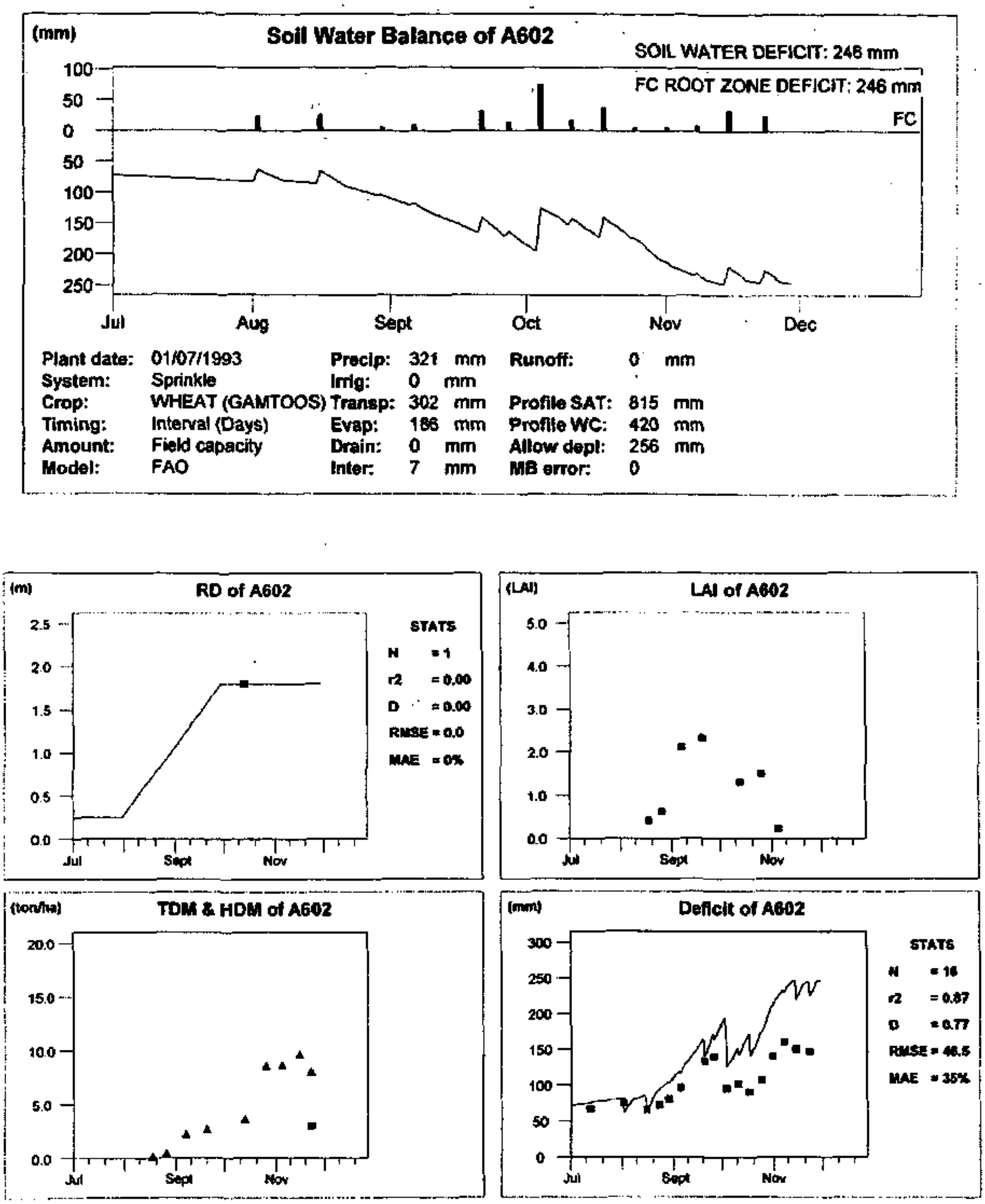


Figure 5.46

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Wheat

Input and measured data sets: Bloemfontein, treatment L1VL (Bennie et al., 1996)

Model type: FAO

Complete data sets were also obtained from Dr TP Fyfield (Institute for Soil, Climate and Water - Agricultural Research Council, Pretoria). Walker et al. (1995) carried out an experiment to test the response of wheat to different levels of water and nitrogen. Spring wheat (cv. SST 86) was grown at Roodeplaat, 28 km NE of Pretoria. The crop was irrigated with a line source sprinkler irrigation system. The soil is Hutton Ventersdorp (Soil Classification Working Group, 1991).

The trial started with a wet soil profile and irrigations were carried out weekly. Several treatments were differentiated with the line source system:

i) W5 (approx. 650 mm of irrigation during the season);
ii) W4 (approx. 500 mm);
iii) W3 (approx. 370 mm);
iv) W2 (approx. 250) and
v) W1 (approx. 0).

Only the treatments with optimum nitrogen level were considered in this study. The soil water balance and crop growth was simulated for treatments W5 (Figure 5.47) and W3 (Figure 5.48). Treatment W5 was used to calibrate the model for the particular cultivar, whilst treatment W3 was used to validate the soil water balance and crop growth subroutines of SWB.

In addition, the soil water balance was simulated with the FAO model for treatments W5 (Figure 5.49) and W3 (Figure 5.50). Crop factors recommended by the FAO were used for these simulations. Root depth for the mid-season and late-season stage was modified.

Crop growth and soil water deficit were simulated with SWB reasonably well.

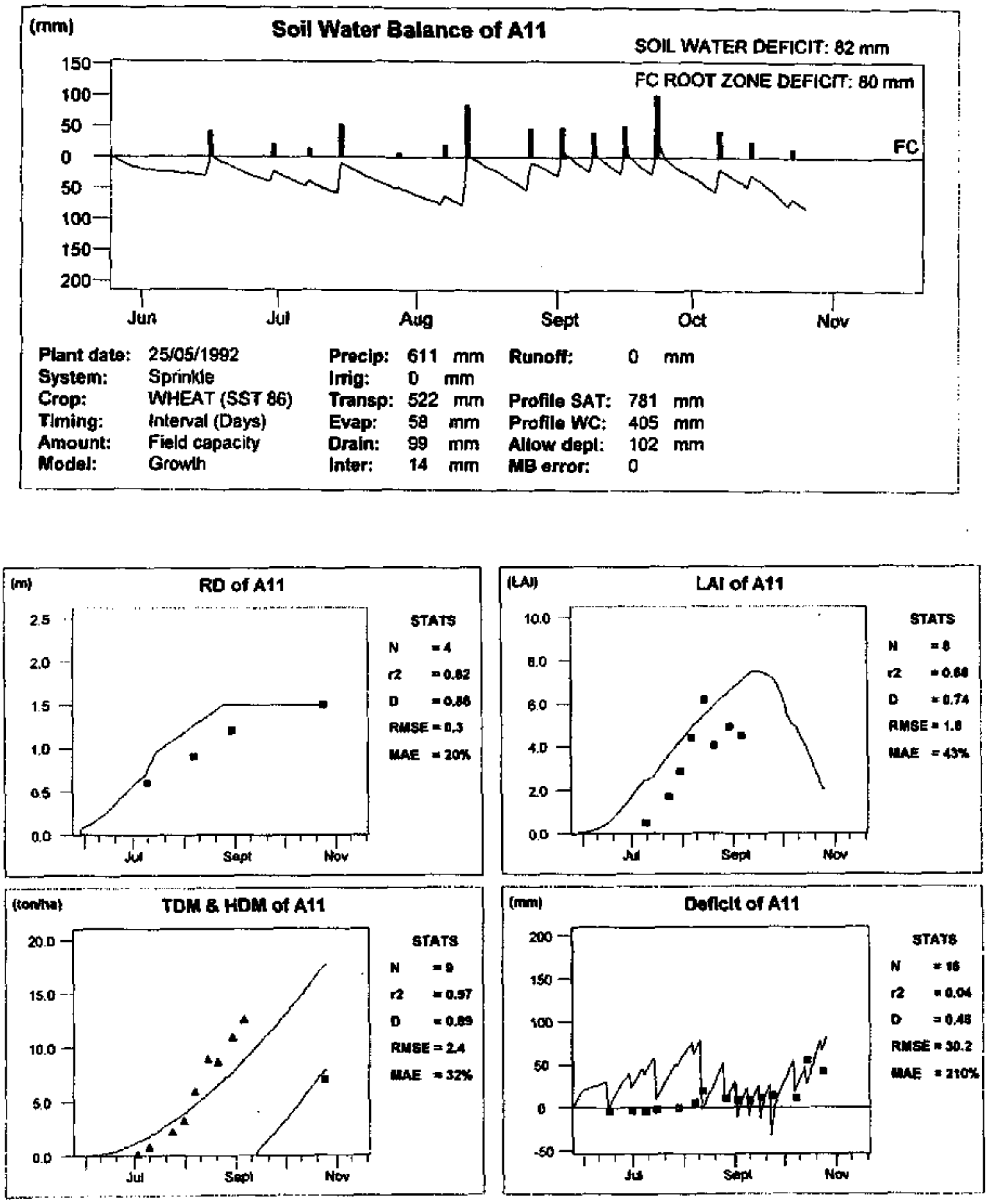


Figure 5.47

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Wheat
Input data set: Roodeplaat, treatment W5 (Walker et al., 1995)
Model type: Crop growth

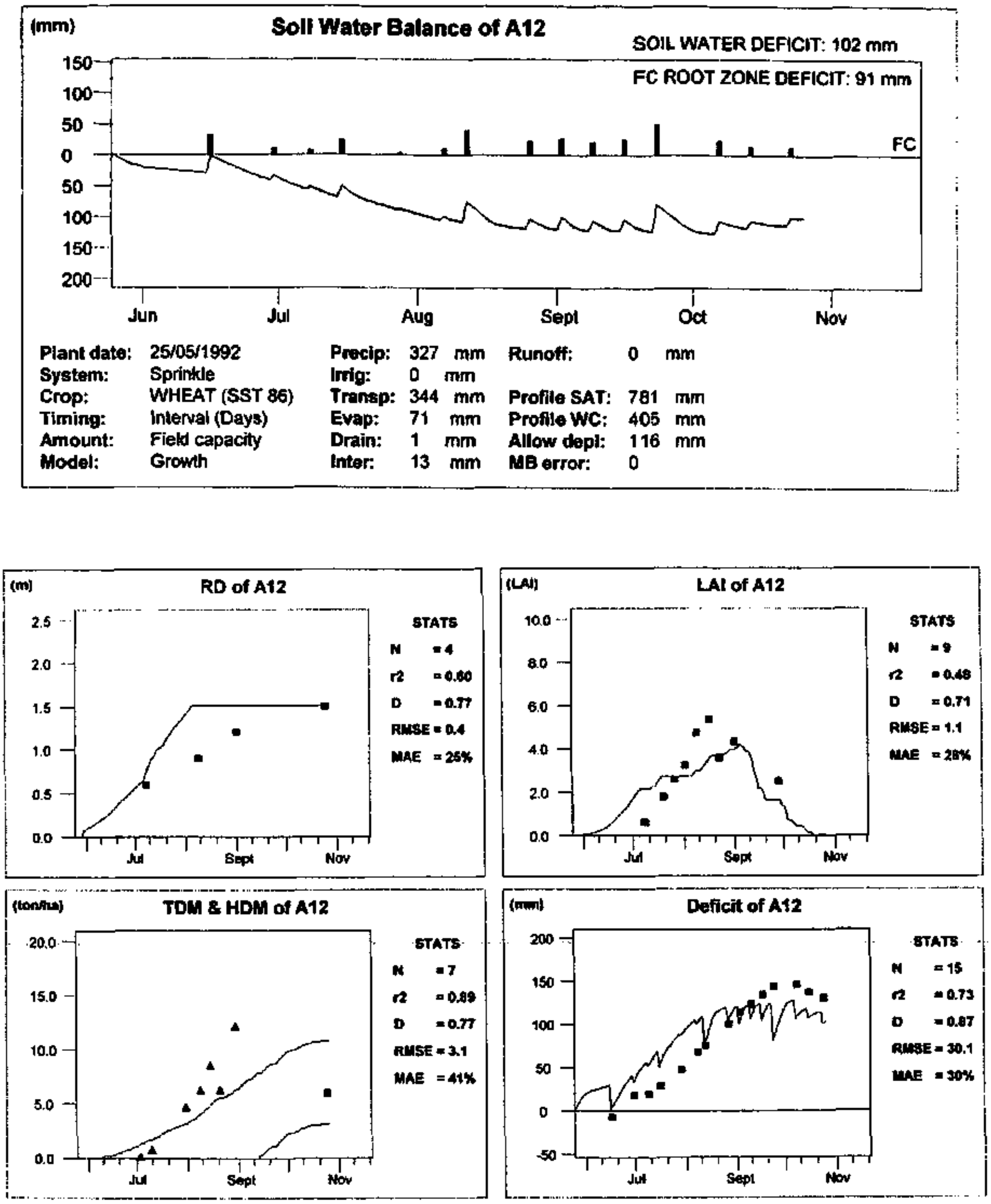


Figure 5.48

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Wheat
Input data set: Roodeplaat, treatment W3 (Walker et al., 1995)
Model type: Crop growth

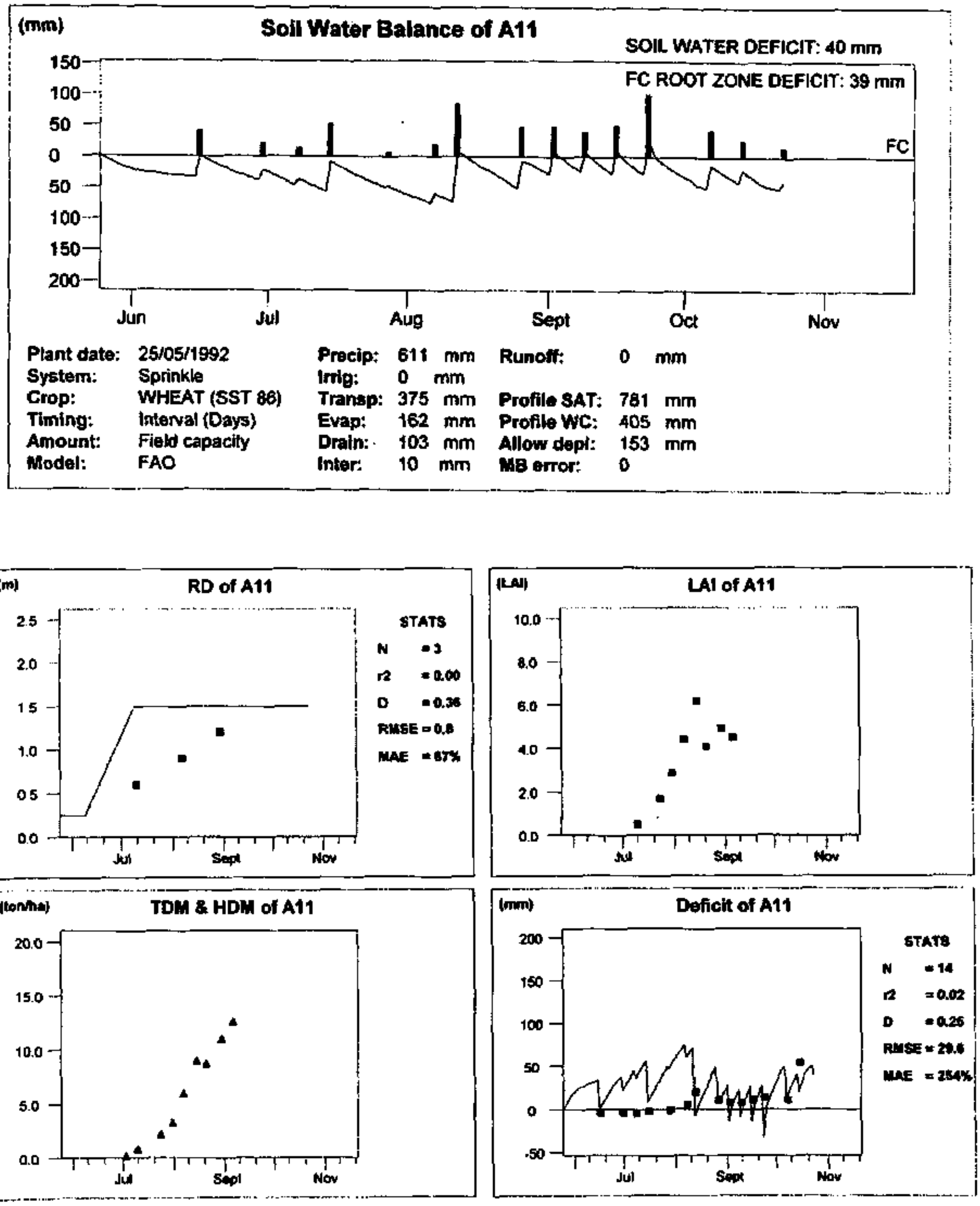


Figure 5.49

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Wheat
Input data set: Roodeplaat, treatment W5 (Walker et al., 1995)
Model type: FAO

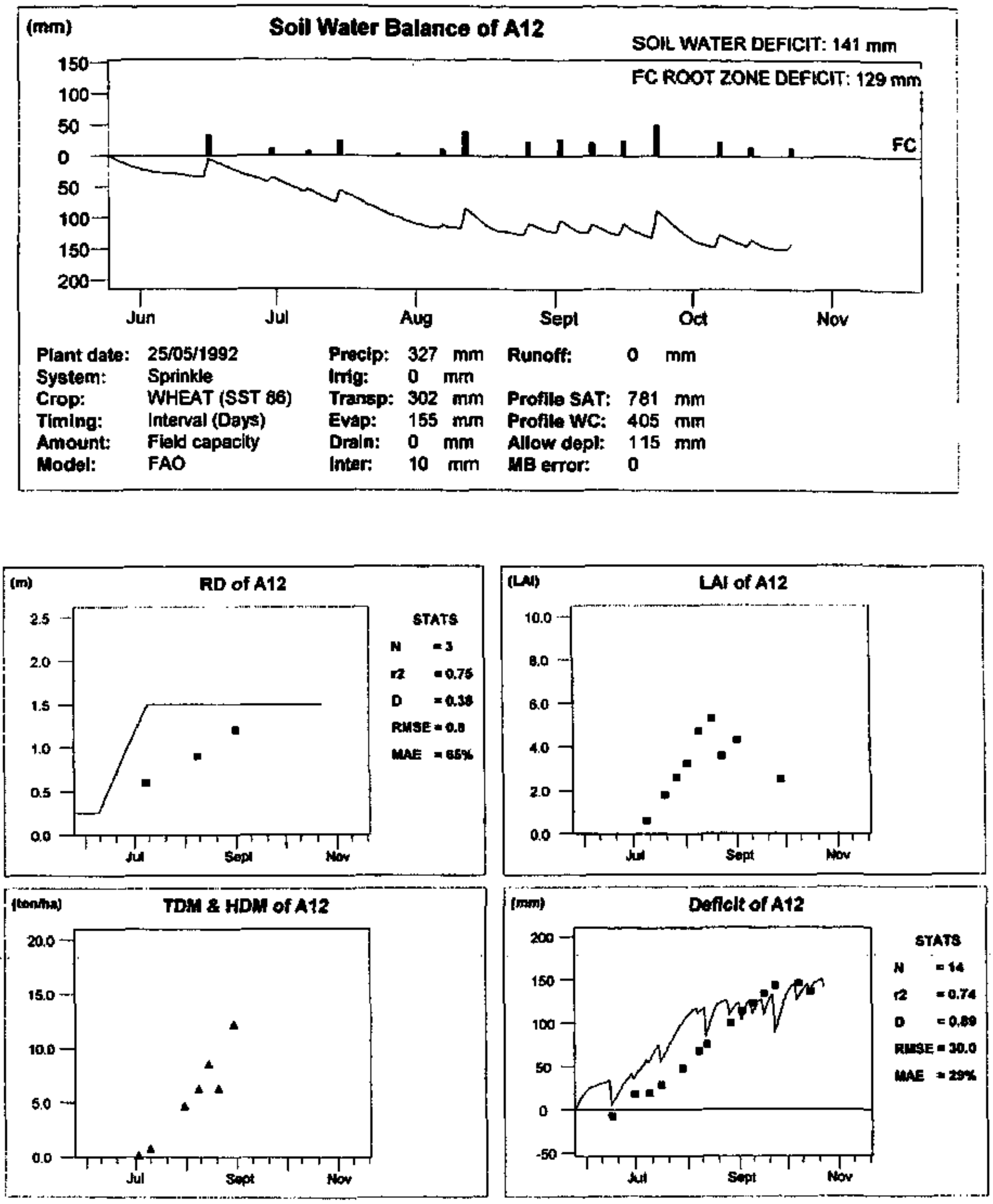


Figure 5.50

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Wheat
Input data set: Roodeplaat, treatment W3 (Walker et al., 1995)
Model type: FAO

5.2 Vegetable crops

5.2.1 Beans (bush)

Data sets for the calibration of SWB were obtained from the Roodeplaat trial (Section 4.1).

Specific crop growth parameters were determined either from the field trial data (Section 4.1.3), or by calibration against measurements of growth, phenology, yield and water use. These are summarized in Table B1 (Appendix B). The parameters required to run the FAO model were determined using measurements of canopy cover and weather data (Section 4.1.4). These are summarized in Table B2 (Appendix B).

Simulations were carried out using both the crop growth and FAO model for cv. Bronco (Figures 5.51 and 5.52) and cv. Provider (Figures 5.53 and 5.54).

The model predicted crop growth and soil water deficit reasonably well for both cultivars. Discrepancies between measured data and simulations of crop growth could have been caused by spatial variability. No replications were taken for growth analysis due to the small plot size.

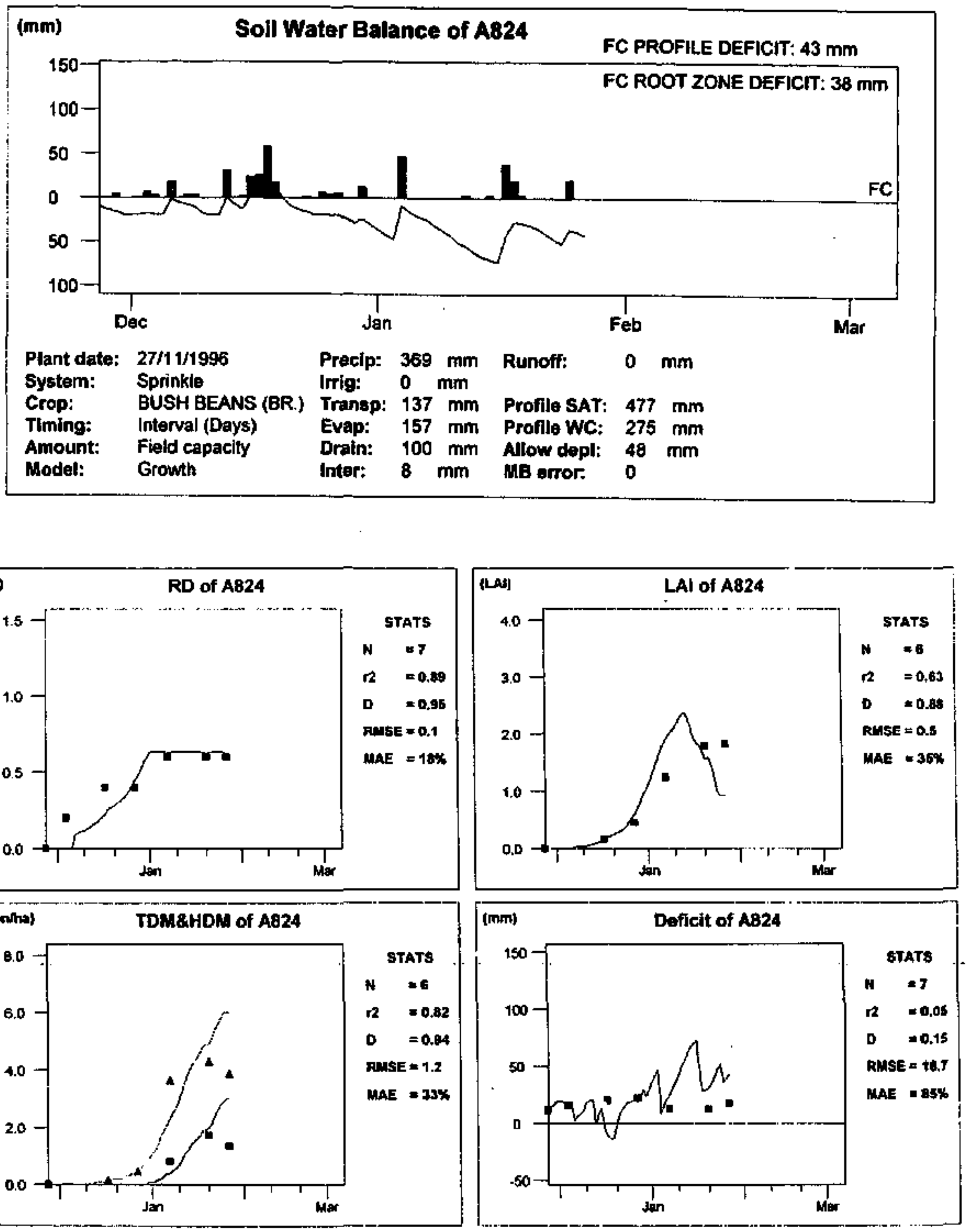


Figure 5.51

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Bush beans (cv. Bronco)
Input data set: Roodeplaat field trial (Section 4.1)
Model type: Crop growth

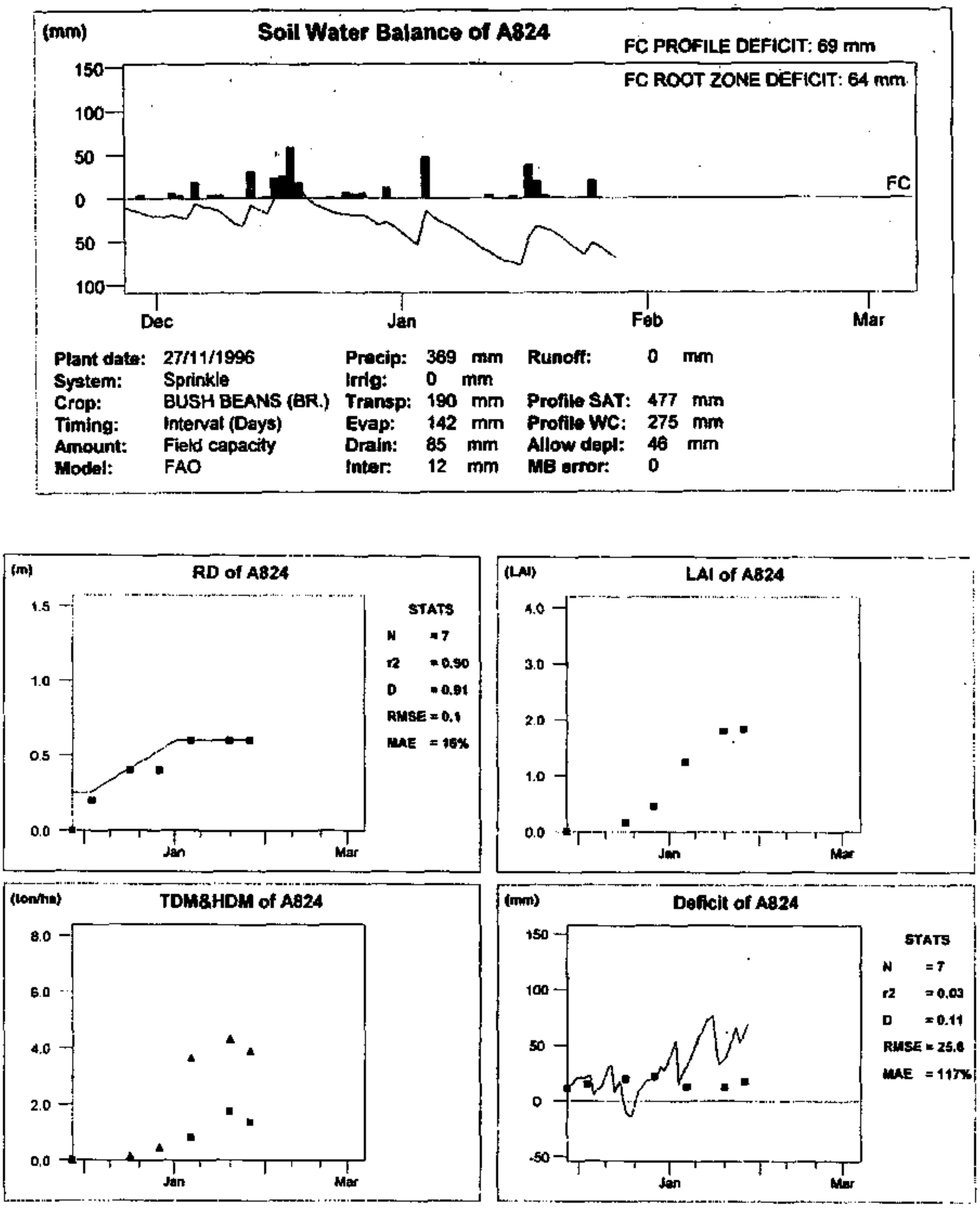


Figure 5.52

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Bush beans (cv. Bronco)

Input data set: Roodeplaat field trial (Section 4.1)

Model type: FAO

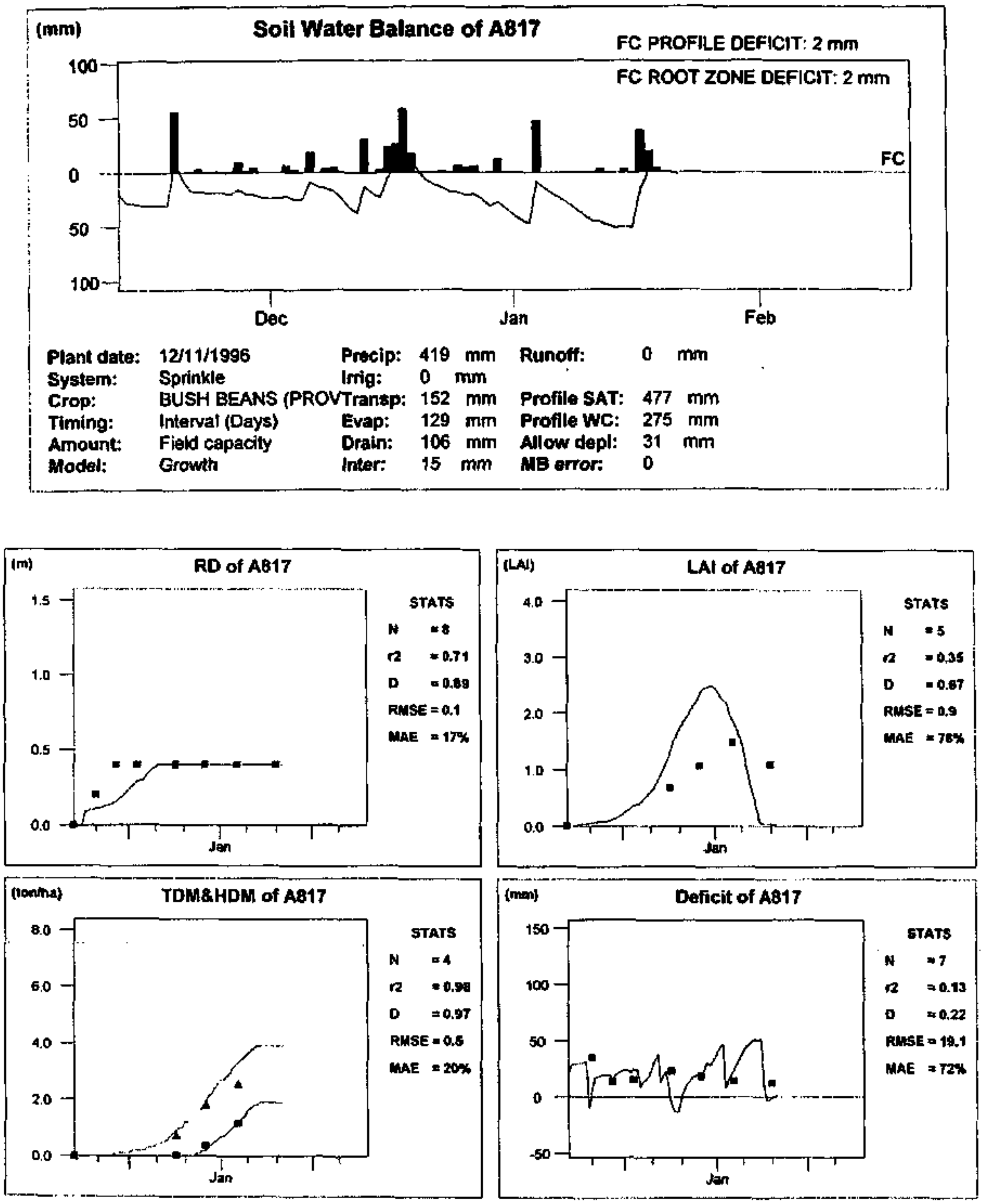


Figure 5.53

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Bush beans (cv. Provider)

Input data set: Roodeplaat field trial (Section 4.1)

Model type: Crop growth

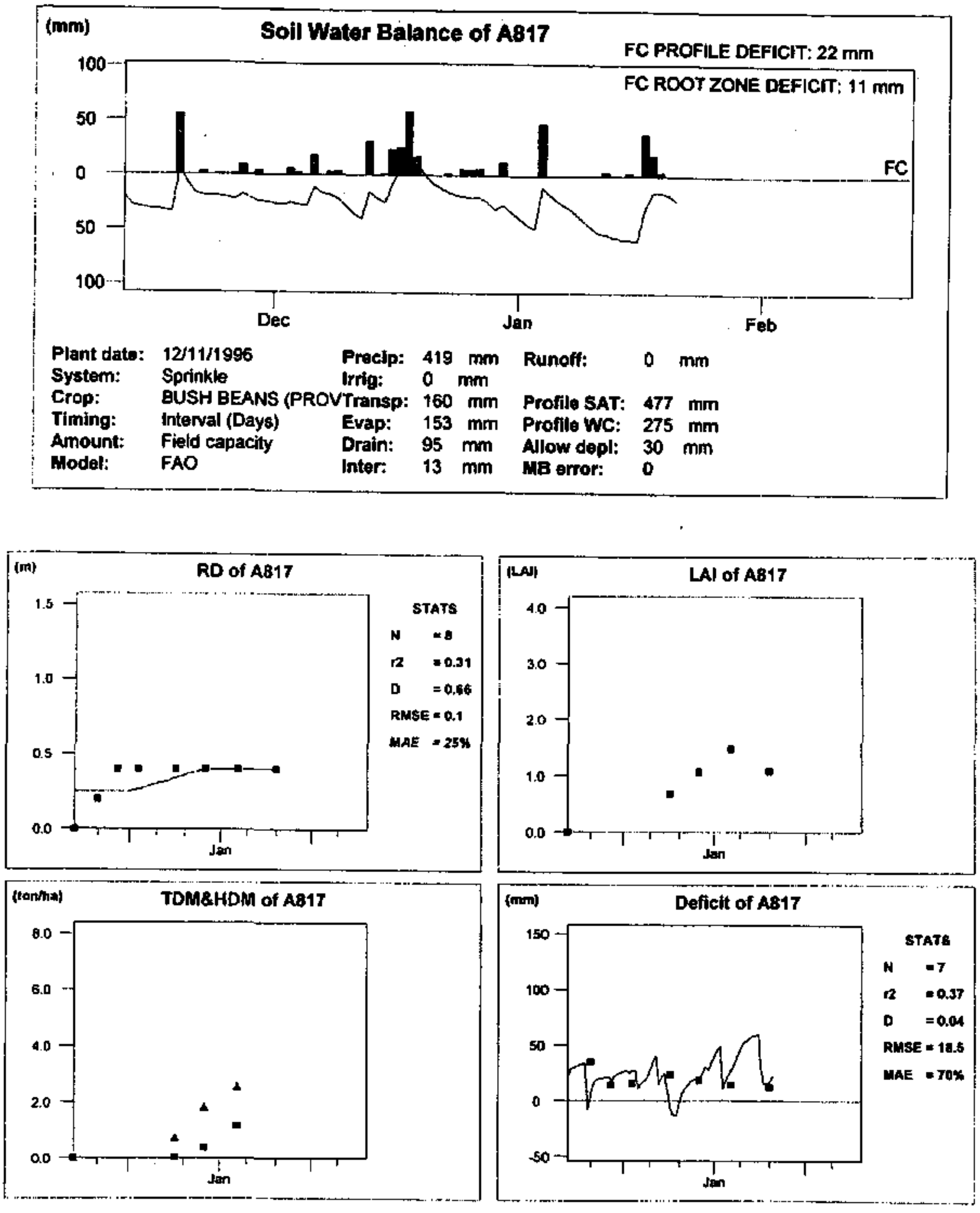


Figure 5.54

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Bush beans (cv. Provider)
Input data set: Roodeplaat field trial (Section 4.1)
Model type: FAO

5.2.2 Beans (runner)

Data sets for the calibration of SWB were obtained from the Roodeplaat trial (Section 4.1).

Specific crop growth parameters were determined either from the field trial data (Section 4.1.3), or by calibration against measurements of growth, phenology, yield and water use. These are summarized in Table B1 (Appendix B). The parameters required to run the FAO model were determined using measurements of canopy cover and weather data (Section 4.1.4). These are summarized in Table B2 (Appendix B).

Simulations were carried out using both the crop growth (Figure 5.55) and FAO model (Figure 5.56). The calibration was successful for both models.

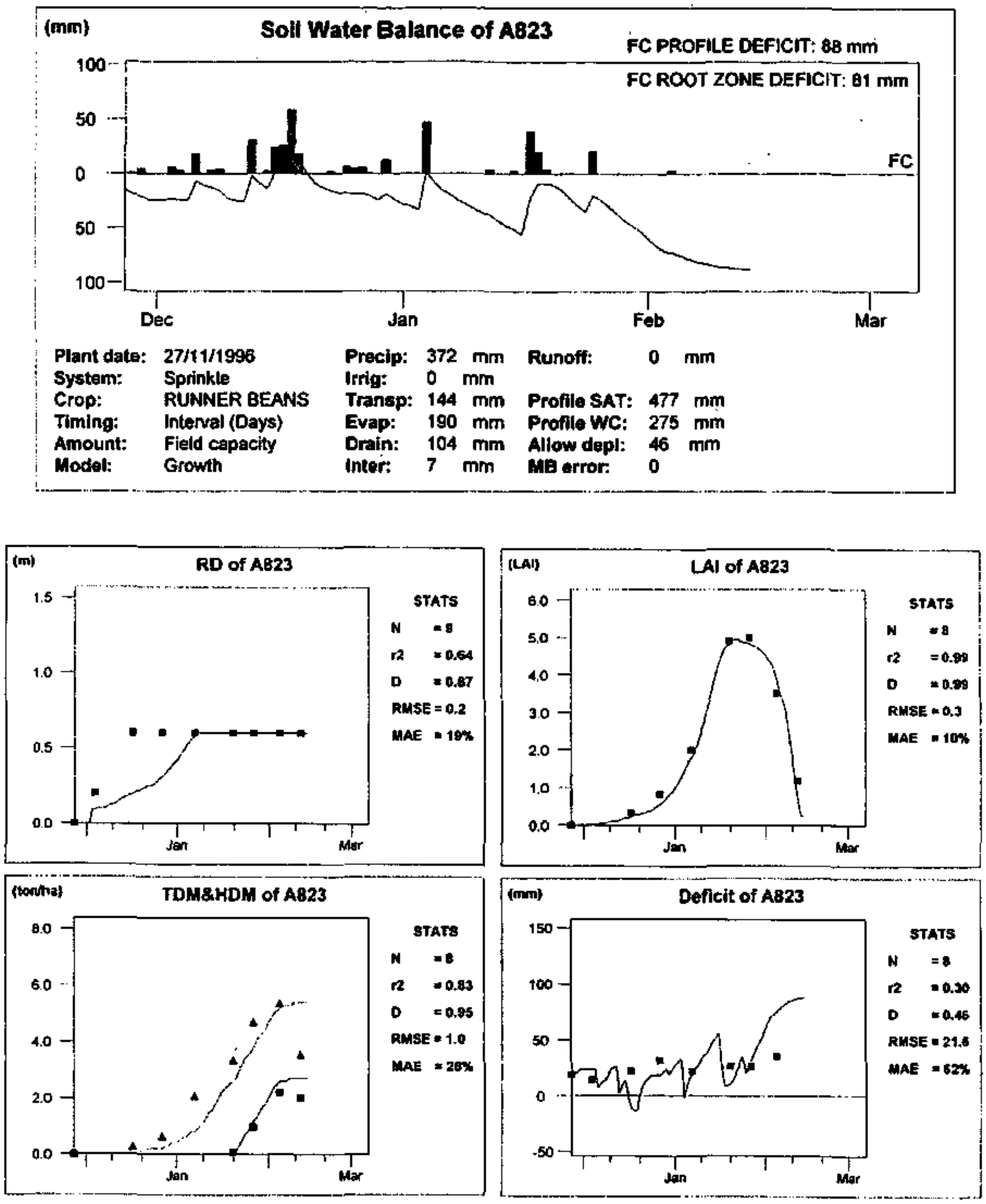


Figure 5.55

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Runner beans

Input data set: Roodeplaat field trial (Section 4.1)

Model type: Crop growth

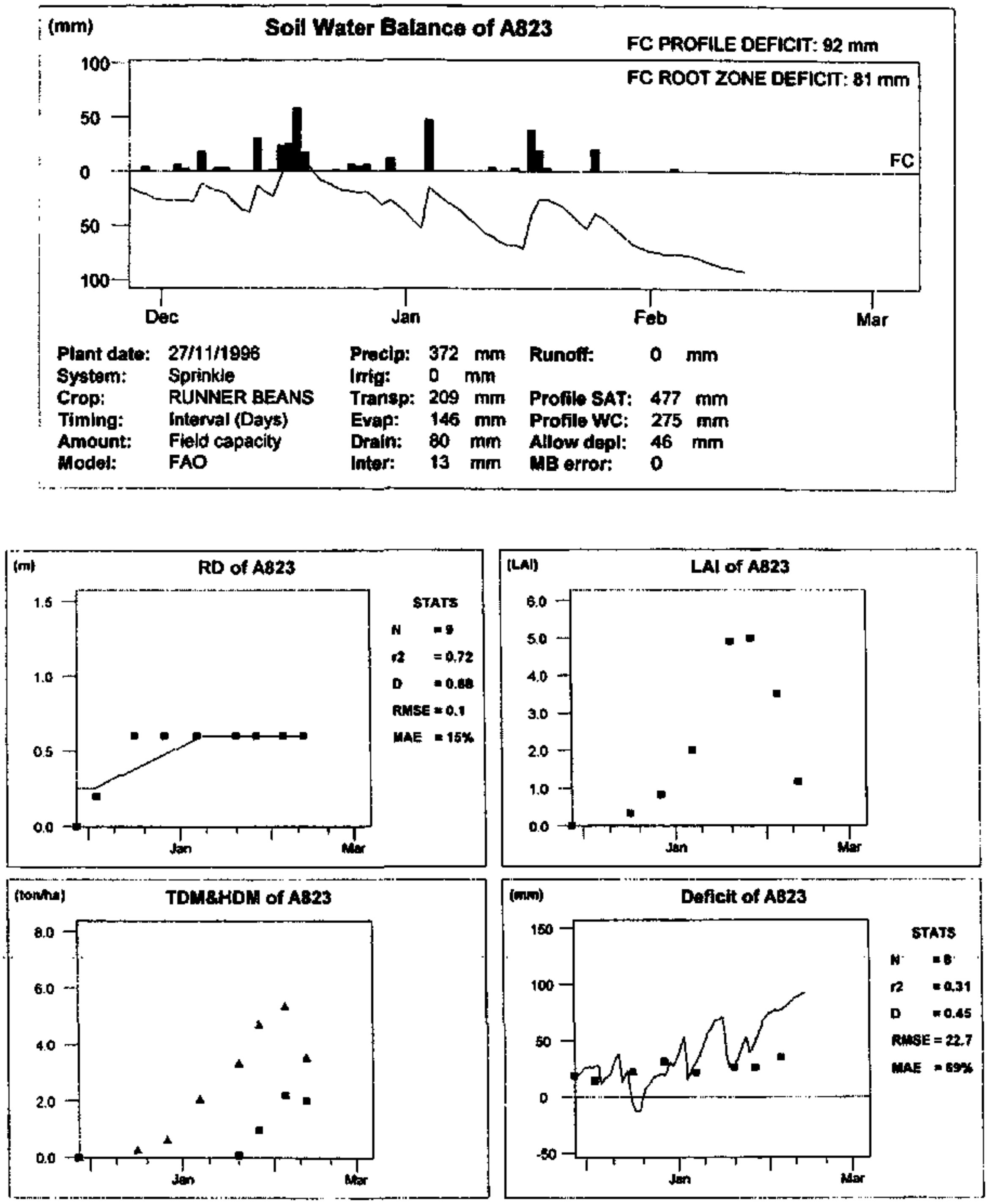


Figure 5.56

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Runner beans
Input data set: Roodeplaat field trial (Section 4.1)
Model type: FAO

5.2.3 Beetroot

Data sets for the calibration of SWB were obtained from the Roodeplaat trial (Section 4.1).

Specific crop growth parameters were determined either from the field trial data (Section 4.1.3), or by calibration against measurements of growth, phenology, yield and water use. These are summarized in Table B1 (Appendix B). The parameters required to run the FAO model were determined using measurements of canopy cover and weather data (Section 4.1.4). These are summarized in Table B2 (Appendix B).

Simulations were carried out using both the crop growth (Figure 5.57) and FAO model (Figure 5.58). The calibration was successful, except for TDM and HDM. Much lower values of dry matter production were predicted by SWB at the end of the growing season compared to measured data (Figure 5.57). It is possible that plant samples were not properly dried in the oven.

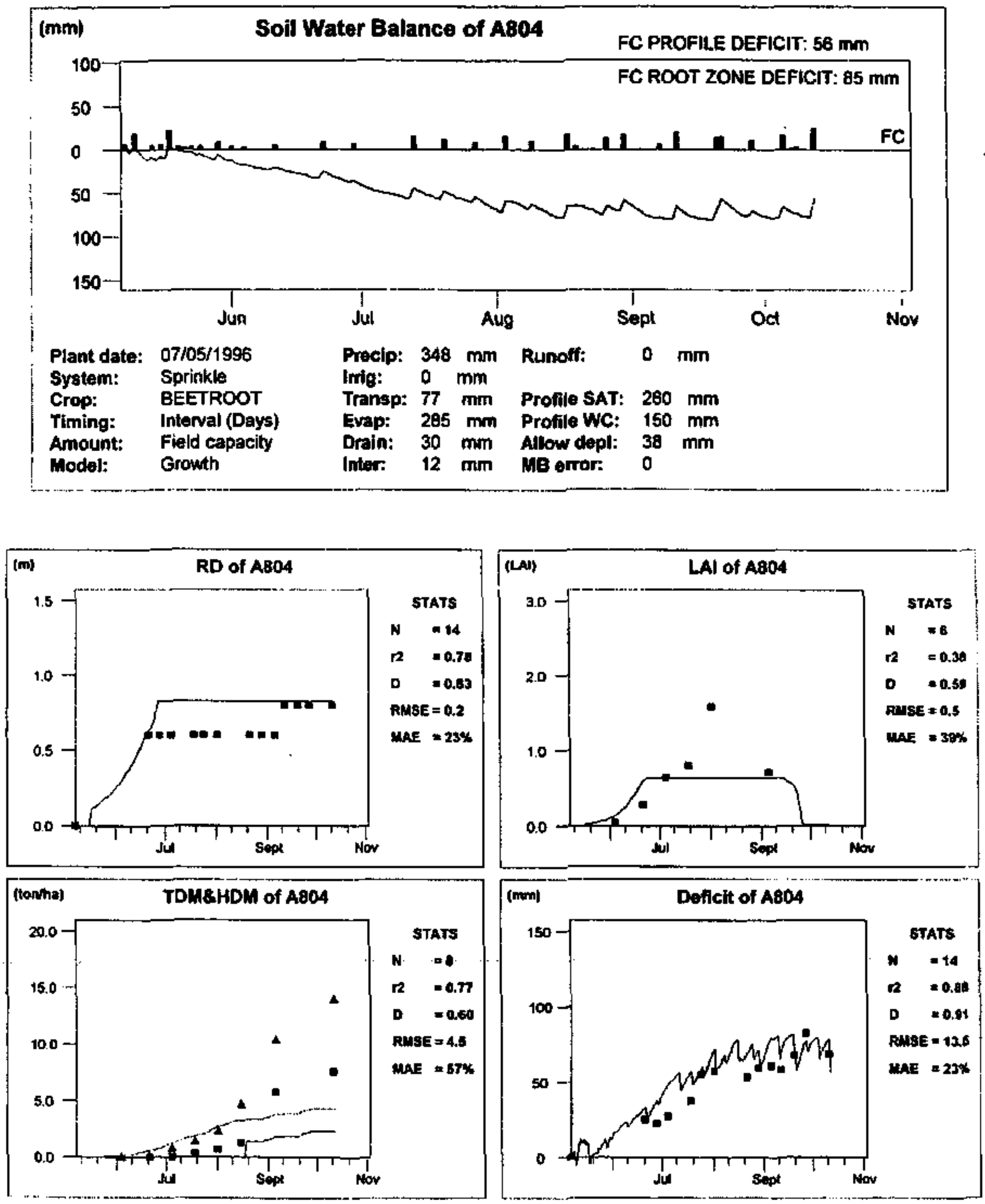


Figure 5.57

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Beetroot

Input data set: Roodeplaat field trial (Section 4.1)

Model type: Crop growth

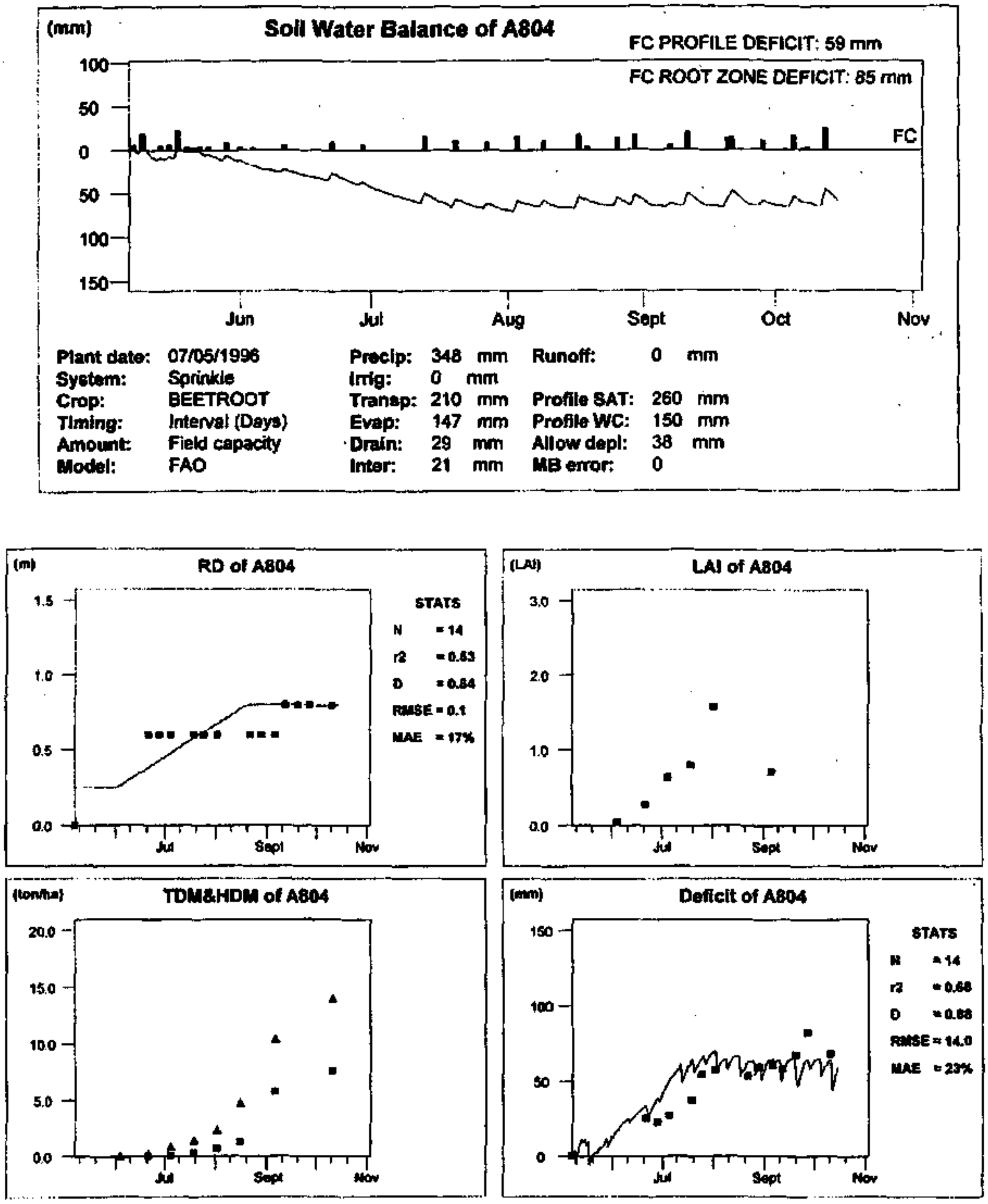


Figure 5.58
Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Beetroot
Input data set: Roodeplaat field trial (Section 4.1)
Model type: FAO

5.2.4 Cabbage

Data sets for the calibration of SWB were obtained from the Roodeplaat trial (Section 4.1).

Specific crop growth parameters were determined either from the field trial data (Section 4.1.3), or by calibration against measurements of growth, phenology, yield and water use. These are summarized in Table B1 (Appendix B). Only outer, green leaves were considered when leaf area index was measured, in order to determine specific leaf area, leaf-stem partition parameter and canopy radiation extinction coefficient. The parameters required to run the FAO model were determined using measurements of canopy cover and weather data (Section 4.1.4). These are summarized in Table B2 (Appendix B). The age of the seedling could affect the length of the initial stage for the FAO model.

Simulations were carried out using both the crop growth (Figure 5.59) and FAO model (Figure 5.60). Much lower values of dry matter production were predicted by SWB at the end of the growing season compared to measured data (Figure 5.59). It is possible that plant samples were not properly dried in the oven.

It is not clear why both the crop growth and FAO model overestimated soil water deficit during the mid-season stage of the crop, as fractional interception of radiation was simulated accurately using both models (Figure 5.61). A possible reason could have been capillary rise which reduced the actual soil water deficit determined from soil water content measurements with the neutron water meter. Capillary rise cannot be accounted for in the cascading water movement of SWB. The crop did not show any visual symptoms of water stress during the mid-season stage. The update soil water content feature which is presented in detail in Section 6.2.6, could be used to correct real-time soil water balance predictions with SWB using field measurements.

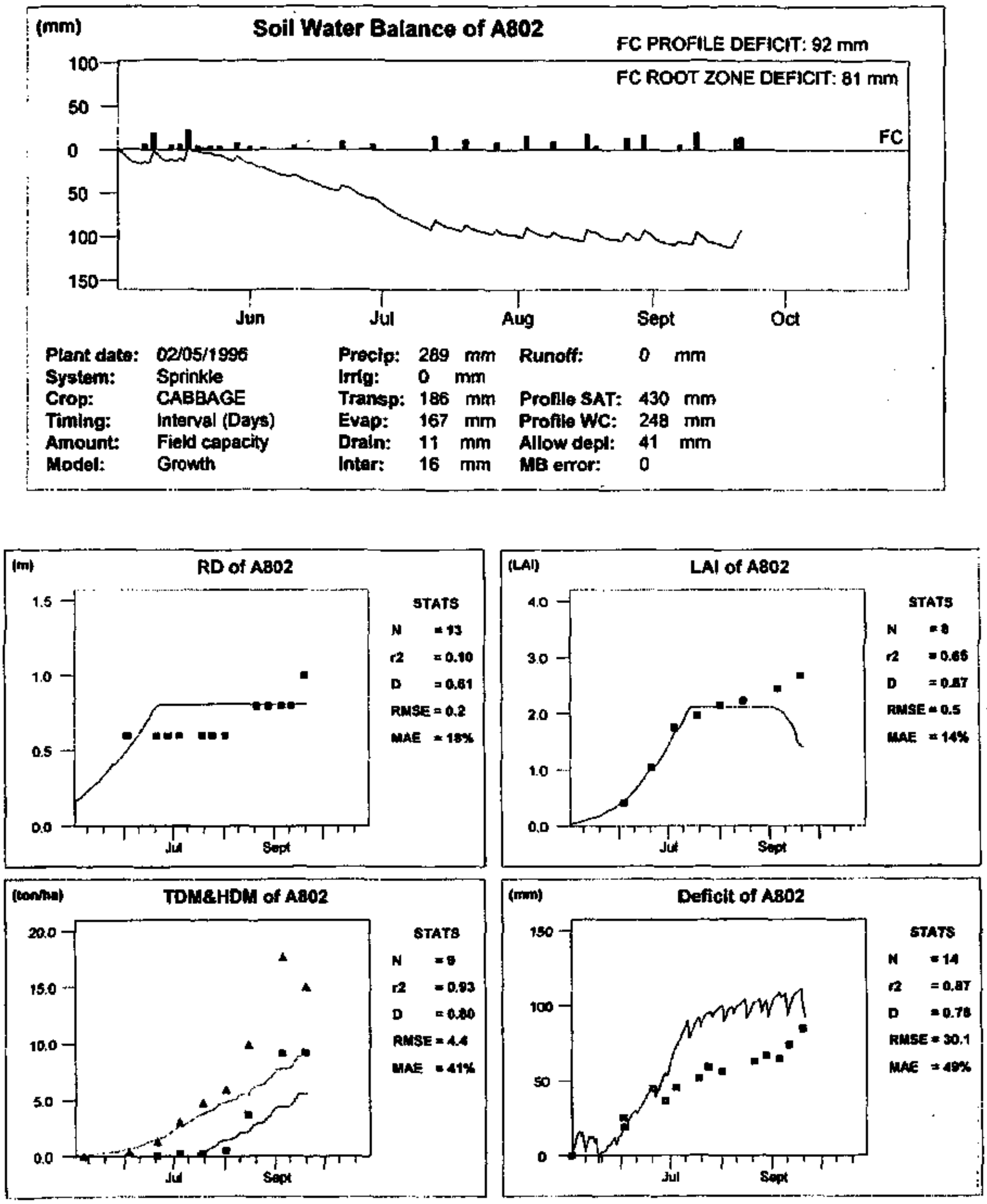


Figure 5.59

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Cabbage
Input data set: Roodeplaat field trial (Section 4.1)
Model type: Crop growth

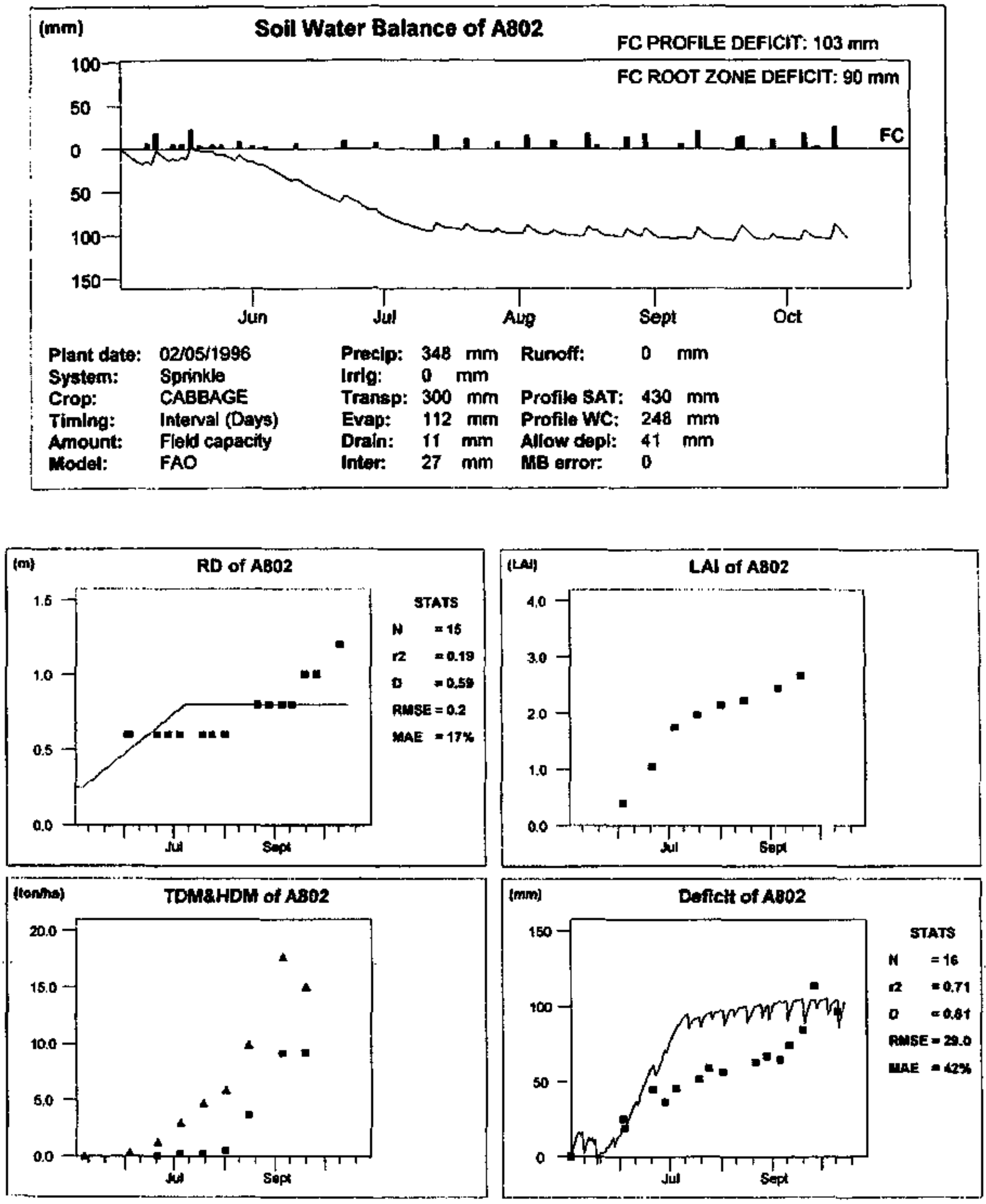


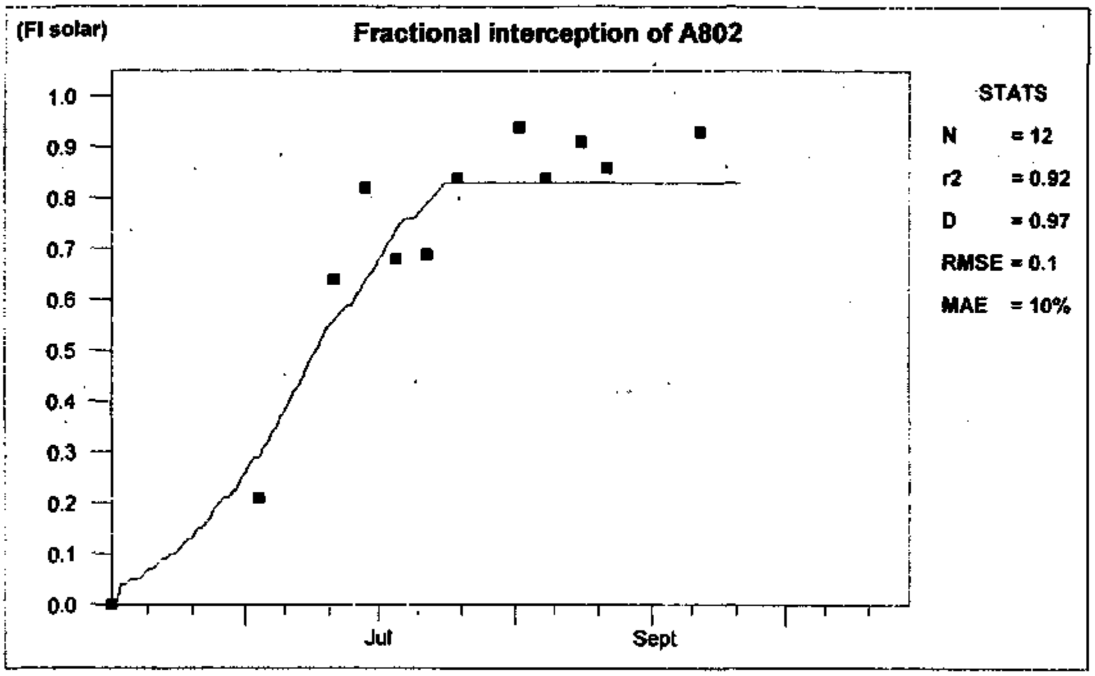
Figure 5.60

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Cabbage

Input data set: Roodeplaat field trial (Section 4.1)

Model type: FAO



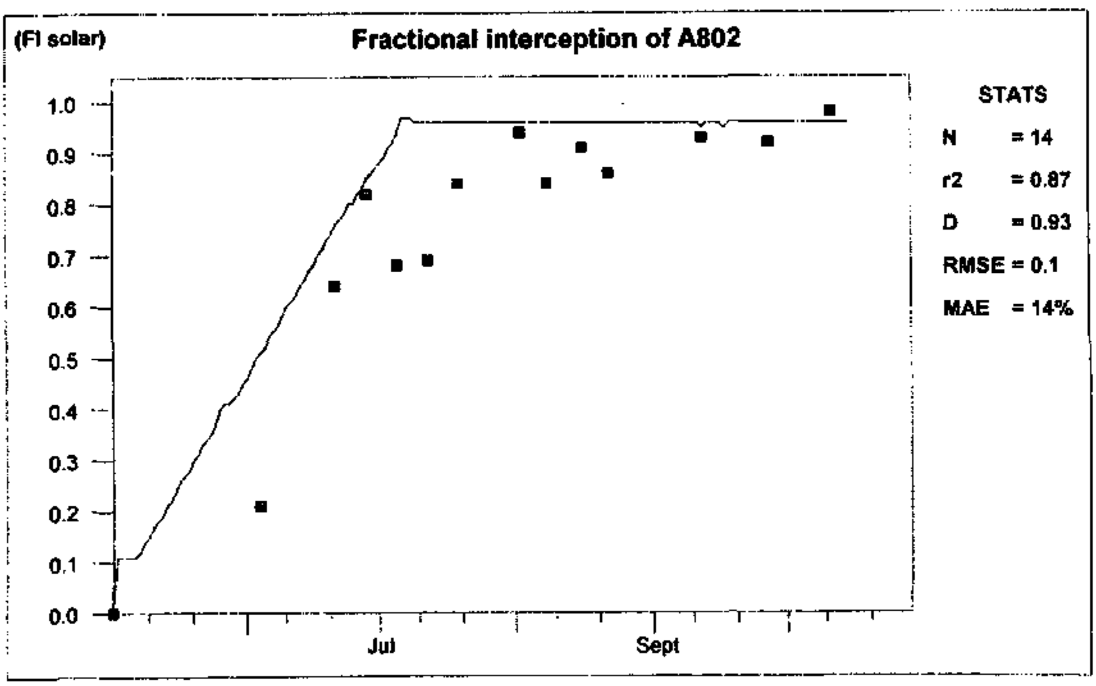


Figure 5.61

Simulated (solid line) and measured (symbols) fractional interception of radiation (FI solar). The top graph shows the simulation obtained with the crop growth model, whilst the bottom graph represents the simulation obtained with the FAO model.

Crop: Cabbage

Input data set: Roodeplaat field trial (Section 4.1)

5.2.5 Carrots

Data sets for the calibration of SWB were obtained from the Roodeplaat trial (Section 4.1).

Specific crop growth parameters were determined either from the field trial data (Section 4.1.3), or by calibration against measurements of growth, phenology, yield and water use. These are summarized in Table B1 (Appendix B). The parameters required to run the FAO model were determined using measurements of canopy cover and weather data (Section 4.1.4). These are summarized in Table B2 (Appendix B).

Simulations were carried out using both the crop growth (Figure 5.62) and FAO model (Figure 5.63). Much lower values of dry matter production were predicted by SWB at the end of the growing season compared to measured data (Figure 5.62). It is possible that plant samples were not properly dried in the oven.

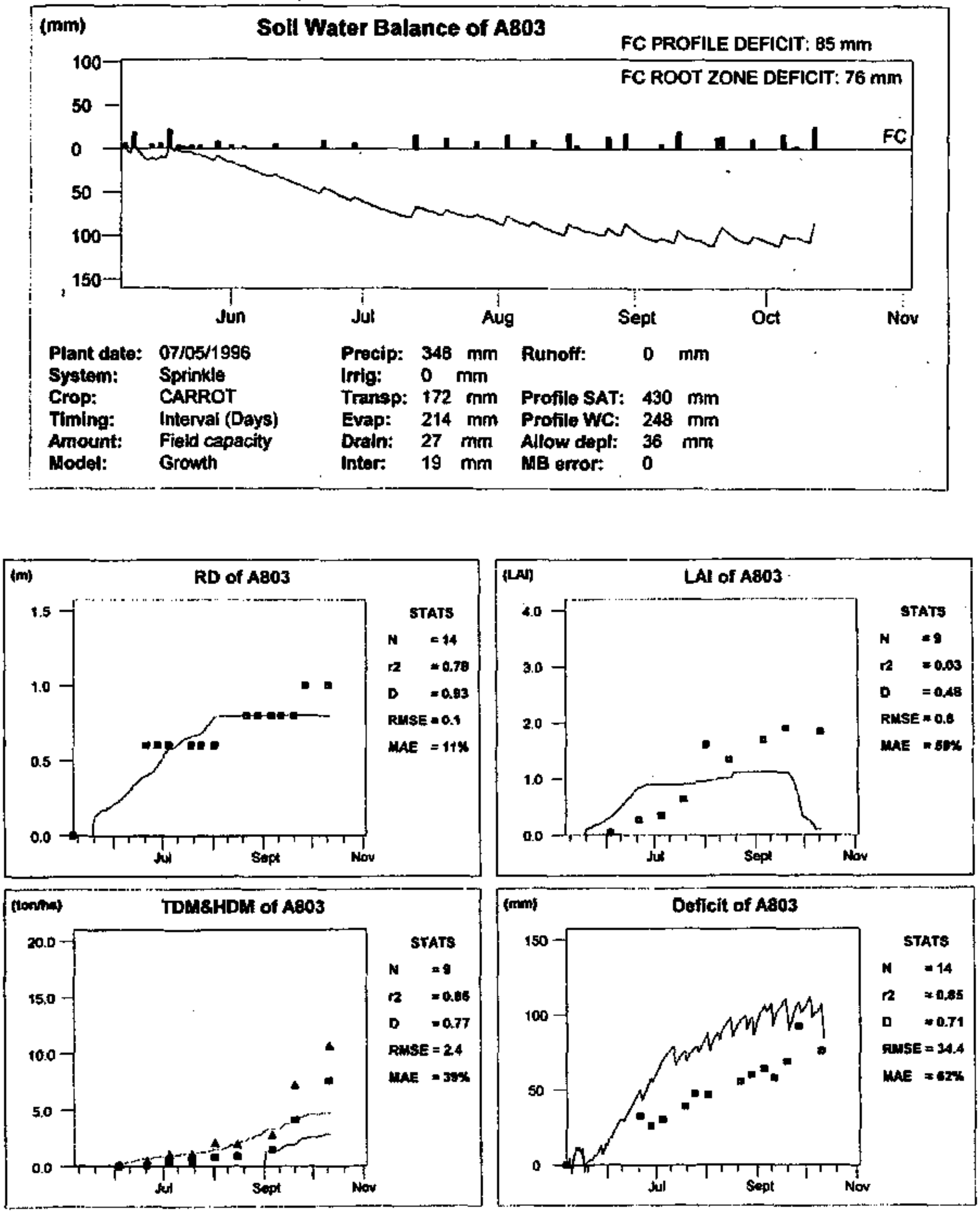


Figure 5.62

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Carrots
Input data set: Roodeplaat field trial (Section 4.1)
Model type: Crop growth

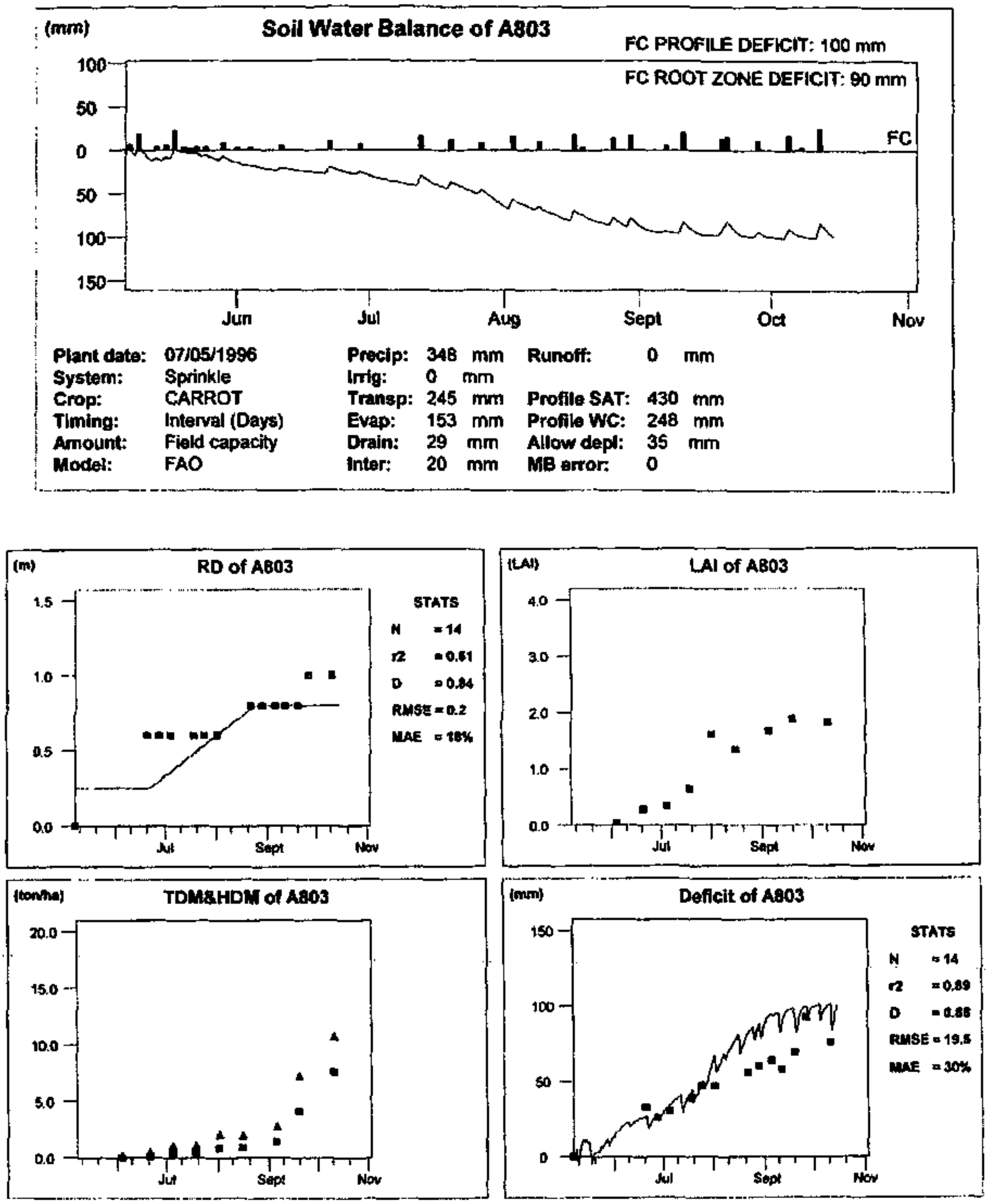


Figure 5.63

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Carrots

Input data set: Roodeplaat field trial (Section 4.1)

Model type: FAO

5.2.6 Eggplant

Data sets for the calibration of SWB were obtained from the Roodeplaat trial (Section 4.1).

Specific crop growth parameters were determined either from the field trial data (Section 4.1.3), or by calibration against measurements of growth, phenology, yield and water use. These are summarized in Table B1 (Appendix B). The parameters required to run the FAO model were determined using measurements of canopy cover and weather data (Section 4.1.4). These are summarized in Table B2 (Appendix B). The age of the seedling could affect the length of the initial stage for the FAO model.

Simulations were carried out using both the crop growth (Figure 5.64) and FAO model (Figure 5.65). The model predicted crop growth and soil water deficit reasonably well. Discrepancies between measured data and simulations of crop growth could have been caused by spatial variability. No replications were taken for growth analysis due to the small plot size. It was not possible to obtain a reliable simulation of dry matter production as fruits were harvested during the growing season.

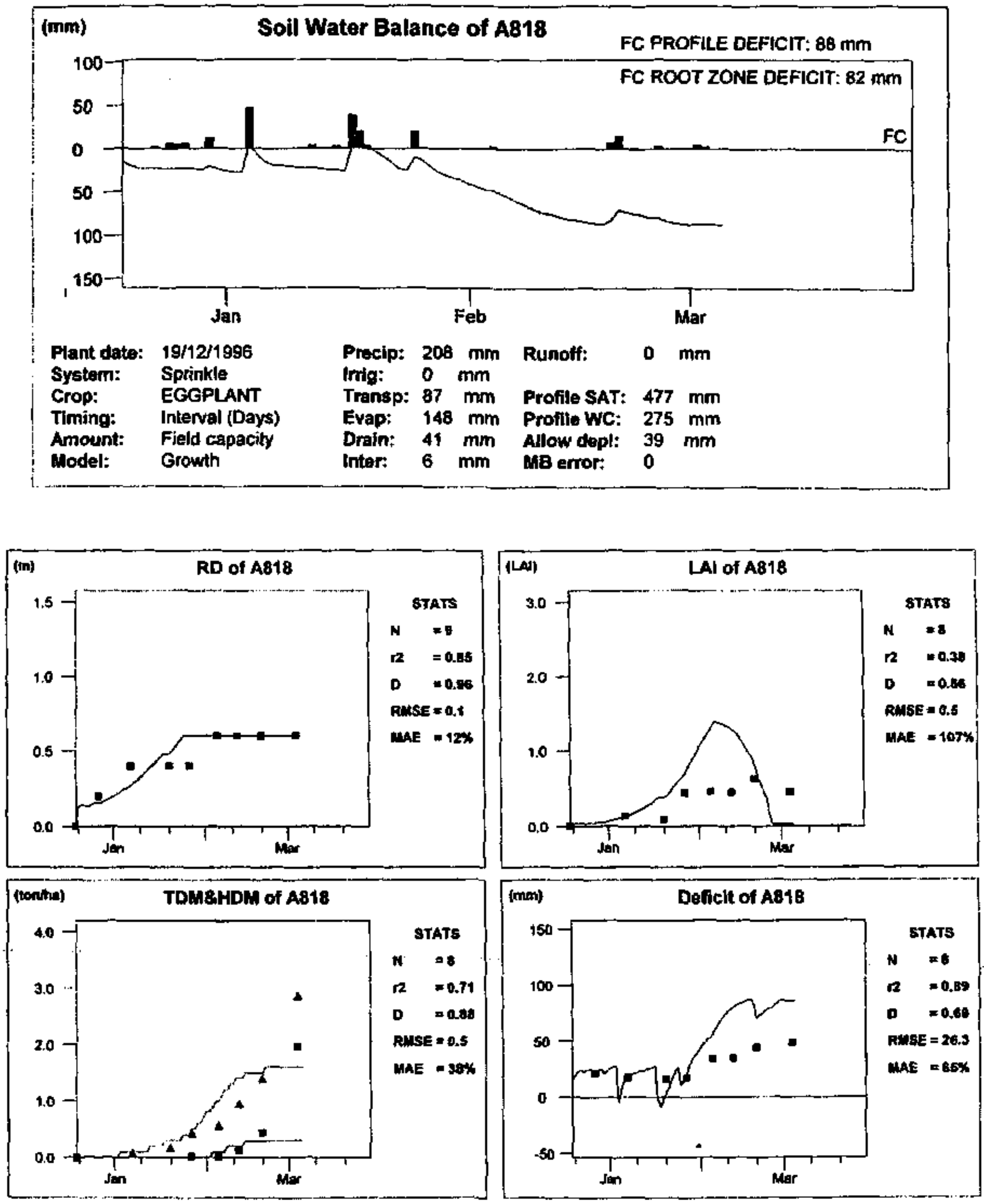


Figure 5.64

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Eggplant

Input data set: Roodeplaat field trial (Section 4.1)

Model type: Crop growth

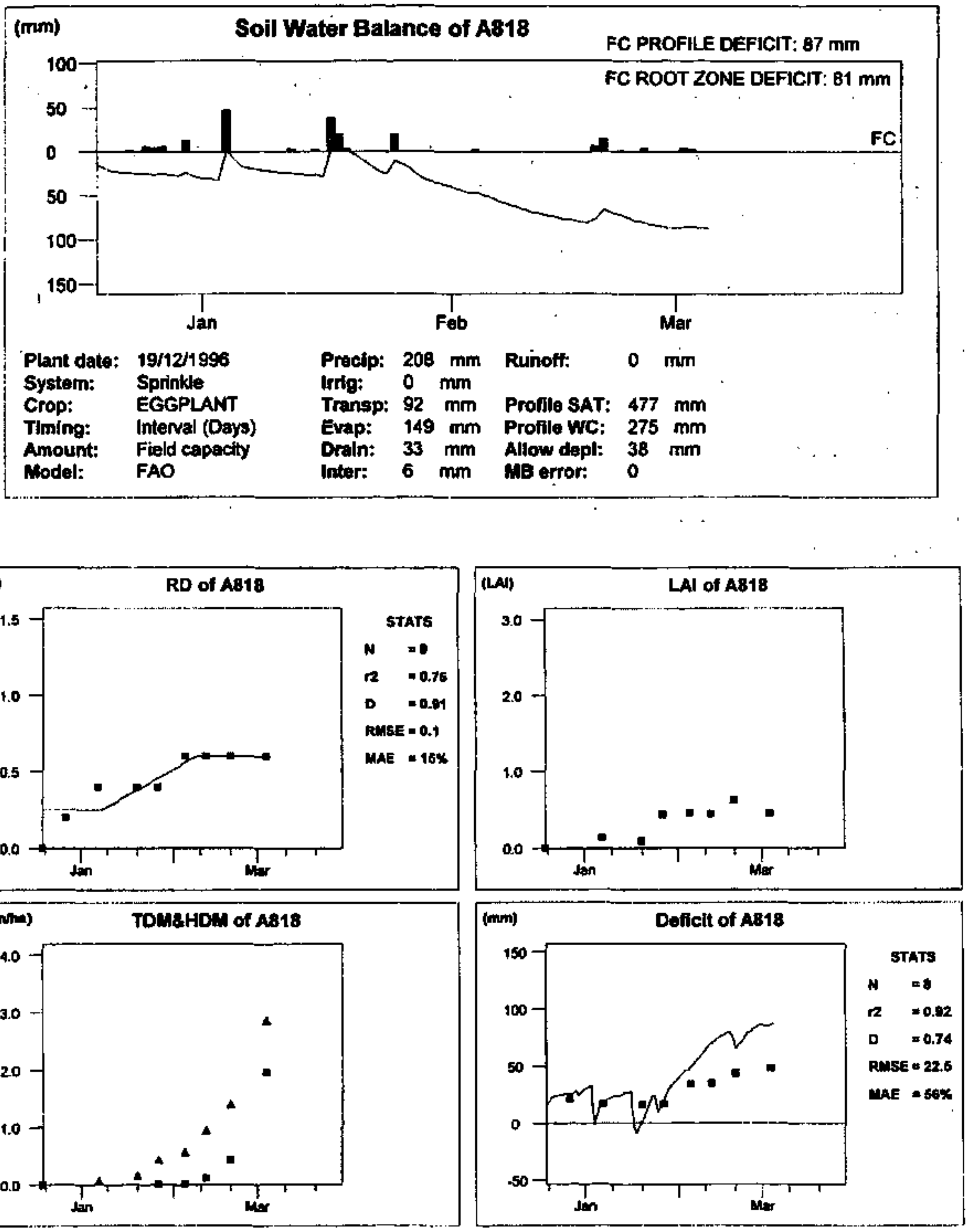


Figure 5.65

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Eggplant
Input data set: Roodeplaat field trial (Section 4.1)
Model type: FAO

5.2.7 Lettuce

Data sets for the calibration of SWB were obtained from the Roodeplaat trial (Section 4.1).

Specific crop growth parameters were determined either from the field trial data (Section 4.1.3), or by calibration against measurements of growth, phenology, yield and water use. These are summarized in Table B1 (Appendix B). Only outer, green leaves were considered when leaf area index was measured in order to determine specific leaf area, leaf-stem partition parameter and canopy radiation extinction coefficient. The parameters required to run the FAO model were determined using measurements of canopy cover and weather data (Section 4.1.4). These are summarized in Table B2 (Appendix B). The age of the seedling could affect the length of the initial stage for the FAO model.

Simulations were carried out using both the crop growth (Figure 5.66) and FAO model (Figure 5.67). The model was successfully calibrated for LAI and soil water deficit. Much lower values of dry matter production were predicted by SWB at the end of the growing season compared to measured data (Figure 5.66). It is possible that plant samples were not properly dried in the oven.

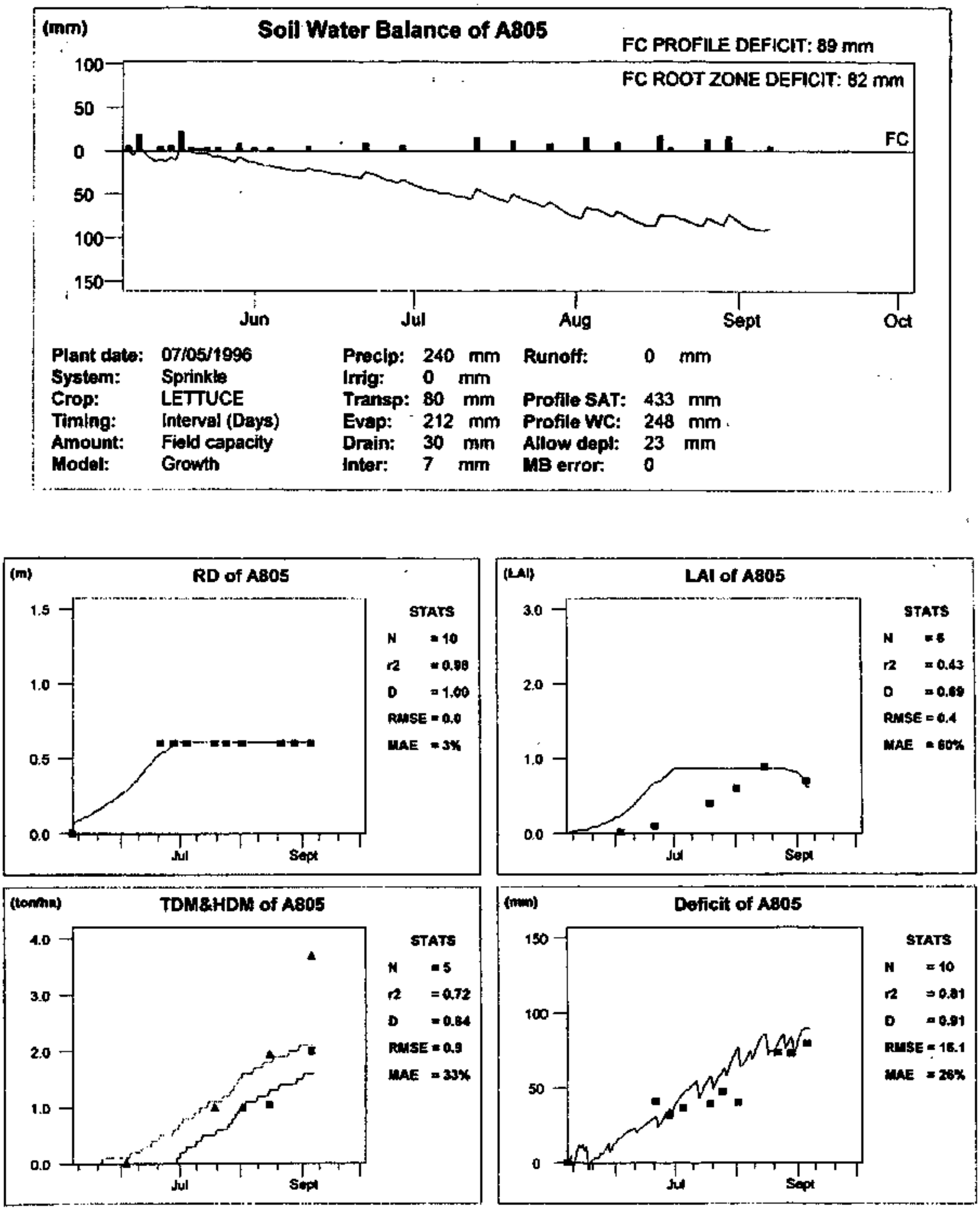


Figure 5.66

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Lettuce
Input data set: Roodeplaat field trial (Section 4.1)
Model type: Crop growth

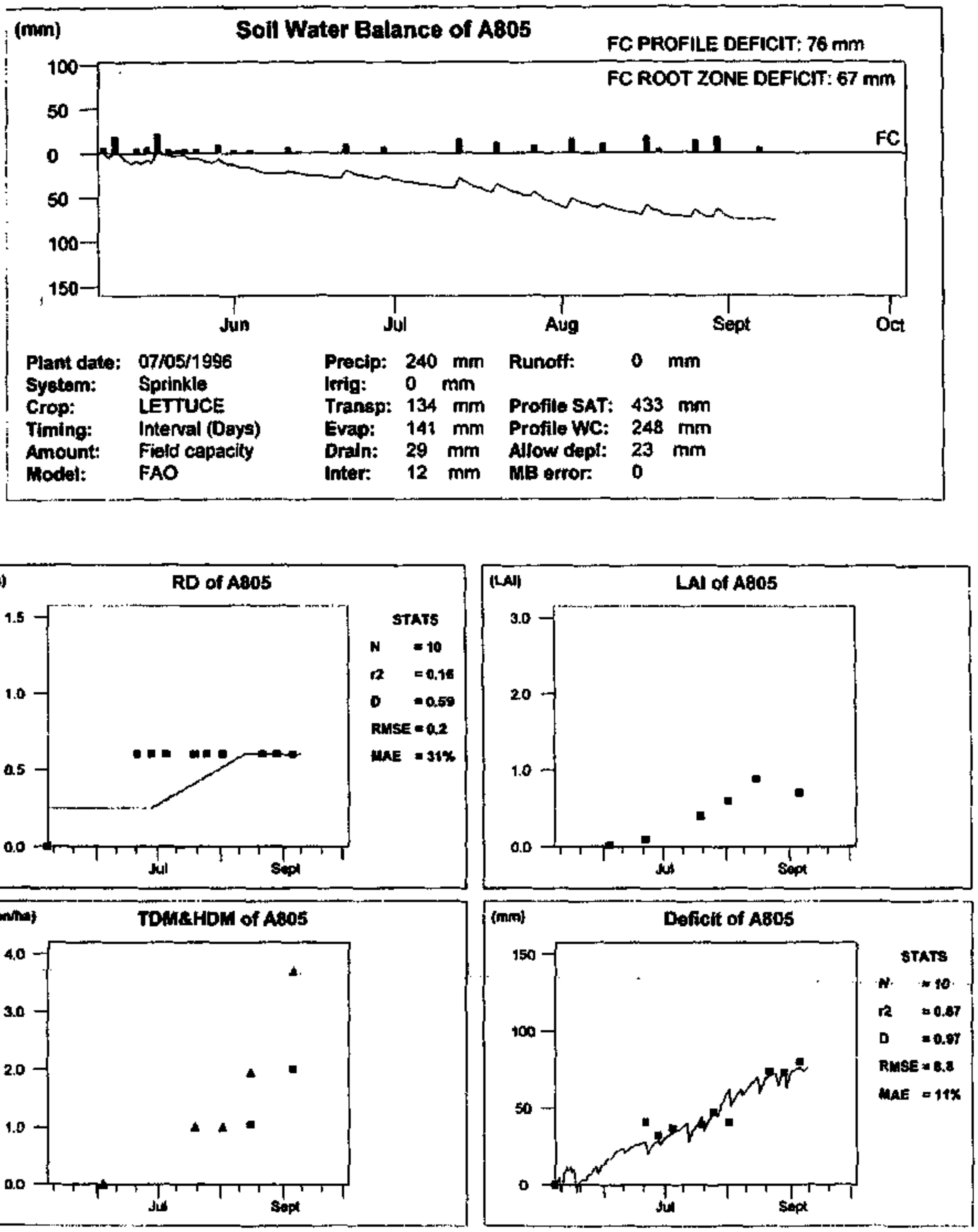


Figure 5.67

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Lettuce

Input data set: Roodeplaat field trial (Section 4.1)

Model type: FAO

5.2.8 Marrow

Data sets for the calibration of SWB were obtained from the Roodeplaat trial (Section 4.1).

Specific crop growth parameters were determined either from the field trial data (Section 4.1.3), or by calibration against measurements of growth, phenology, yield and water use. These are summarized in Table B1 (Appendix B). The parameters required to run the FAO model were determined using measurements of canopy cover and weather data (Section 4.1.4). These are summarized in Table B2 (Appendix B). The age of the seedling could affect the length of the initial stage for the FAO model.

Simulations were carried out using both the crop growth and FAO model for cv. Long White Bush (Figures 5.68 and 5.69) and cv. President (Figure 5.70 and 5.71). The model predicted crop growth and soil water deficit reasonably well. Discrepancies between measured data and simulations of crop growth could have been caused by spatial variability. No replications were taken for growth analysis due to the small plot size. It was not possible to obtain a reliable simulation of dry matter production as fruits were harvested during the growing season.

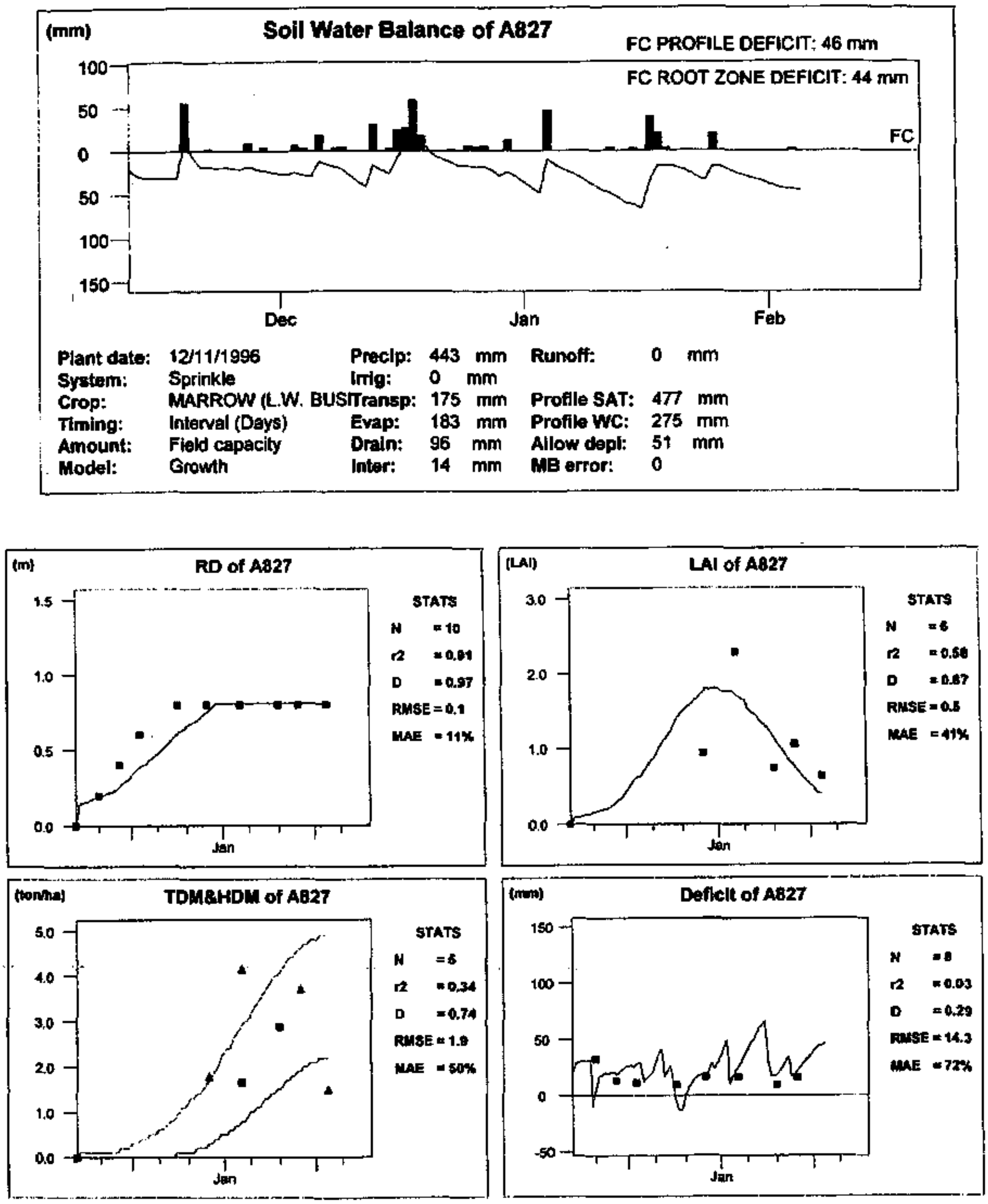


Figure 5.68

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Marrow (cv. Long White Bush)

Input data set: Roodeplaat field trial (Section 4.1)

Model type: Crop growth

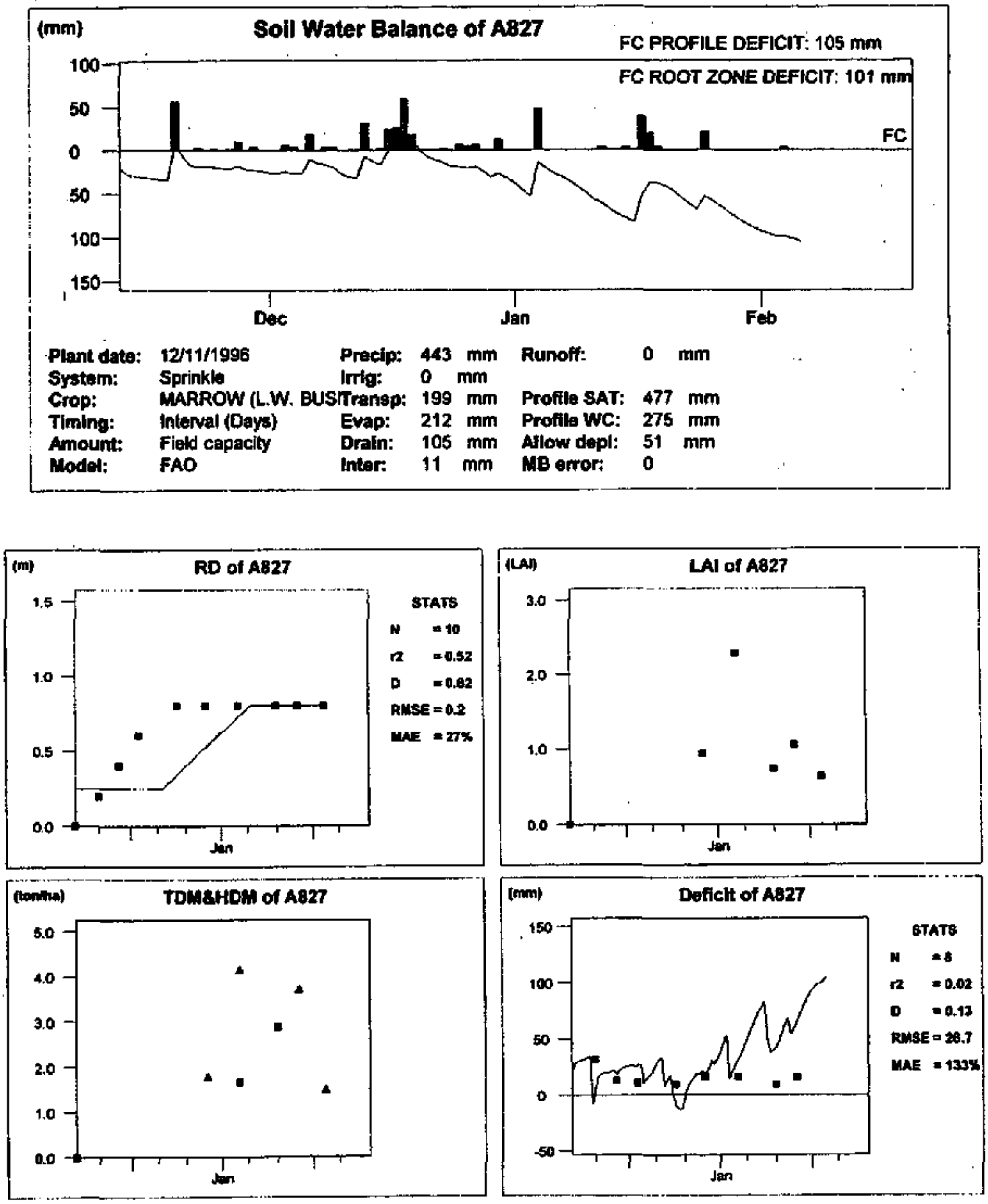


Figure 5.69

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Marrow (cv. Long White Bush)

Input data set: Roodeplaat field trial (Section 4.1)

Model type: FAO

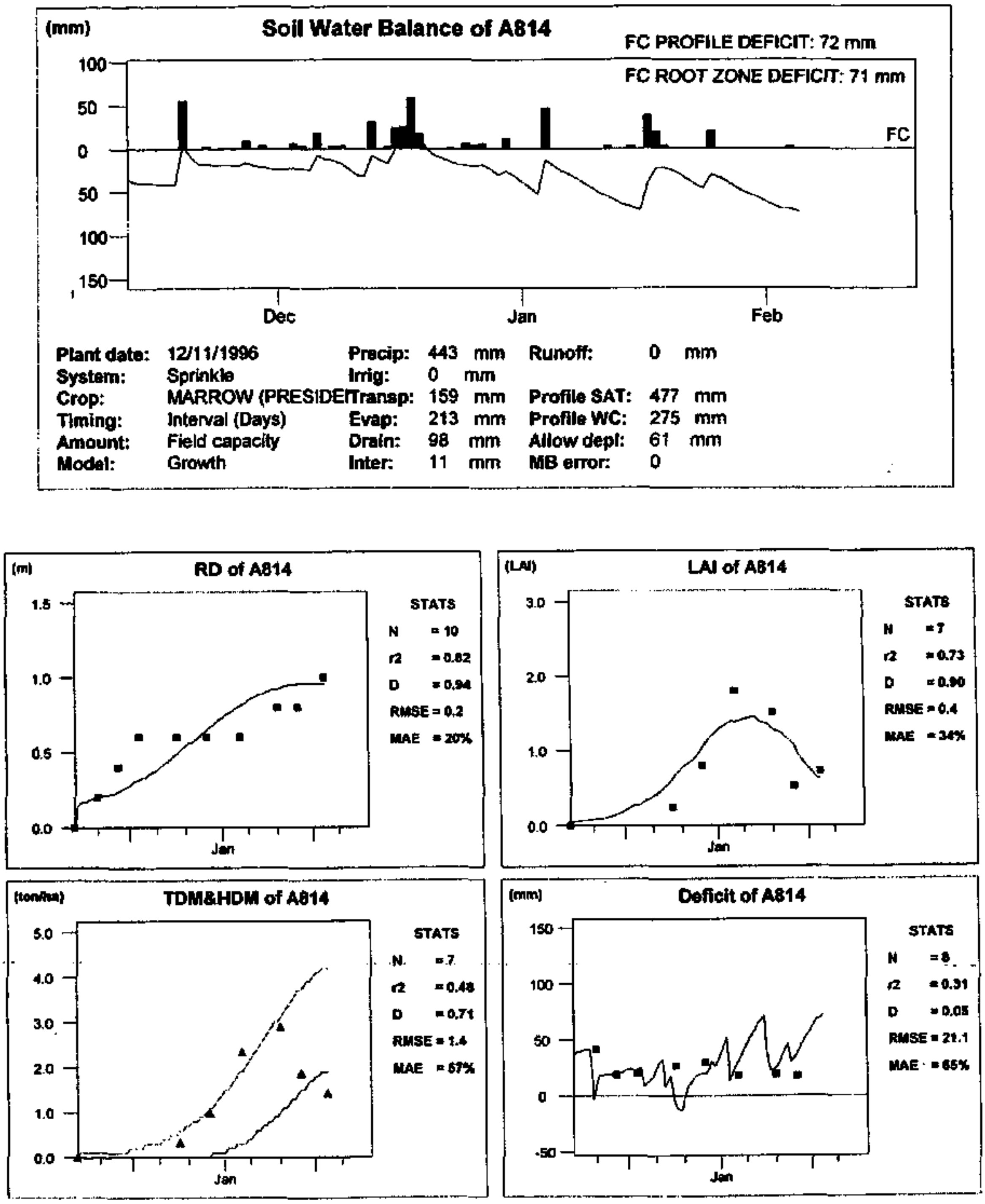


Figure 5.70

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Marrow (cv. President)
Input data set: Roodeplaat field trial (Section 4.1)
Model type: Crop growth

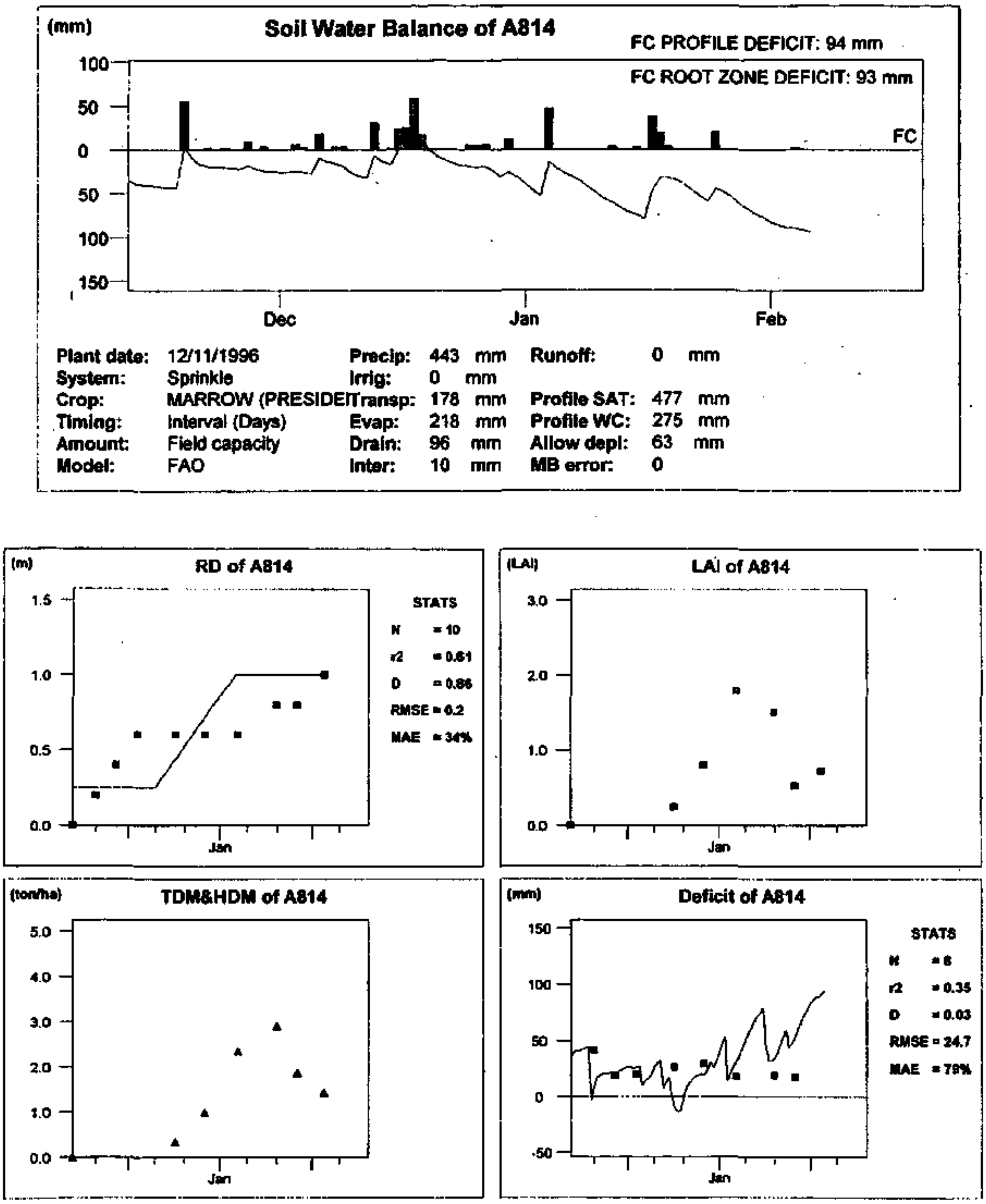


Figure 5.71

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Marrow (cv. President)
Input data set: Roodeplaat field trial (Section 4.1)
Model type: FAO

5.2.9 Onions

Data sets for the calibration of SWB were obtained from the Roodeplaat trial (Section 4.1).

Specific crop growth parameters were determined either from the field trial data (Section 4.1.3), or by calibration against measurements of growth, phenology, yield and water use. These are summarized in Table B1 (Appendix B). The parameters required to run the FAO model were determined using measurements of canopy cover and weather data (Section 4.1.4). These are summarized in Table B2 (Appendix B). The age of the seedling could affect the length of the initial stage for the FAO model.

Simulations were carried out using both the crop growth (Figure 5.72) and FAO model (Figure 5.73). The model was successfully calibrated for soil water deficit. Much lower values of dry matter production were predicted by SWB at the end of the growing season compared to measured data (Figure 5.72). It is possible that plant samples were not properly dried in the oven.

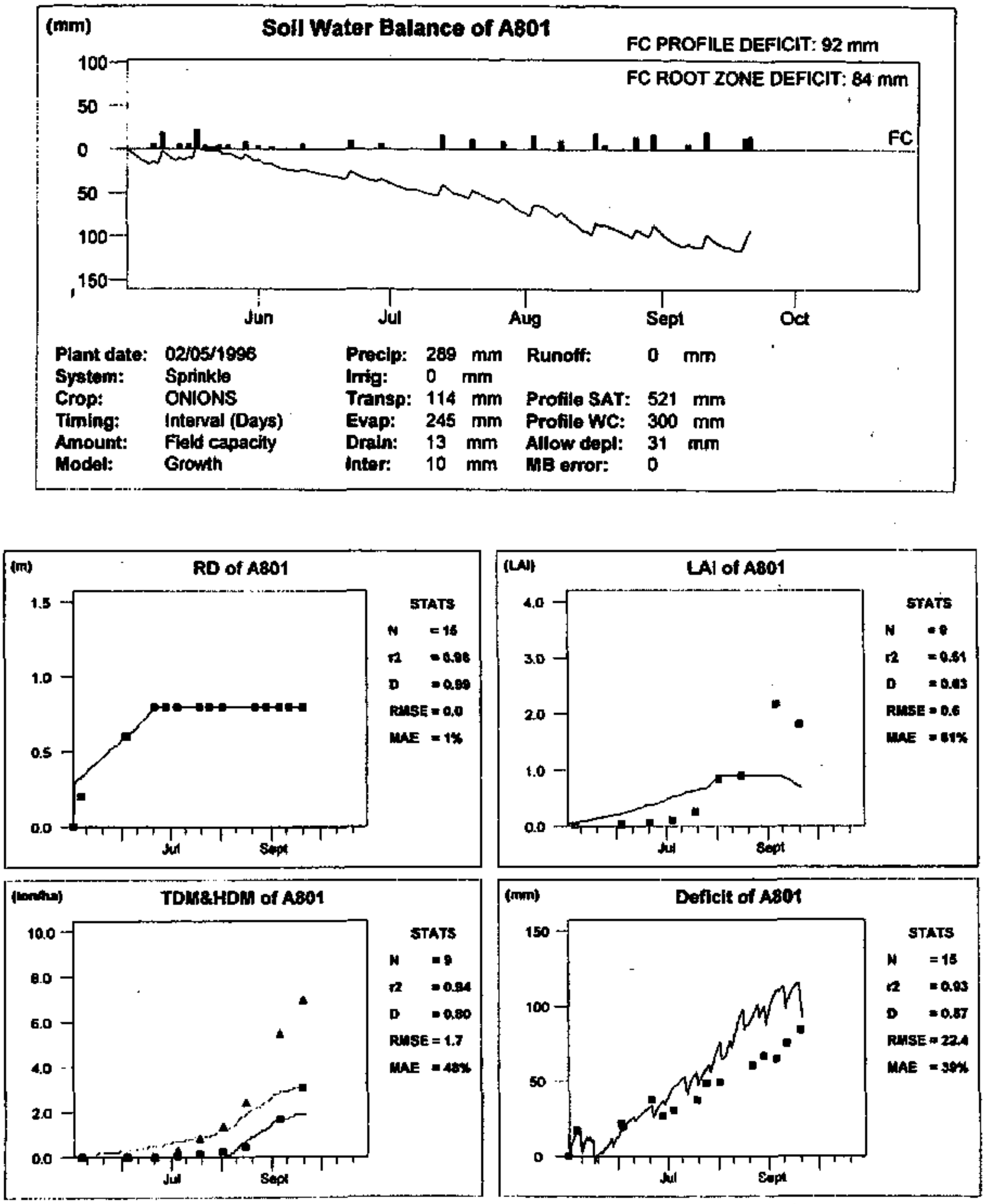


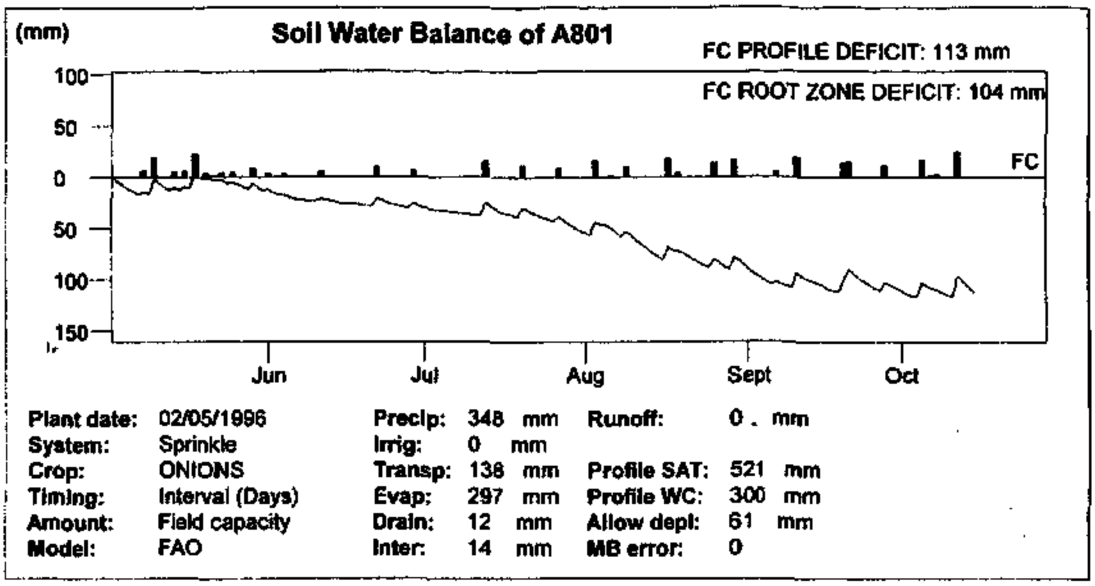
Figure 5.72

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Onions

Input data set: Roodeplaat field trial (Section 4.1)

Model type: Crop growth



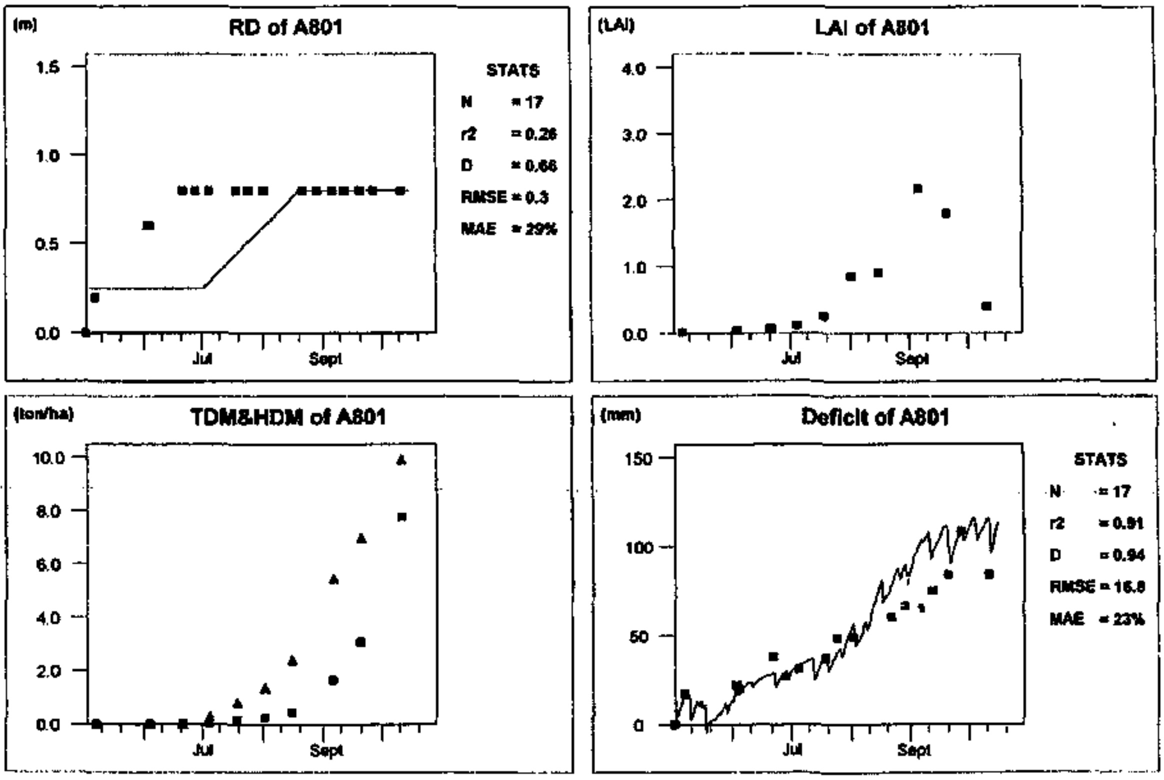


Figure 5.73

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Onions

Input data set: Roodeplaat field trial (Section 4.1)

Model type: FAO

5.2.10 Pepper (chilli)

Data sets for the calibration of SWB were obtained from the Roodeplaat trial (Section 4.1).

Specific crop growth parameters were determined either from the field trial data (Section 4.1.3), or by calibration against measurements of growth, phenology, yield and water use. These are summarized in Table B1 (Appendix B). The parameters required to run the FAO model were determined using measurements of canopy cover and weather data (Section 4.1.4). These are summarized in Table B2 (Appendix B). The age of the seedling could affect the length of the initial stage for the FAO model.

Simulations were carried out using both the crop growth (Figure 5.74) and FAO model (Figure 5.75). The model predicted crop growth and soil water deficit reasonably well. It was not possible to obtain a reliable simulation of dry matter production as fruits were harvested during the growing season.

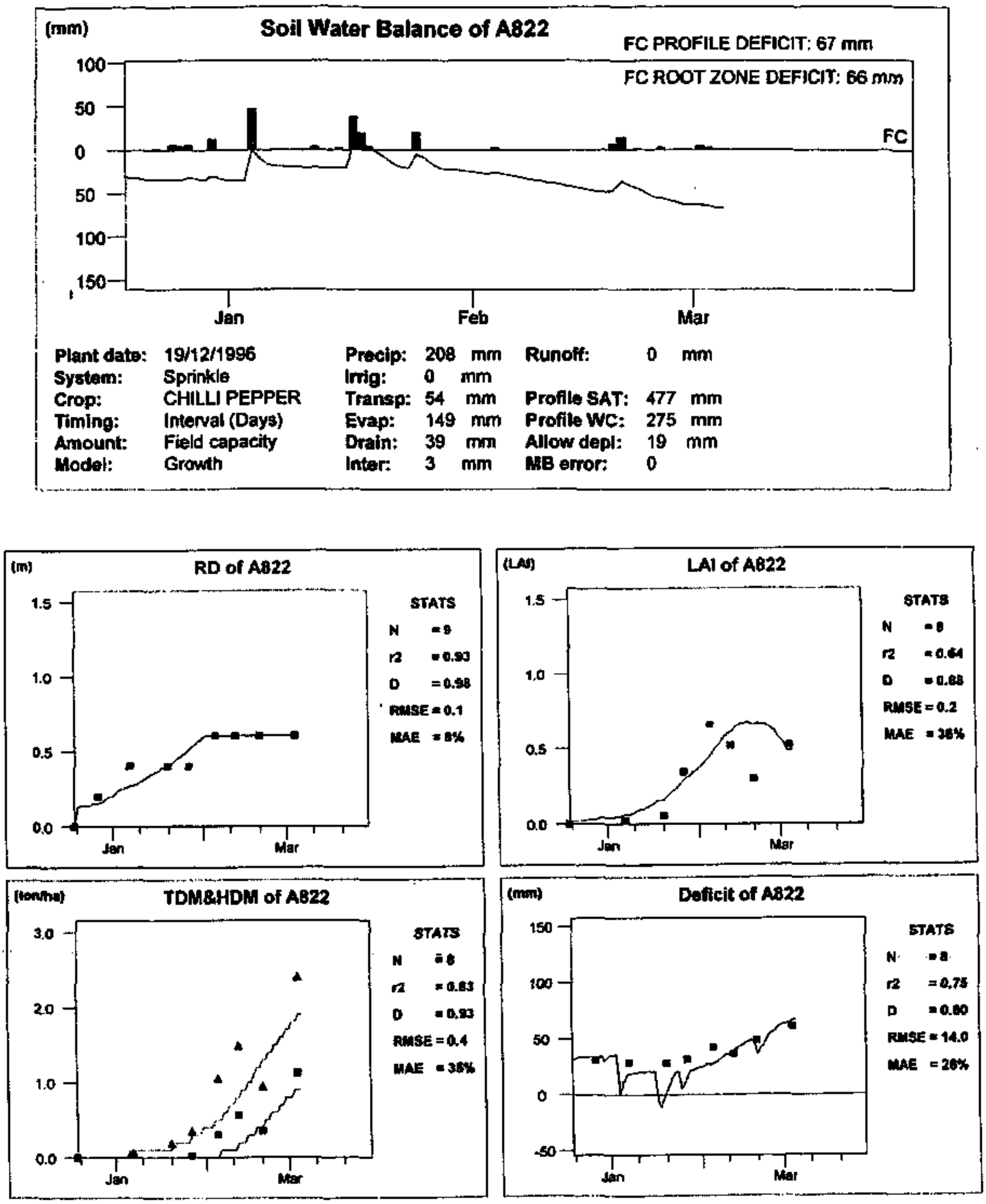


Figure 5.74

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Chilli pepper

Input data set: Roodeplaat field trial (Section 4.1)

Model type: Crop growth

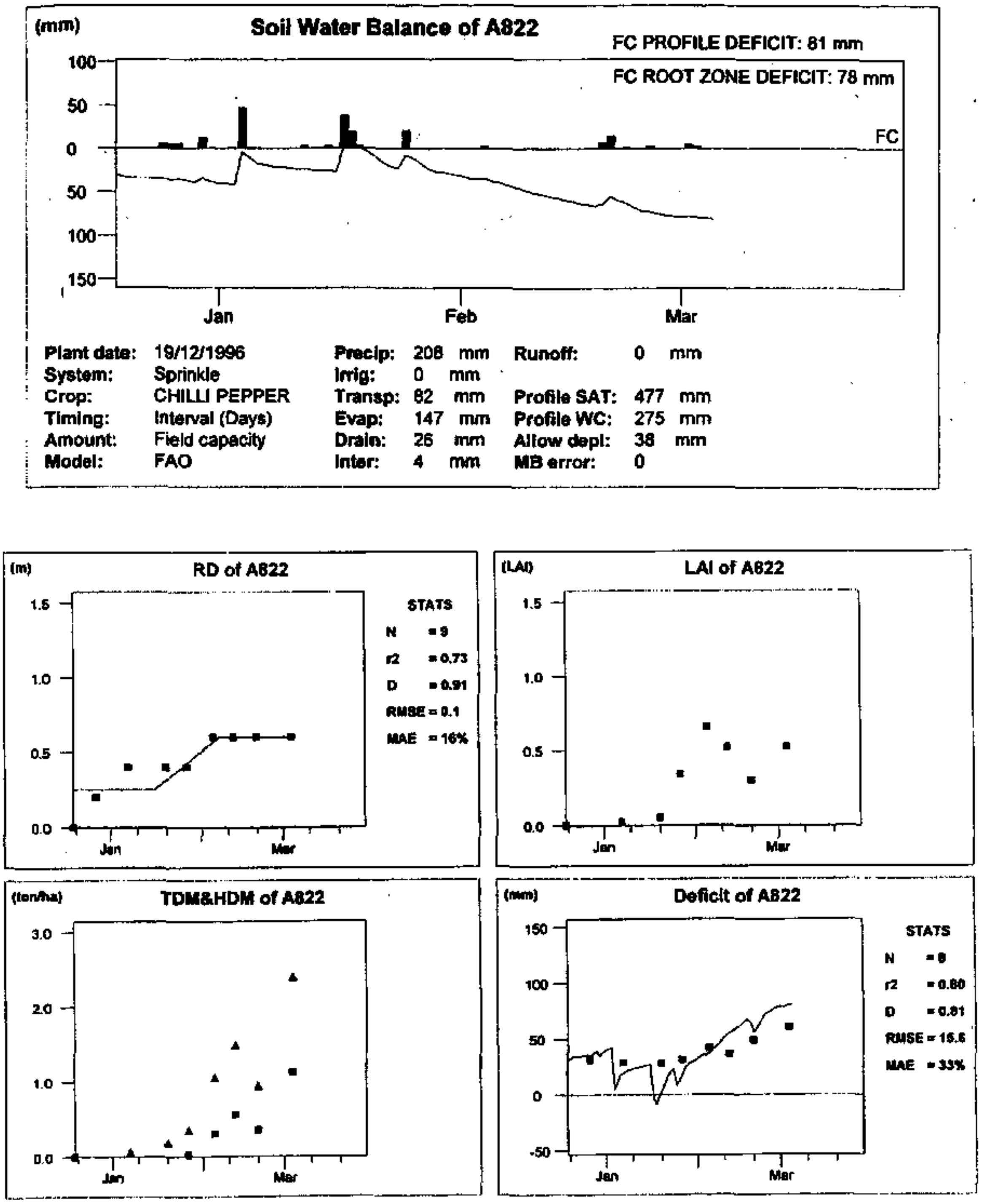


Figure 5.75

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Chilli pepper

Input data set: Roodeplaat field trial (Section 4.1)

Model type: FAO

5.2.11 Pepper (green)

Data sets for the calibration of SWB were obtained from the Roodeplaat trial (Section 4.1).

Specific crop growth parameters were determined either from the field trial data (Section 4.1.3), or by calibration against measurements of growth, phenology, yield and water use. These are summarized in Table B1 (Appendix B). The parameters required to run the FAO model were determined using measurements of canopy cover and weather data (Section 4.1.4). These are summarized in Table B2 (Appendix B). The age of the seedling could affect the length of the initial stage for the FAO model.

Simulations were carried out using both the crop growth (Figure 5.76) and FAO model (Figure 5.77). The model predicted crop growth and soil water deficit very well.

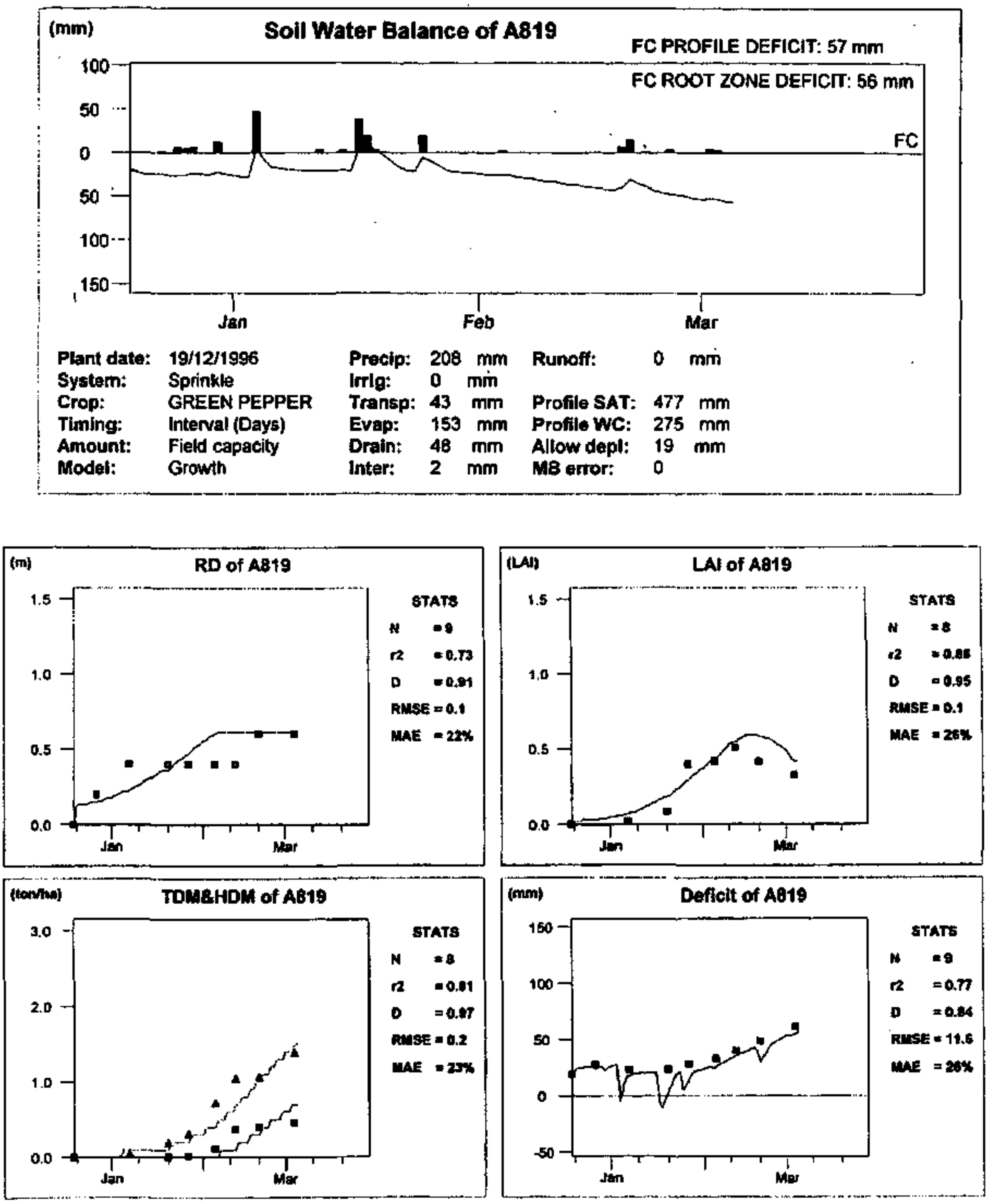


Figure 5.76

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Green pepper

Input data set: Roodeplaat field trial (Section 4.1)

Model type: Crop growth

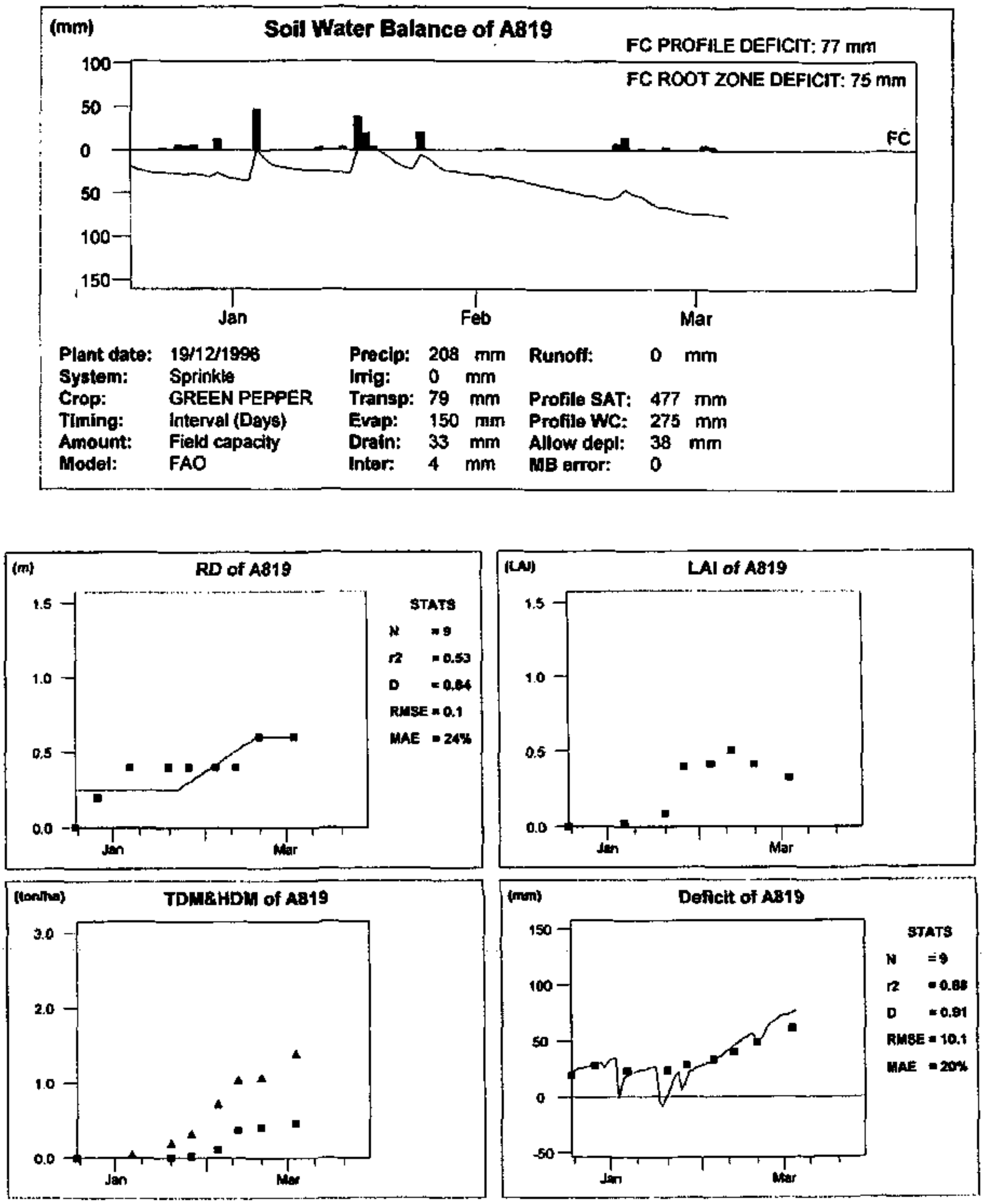


Figure 5.77

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Green pepper
Input data set: Roodeplaat field trial (Section 4.1)
Model type: FAO

5.2.12 Pumpkin

Data sets for the calibration of SWB were obtained from the Roodeplaat trial (Section 4.1).

Specific crop growth parameters were determined either from the field trial data (Section 4.1.3), or by calibration against measurements of growth, phenology, yield and water use. These are summarized in Table B1 (Appendix B). The parameters required to run the FAO model were determined using measurements of canopy cover and weather data (Section 4.1.4). These are summarized in Table B2 (Appendix B). The age of the seedling could affect the length of the initial stage for the FAO model.

Simulations were carried out using both the crop growth and FAO model for "Boer pampoen" cv. Minette (Figures 5.78 and 5.79) and cv. Miniboer (Figures 5.80 and 5.81). The crop growth model predicted LAI and soil water deficit reasonably well. It was not possible to obtain reliable simulations of dry matter production as fruits were harvested during the growing season. Reasonable simulations of soil water deficit with the FAO model were obtained.

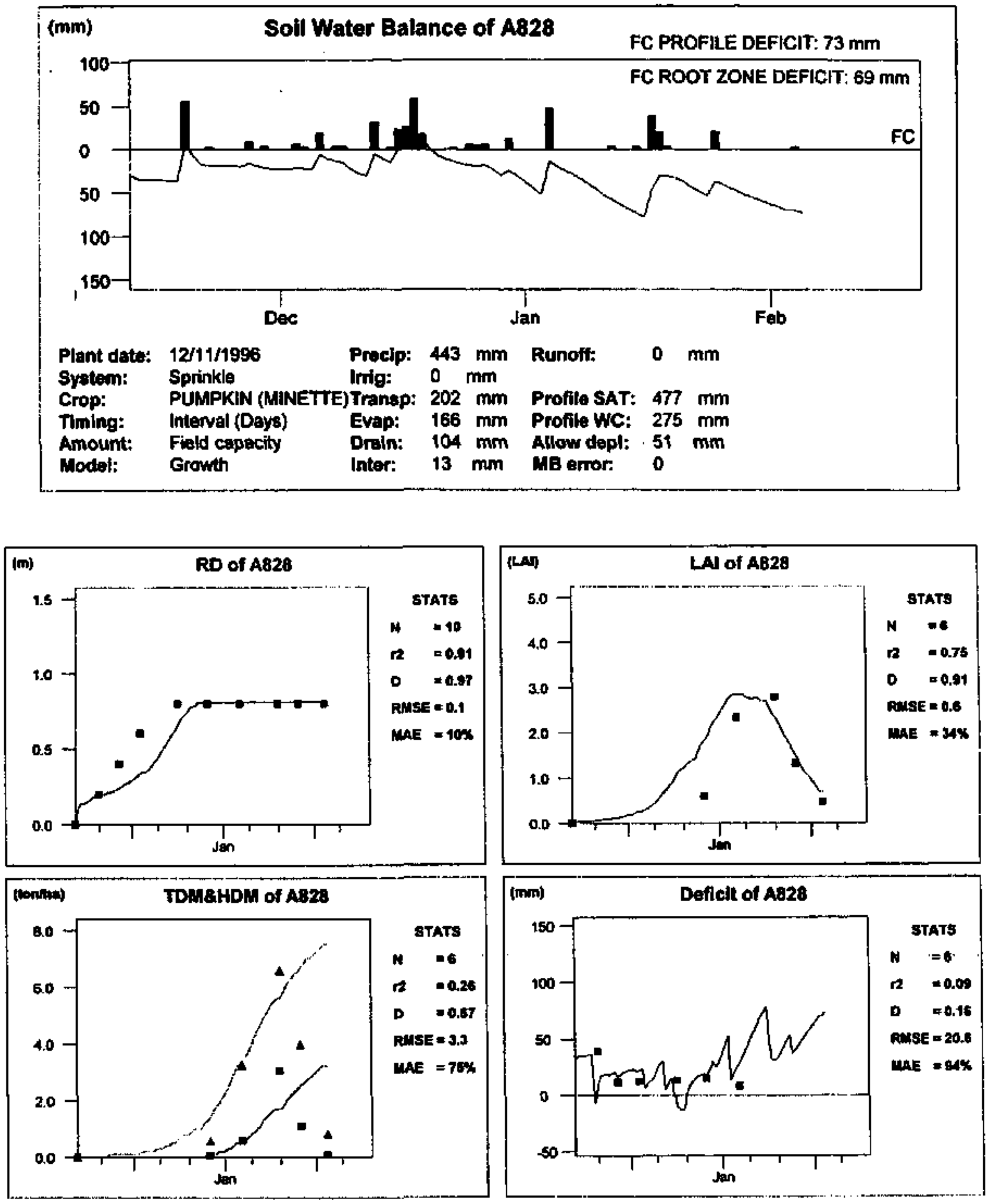


Figure 5.78

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Pumpkin (cv. Minette)

Input data set: Roodeplaat field trial (Section 4.1)

Model type: Crop growth

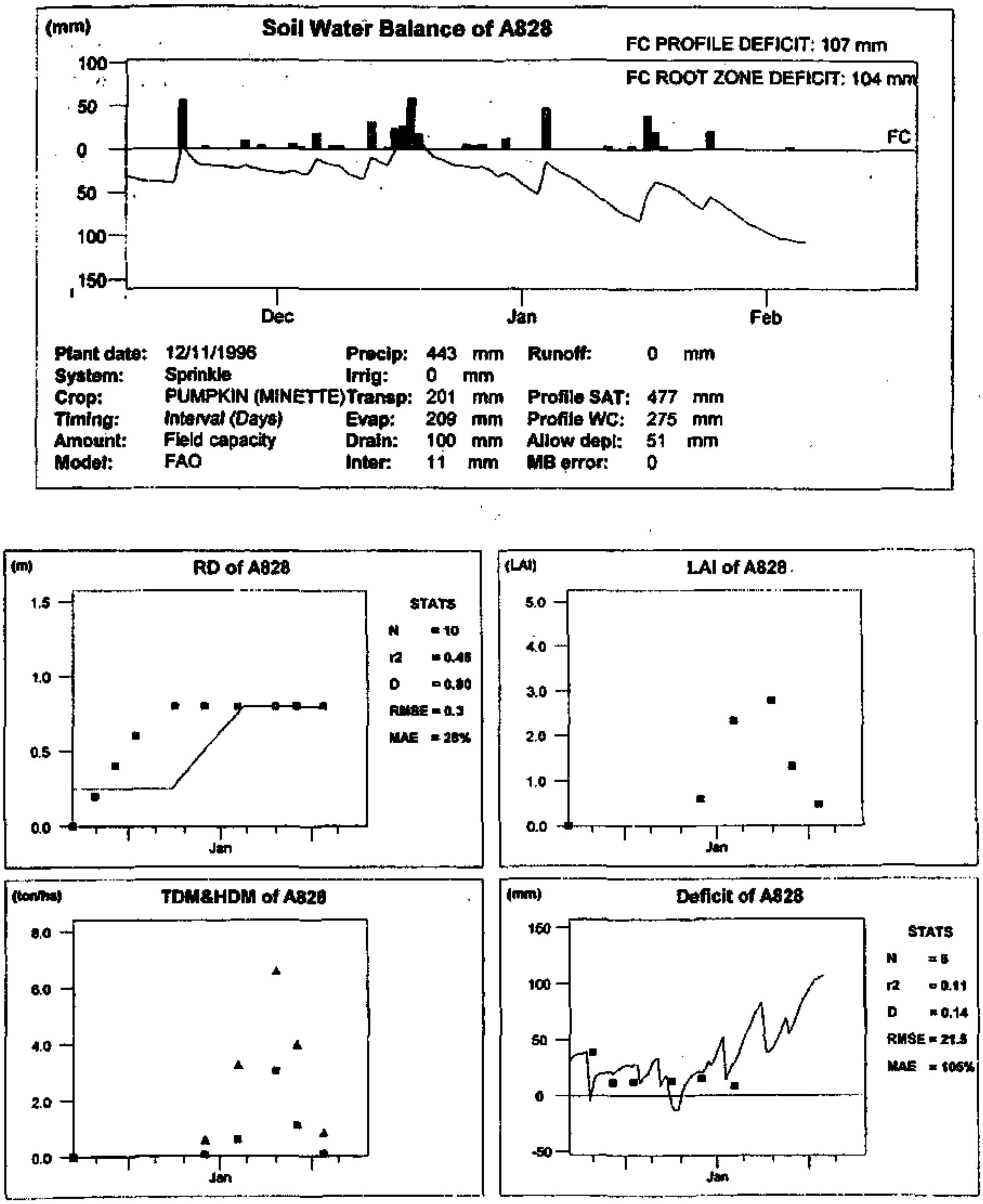


Figure 5.79

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Pumpkin (cv. Minette)

Input data set: Roodeplaat field trial (Section 4.1)

Model type: FAO

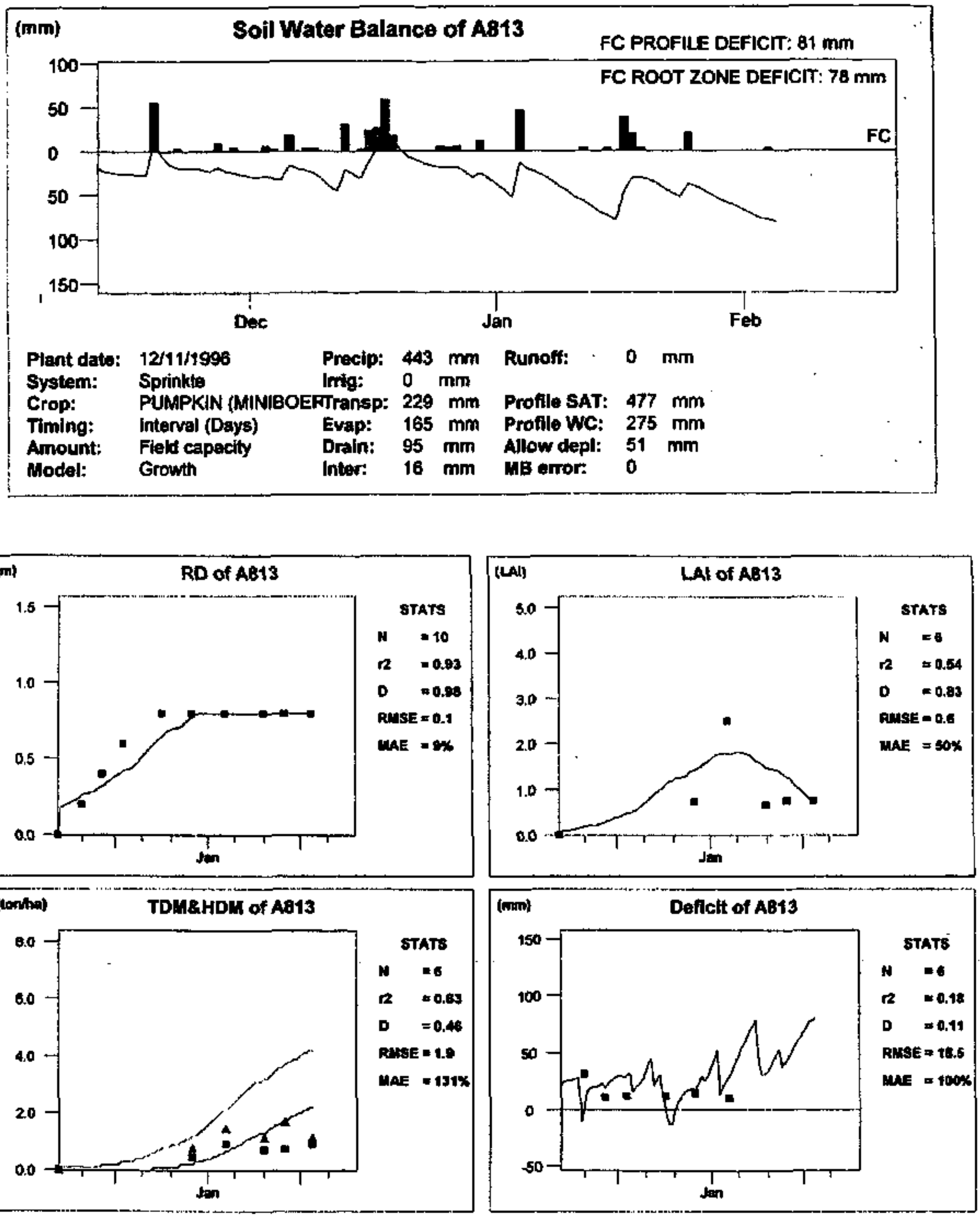


Figure 5.80

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Pumpkin (cv. Miniboer)

Input data set: Roodeplaat field trial (Section 4.1)

Model type: Crop growth

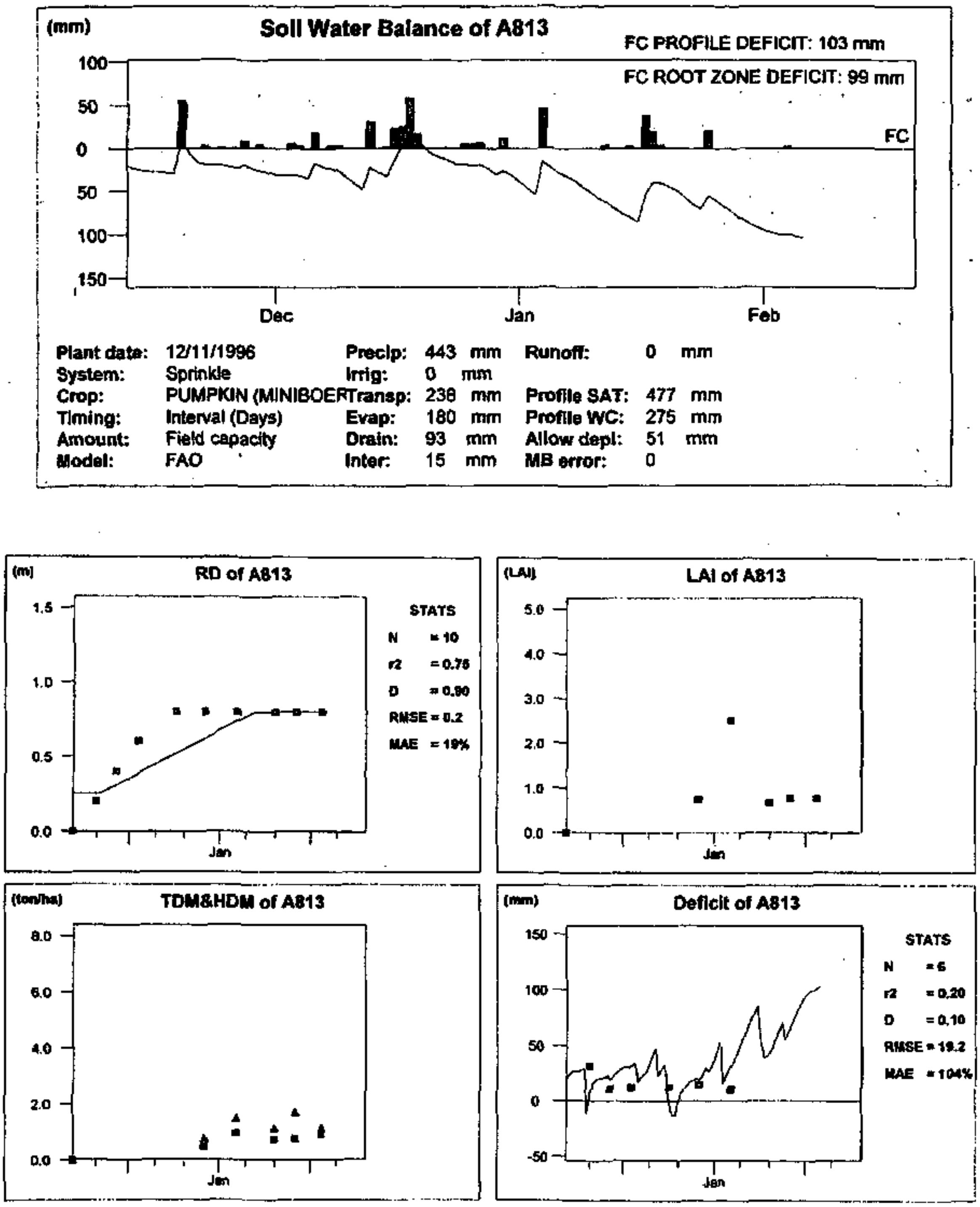


Figure 5.81

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Pumpkin (cv. Miniboer)

Input data set: Roodeplaat field trial (Section 4.1)

Model type: FAO

5.2.13 Squash

Data sets for the calibration of SWB were obtained from the Roodeplaat trial (Section 4.1).

Specific crop growth parameters were determined either from the field trial data (Section 4.1.3), or by calibration against measurements of growth, phenology, yield and water use. These are summarized in Table B1 (Appendix B). The parameters required to run the FAO model were determined using measurements of canopy cover and weather data (Section 4.1.4). These are summarized in Table B2 (Appendix B). The age of the seedling could affect the length of the initial stage for the FAO model.

Simulations were carried out using both the crop growth and FAO model for butternuts cv. Table Queen (Figure 5.82 and 5.83) and cv. Waltham (Figure 5.84 and 5.85). The model predicted soil water deficit reasonably well. Discrepancies between measured data and simulations of LAI could have been caused by spatial variability (Figures 5.82 and 5.84). No replications were taken for growth analysis due to the small plot size. It was not possible to obtain a reliable simulation of dry matter production as fruits were harvested during the growing season.

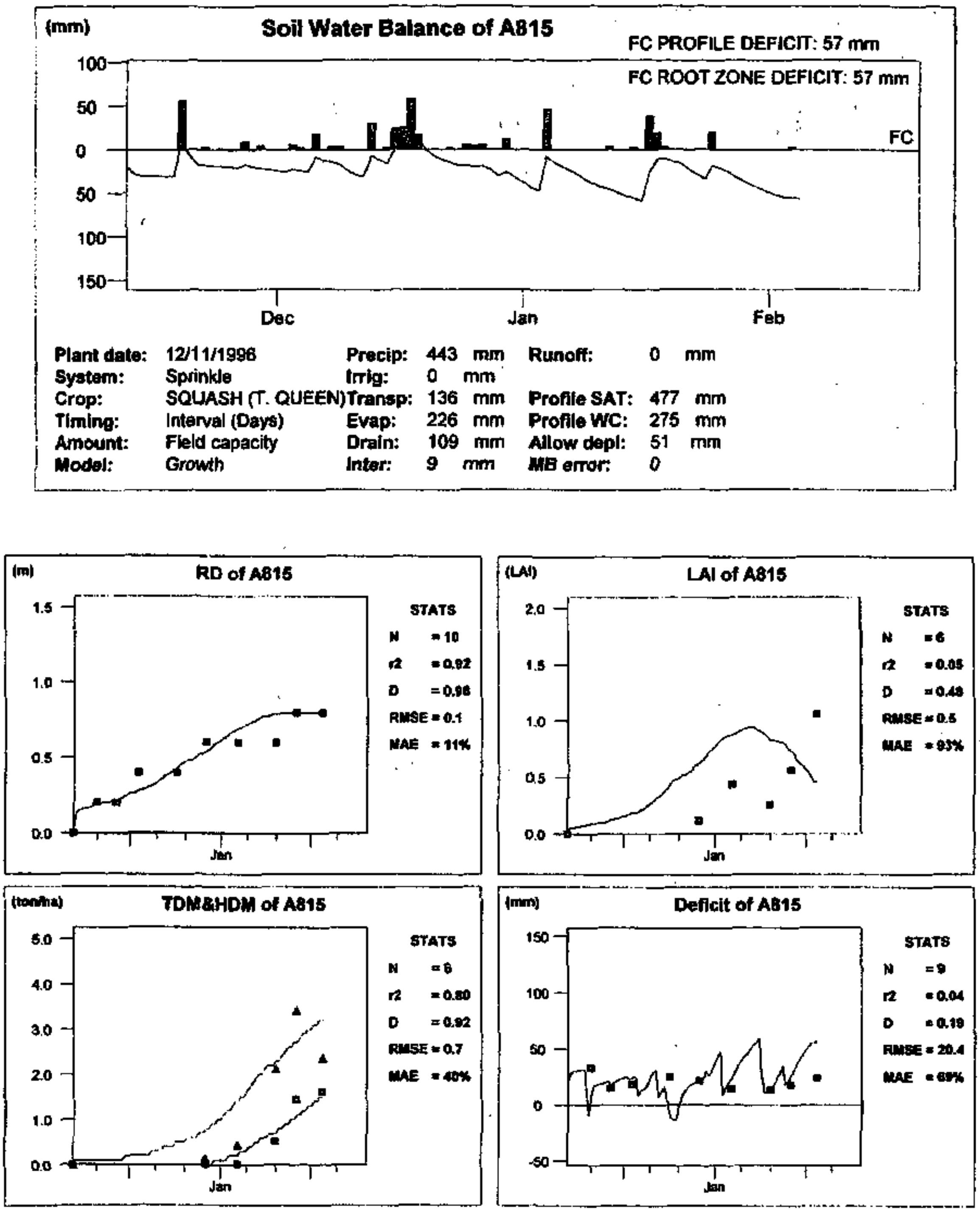


Figure 5.82

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Squash (cv. Table Queen)
Input data set: Roodeplaat field trial (Section 4.1)
Model type: Crop growth

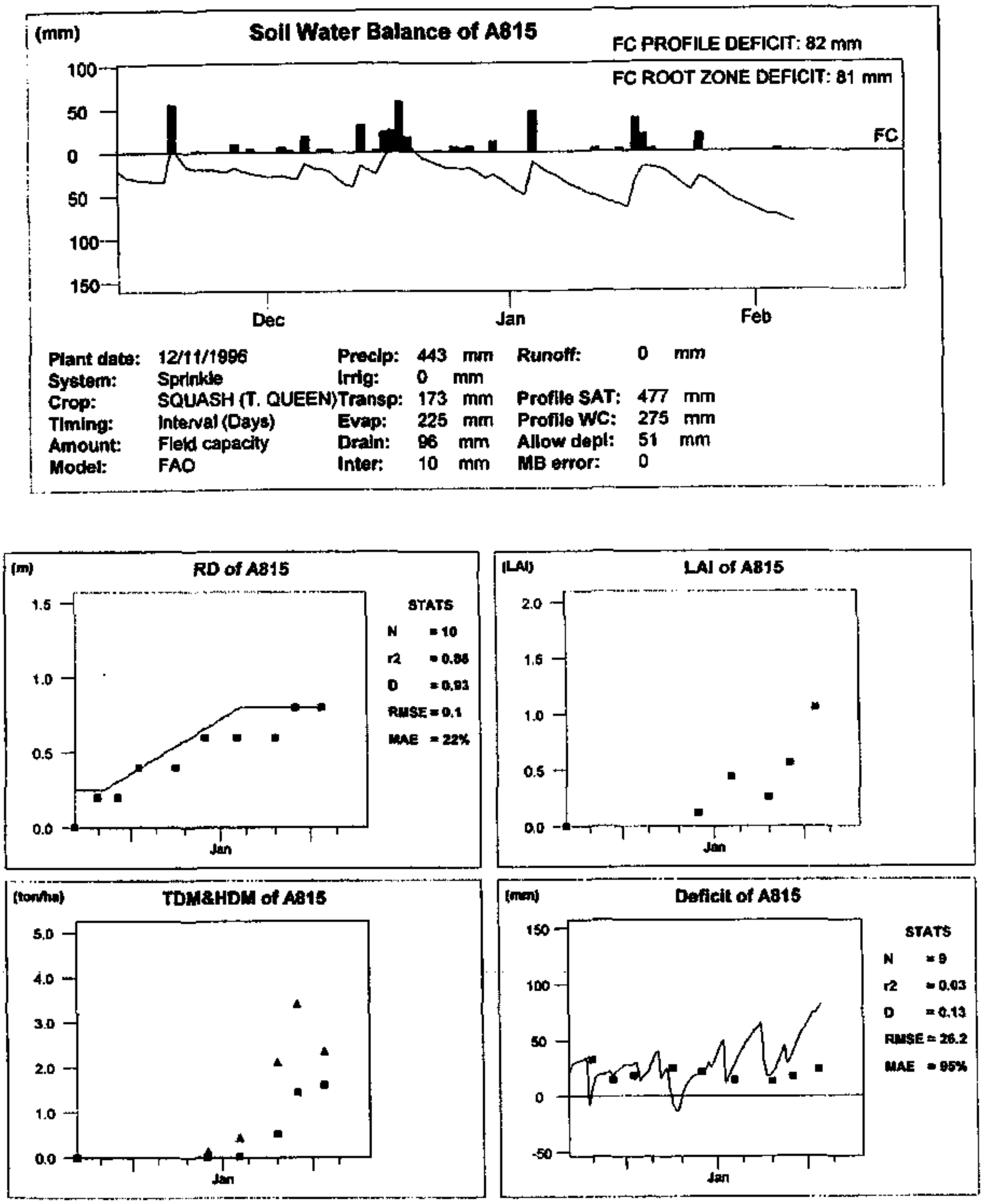


Figure 5.83

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Squash (cv. Table Queen)

Input data set: Roodeplaat field trial (Section 4.1)

Model type: FAO

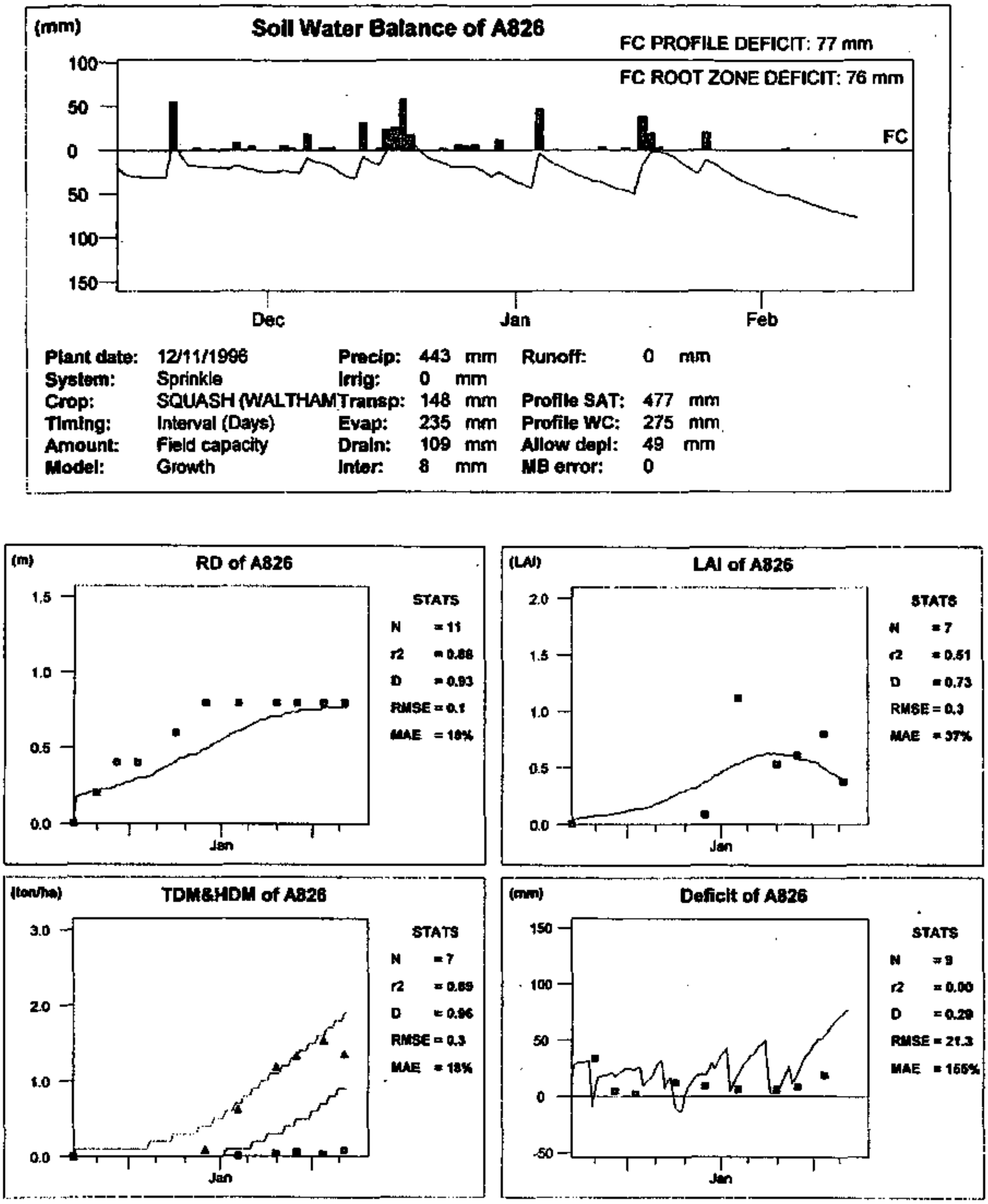


Figure 5.84

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Squash (cv. Waltham)

Input data set: Roodeplaat field trial (Section 4.1)

Model type: Crop growth

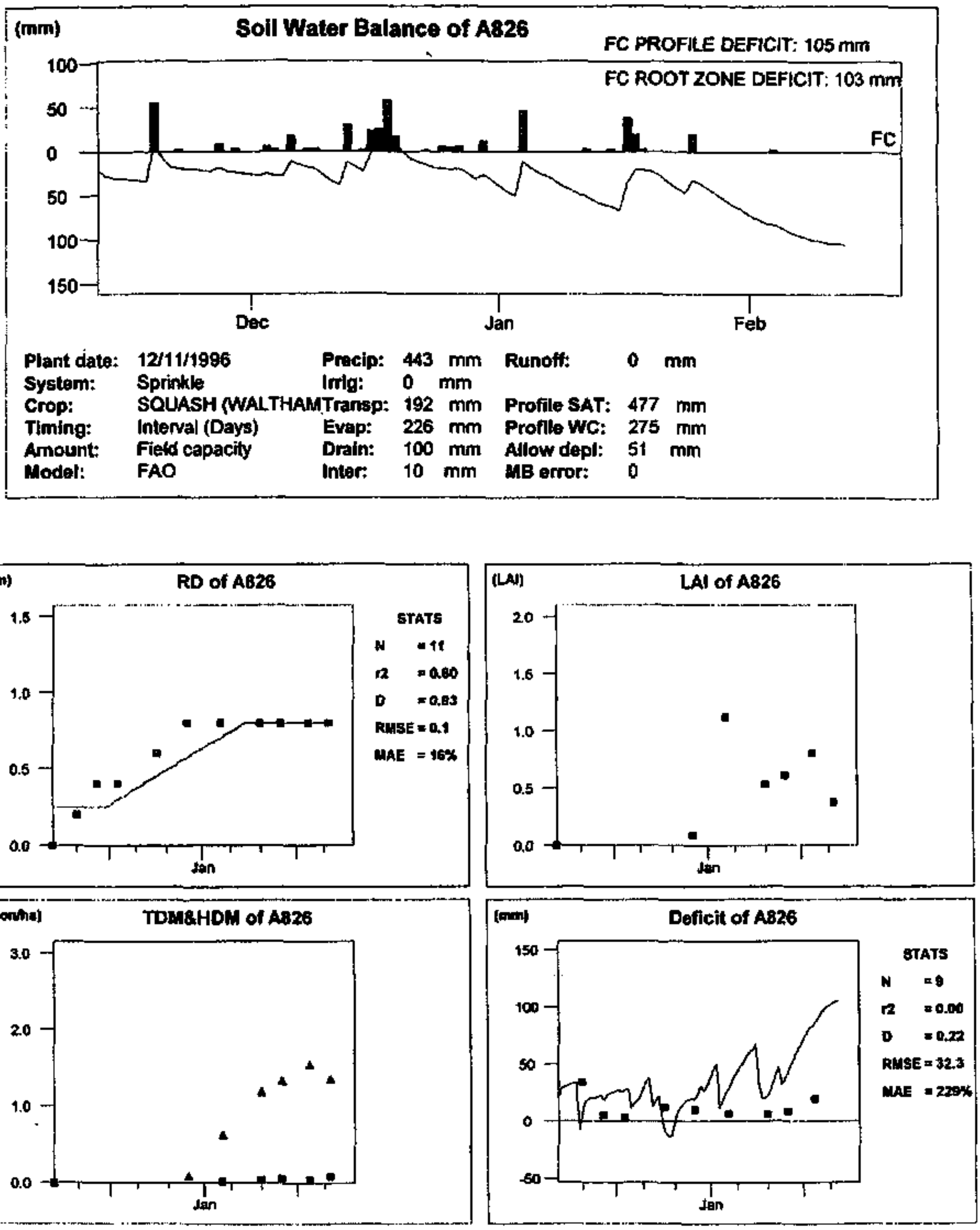


Figure 5.85

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Squash (cv. Waltham)

Input data set: Roodeplaat field trial (Section 4.1)

Model type: FAO

5.2.14 Sweet corn

Data sets for the calibration of SWB were obtained from the Roodeplaat trial (Section 4.1).

Specific crop growth parameters were determined either from the field trial data (Section 4.1.3), or by calibration against measurements of growth, phenology, yield and water use. These are summarized in Table B1 (Appendix B). The parameters required to run the FAO model were determined using measurements of canopy cover and weather data (Section 4.1.4). These are summarized in Table B2 (Appendix B).

Simulations were carried out using both the crop growth and FAO model for cv. Cabaret (Figure 5.86 and 5.87), cv. Dorado (Figure 5.88 and 5.89), cv. Jubilee (Figure 5.90 and 5.91) and cv. Paradise (Figure 5.92 and 5.93). The calibration was generally successful for all cultivars.

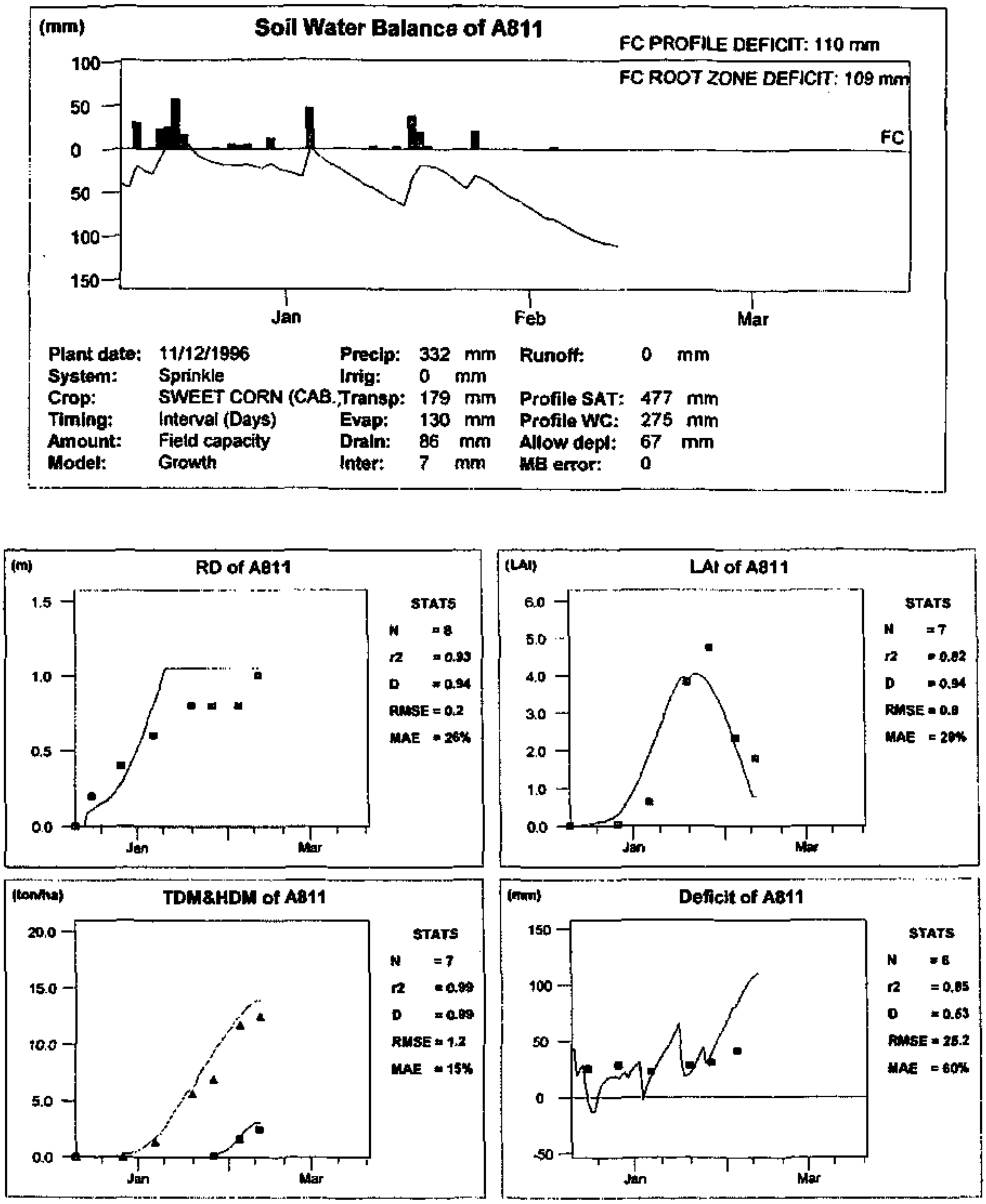


Figure 5.86

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Sweet corn (cv. Cabaret)

Input data set: Roodeplaat field trial (Section 4.1)

Model type: Crop growth

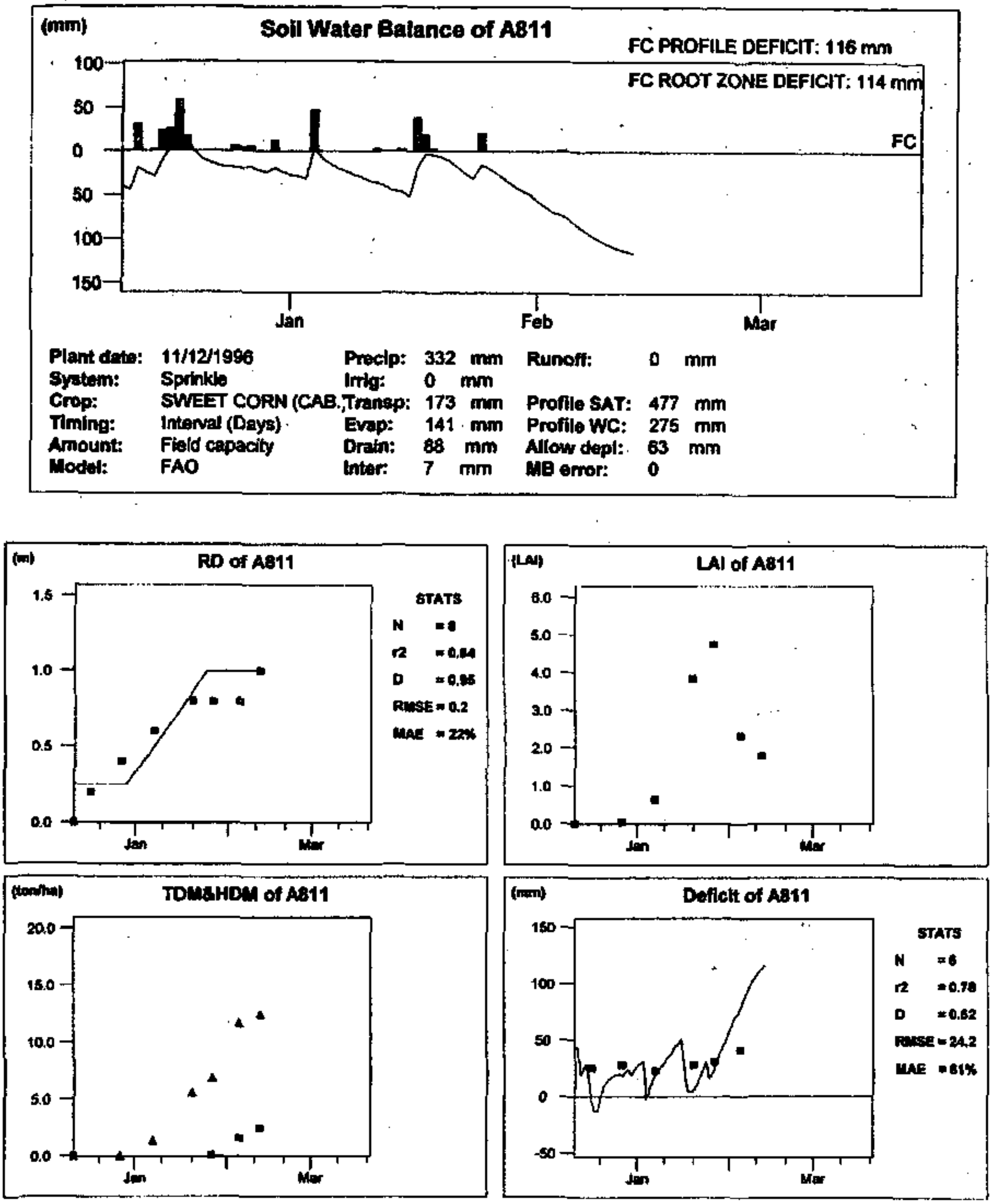


Figure 5.87

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Sweet corn (cv. Cabaret)

Input data set: Roodeplaat field trial (Section 4.1)

Model type: FAO

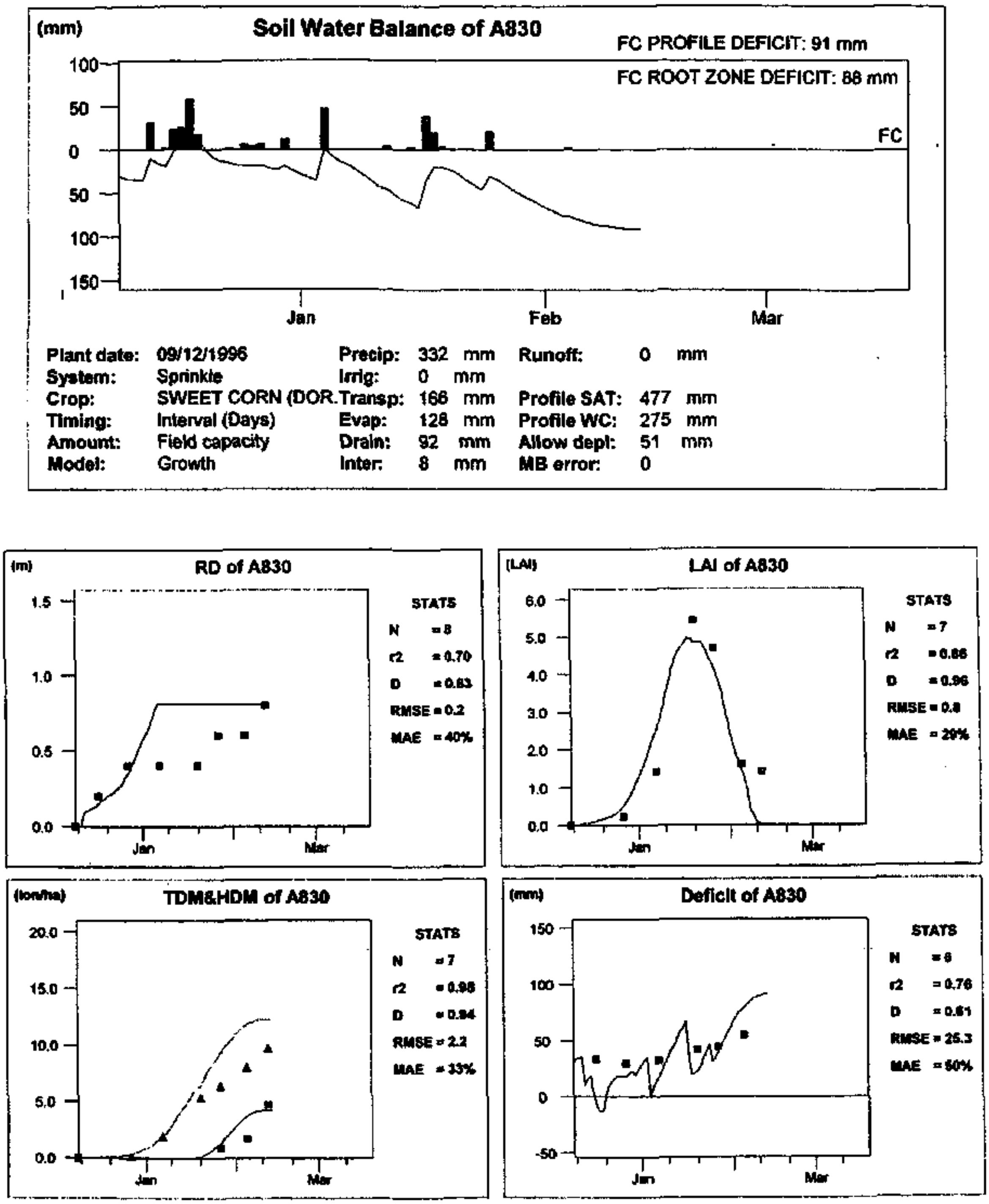


Figure 5.88

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Sweet corn (cv. Dorado)

Input data set: Roodeplaat field trial (Section 4.1)

Model type: Crop growth

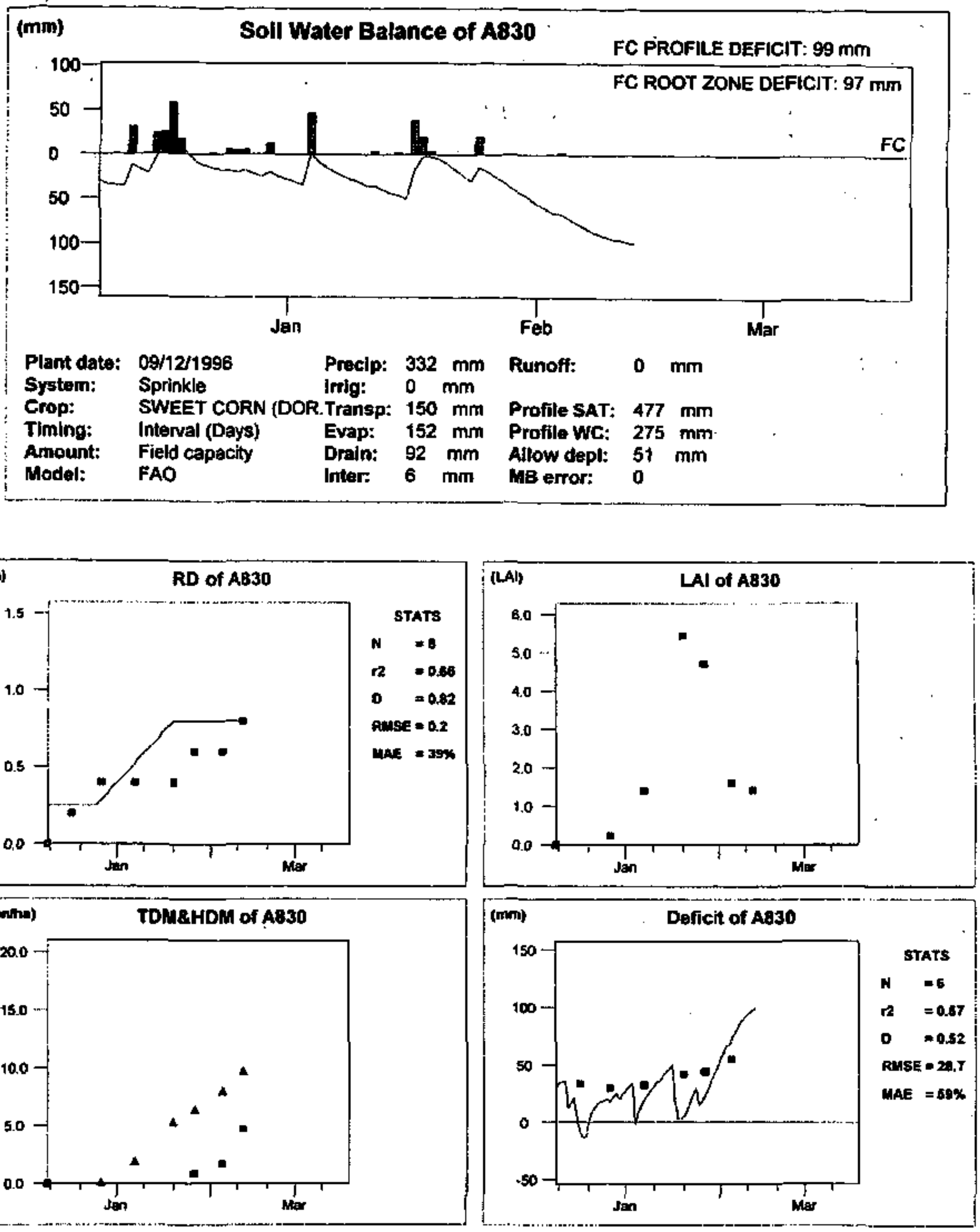


Figure 5.89

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Sweet corn (cv. Dorado)

Input data set: Roodeplaat field trial (Section 4.1)

Model type: FAO

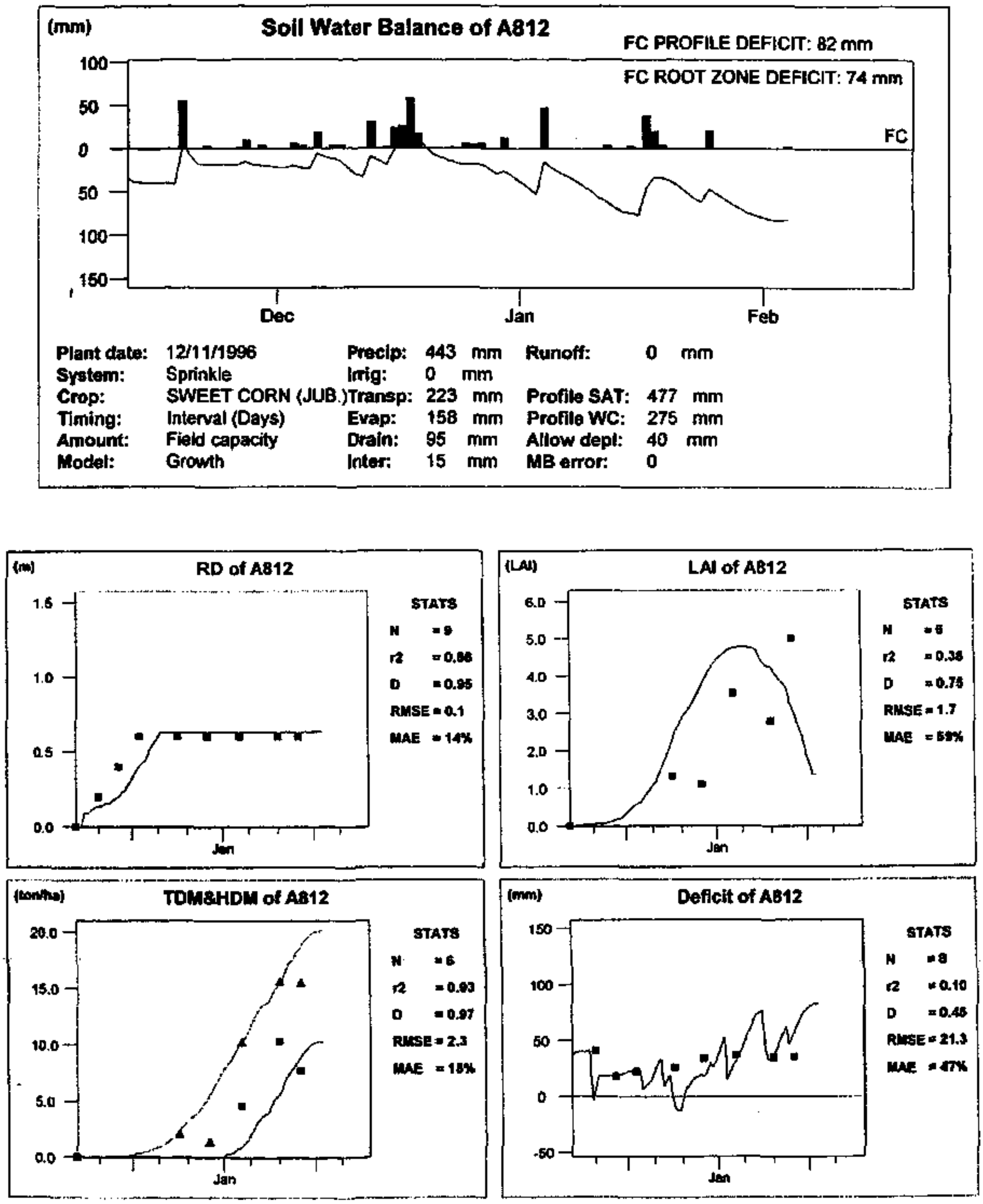


Figure 5.90

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Sweet corn (cv. Jubilee)

Input data set: Roodeplaat field trial (Section 4.1)

Model type: Crop growth

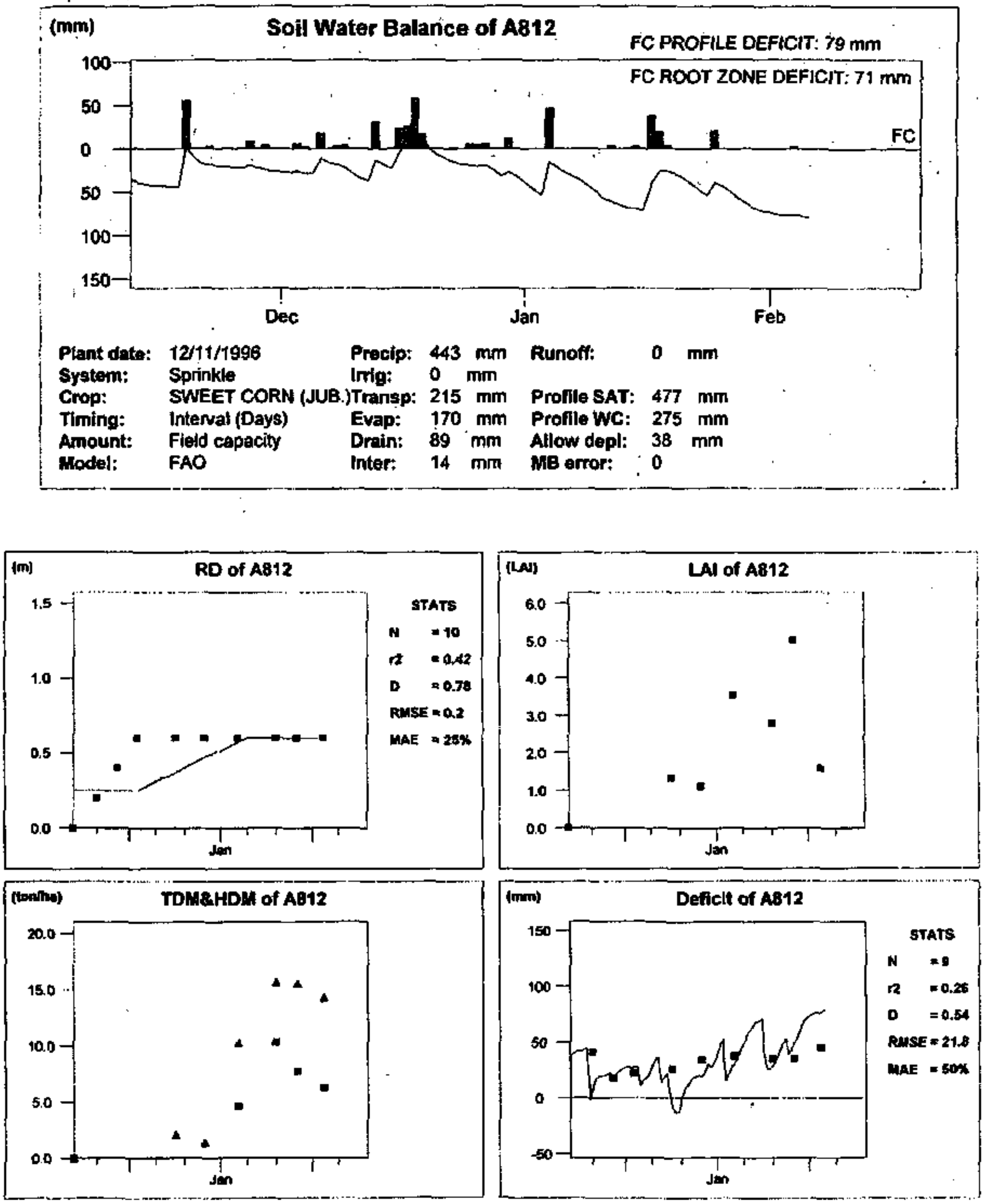


Figure 5.91

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Sweet corn (cv. Jubilee)
Input data set: Roodeplaat field trial (Section 4.1)
Model type: FAO

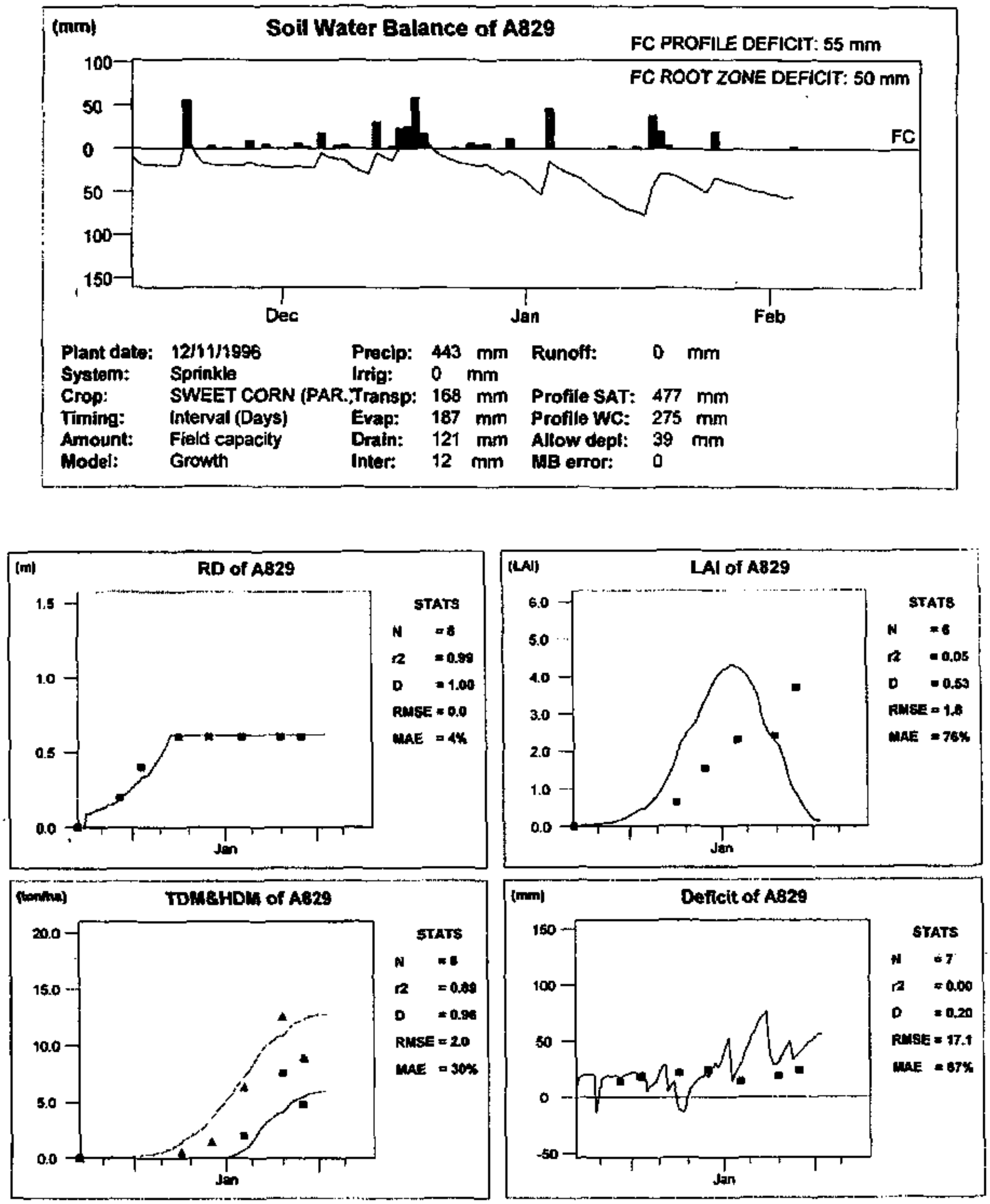


Figure 5.92

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Sweet corn (cv. Paradise)
Input data set: Roodeplaat field trial (Section 4.1)
Model type: Crop growth

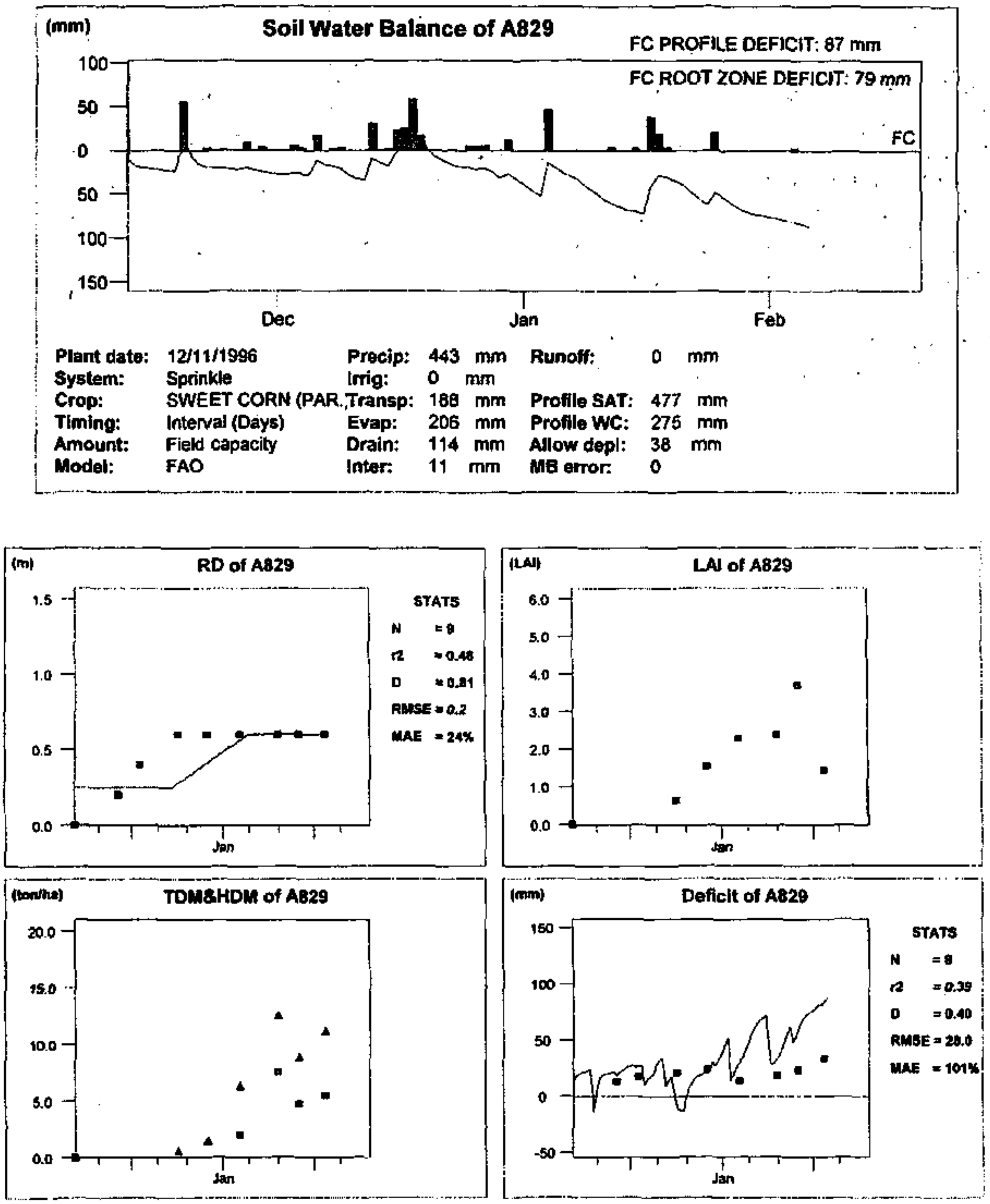


Figure 5.93

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Sweet corn (cv. Paradise)

Input data set: Roodeplaat field trial (Section 4.1)

Model type: FAO

5.2.15 Swisschard

Data sets for the calibration of SWB were obtained from the Roodeplaat trial (Section 4.1).

Specific crop growth parameters were determined either from the field trial data (Section 4.1.3), or by calibration against measurements of growth, phenology, yield and water use. These are summarized in Table B1 (Appendix B). The parameters required to run the FAO model were determined using measurements of canopy cover and weather data (Section 4.1.4). These are summarized in Table B2 (Appendix B).

Simulations were carried out using both the crop growth (Figure 5.94) and FAO model (Figure 5.95). SWB predicted well crop growth and soil water deficit with both models.

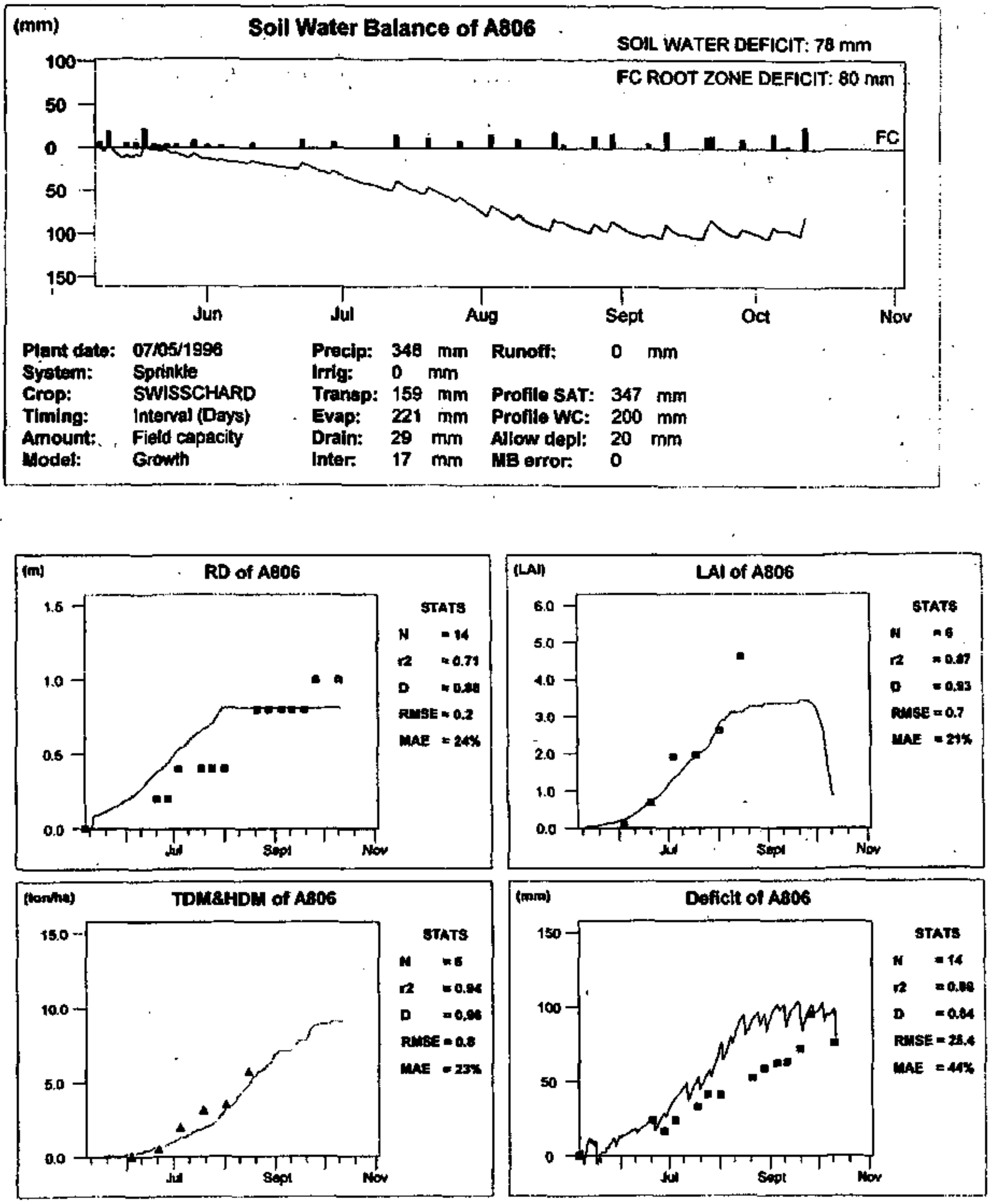


Figure 5.94

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Swisschard
Input data set: Roodeplaat field trial (Section 4.1)
Model type: Crop growth

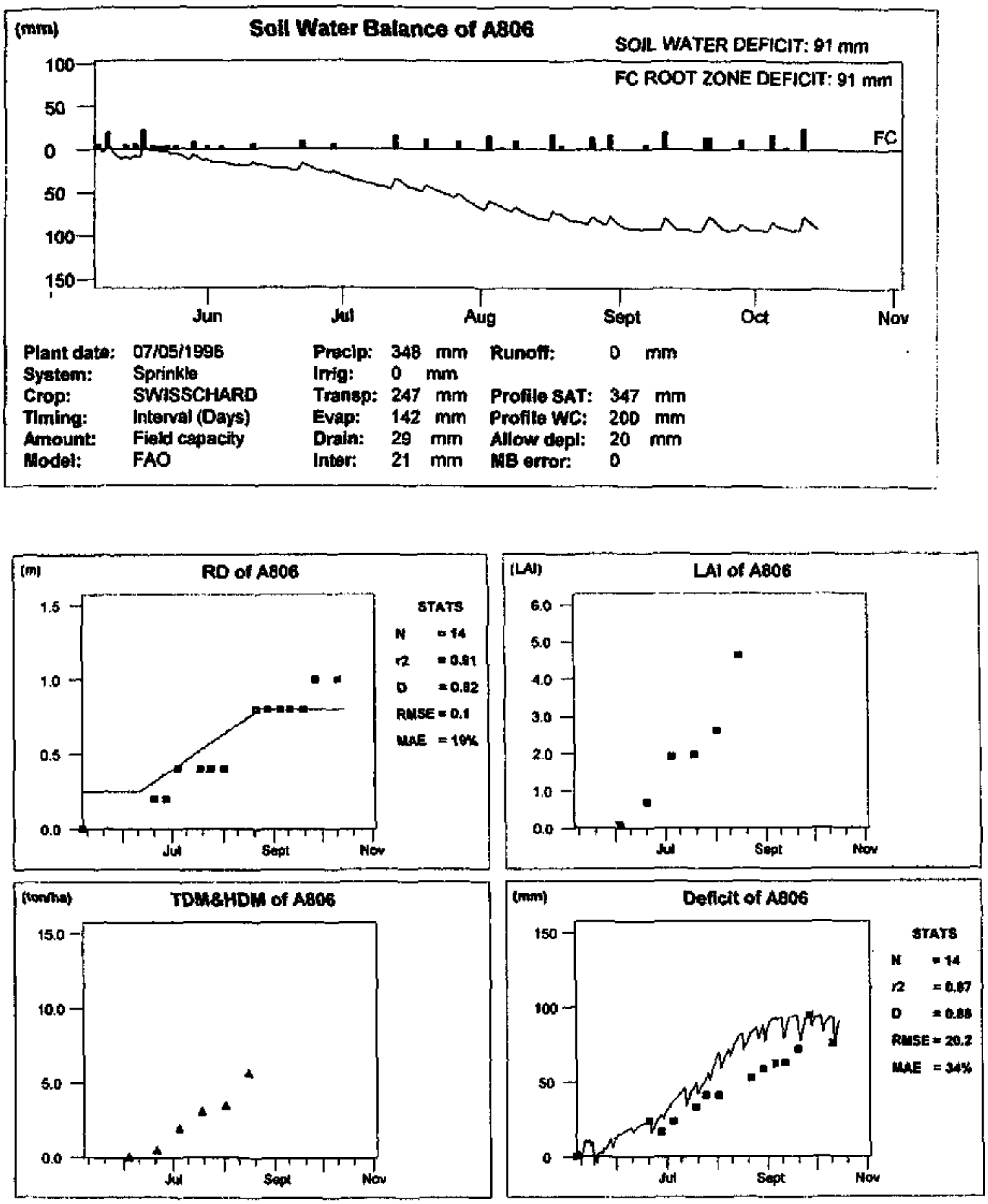


Figure 5.95

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Swisschard

Input data set: Roodeplaat field trial (Section 4.1)

Model type: FAO

5.2.16 Tomato

Data sets for the calibration of SWB were obtained from the Roodeplaat trial (Section 4.1).

Specific crop growth parameters were determined either from the field trial data (Section 4.1.3), or by calibration against measurements of growth, phenology, yield and water use. These are summarized in Table B1 (Appendix B). The parameters required to run the FAO model were determined using measurements of canopy cover and weather data (Section 4.1.4). These are summarized in Table B2 (Appendix B). The age of the seedling could affect the length of the initial stage for the FAO model.

Simulations were carried out using both the crop growth and FAO model for processing tomatoes cv. HTX4 (Figures 5.96 and 5.97) and cv. P747 (Figures 5.98 and 5.99), as well as table tomatoes cv. Zeal (Figures 5.100 and 5.101). The model predicted soil water deficit reasonably well. Discrepancies between measured data and simulations of LAI could have been caused by spatial variability (Figures 5.96, 5.98 and 5.100). No replications were taken for growth analysis due to the small plot size. It was not possible to obtain a reliable simulation of dry matter production as fruits were harvested during the growing season.

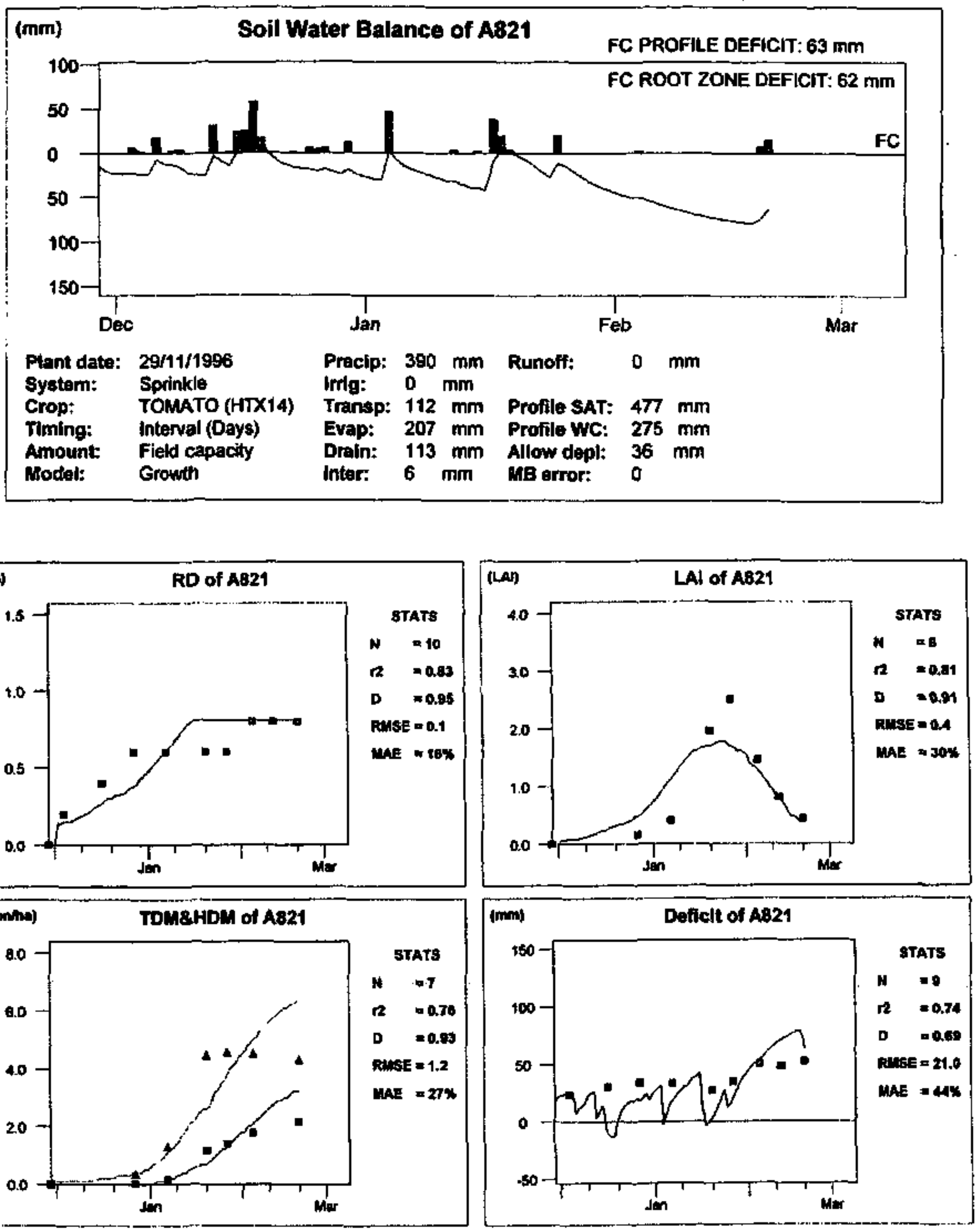


Figure 5.96

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Tomato (cv. HTX4)

Input data set: Roodeplaat field trial (Section 4.1)

Model type: Crop growth

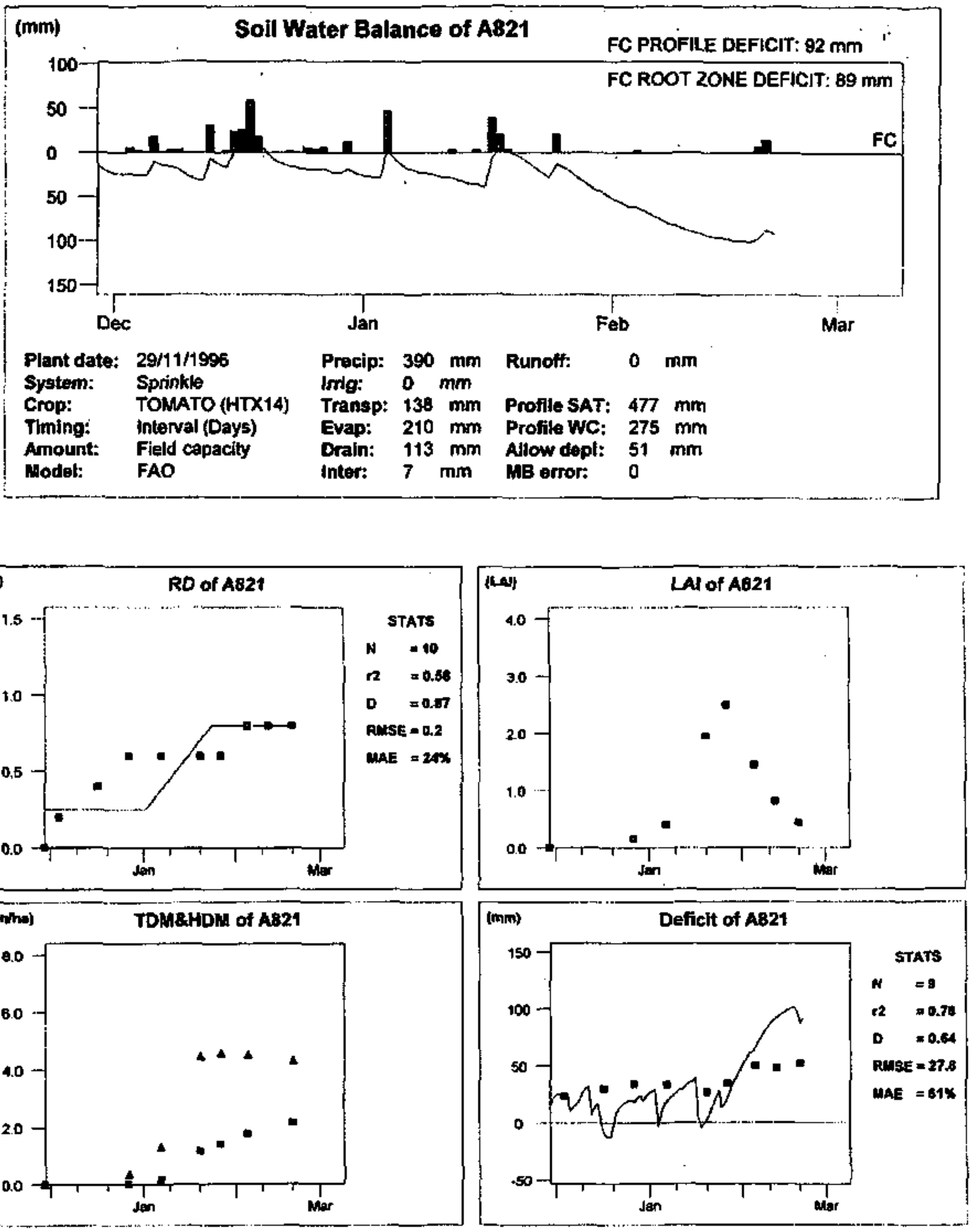


Figure 5.97

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Tomato (cv. HTX4)
Input data set: Roodeplaat field trial (Section 4.1)
Model type: FAO

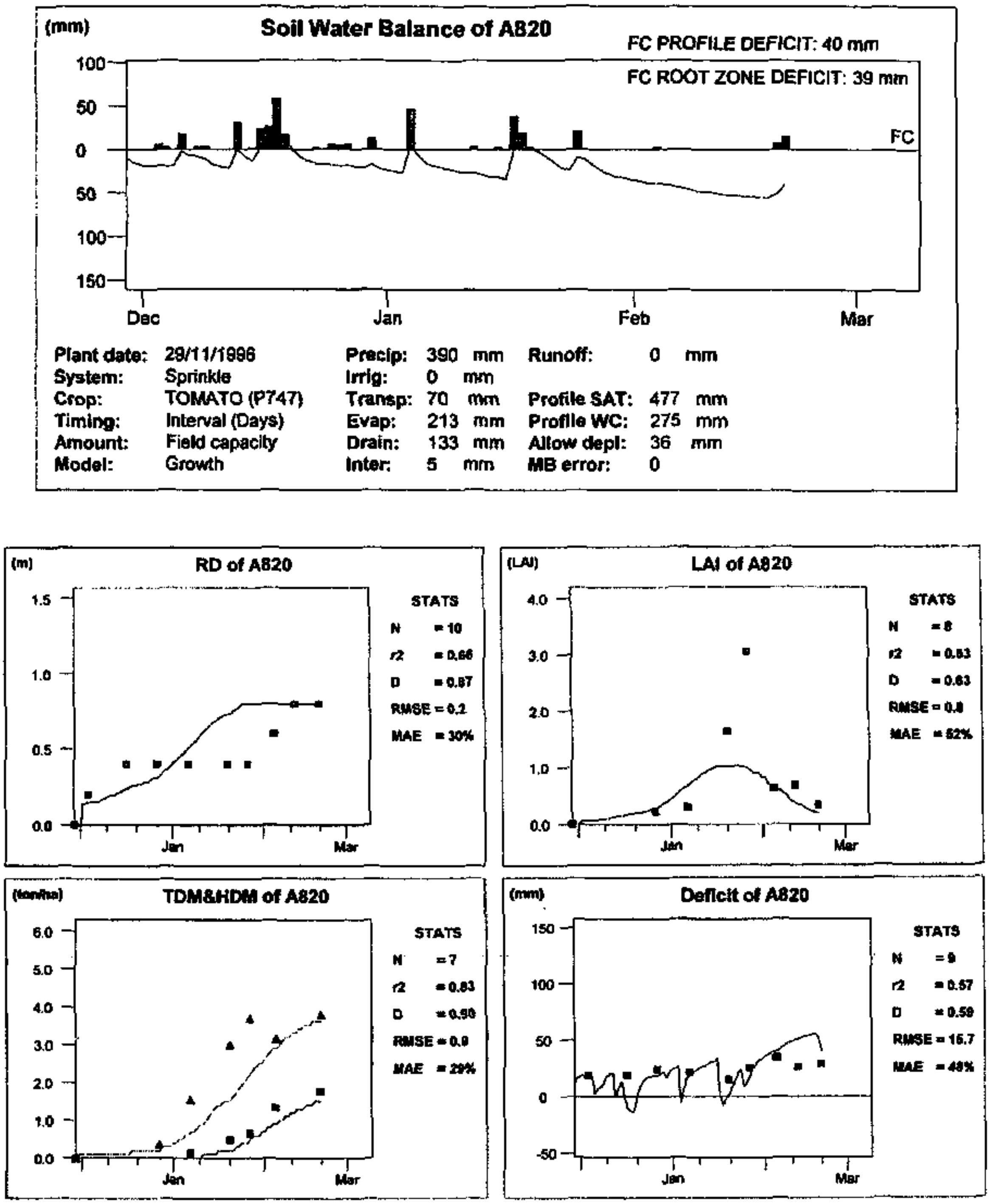


Figure 5.98

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Tomato (cv. P747)
Input data set: Roodeplaat field trial (Section 4.1)
Model type: Crop growth

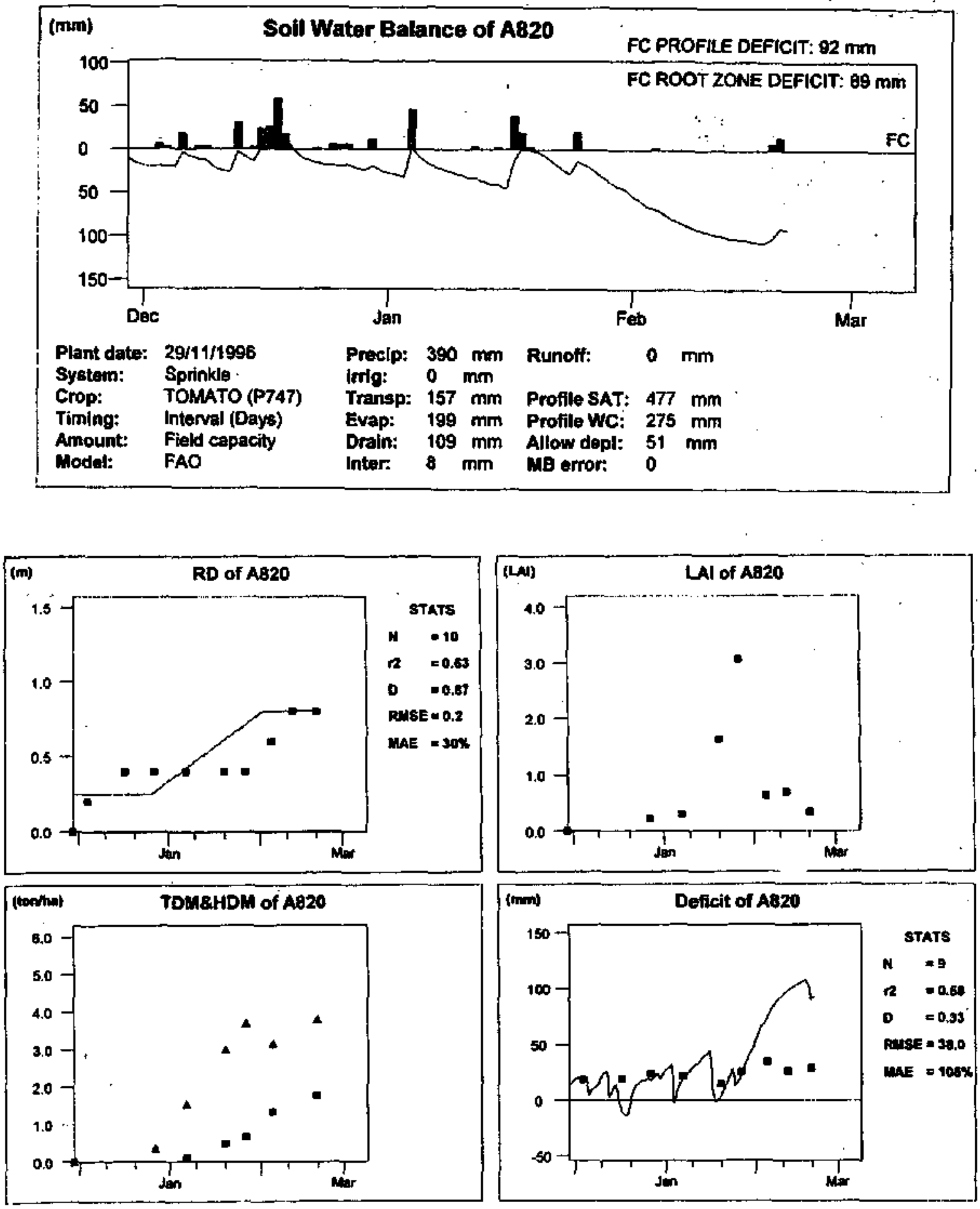


Figure 5.99

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Tomato (cv. P747)
Input data set: Roodeplaat field trial (Section 4.1)
Model type: FAO

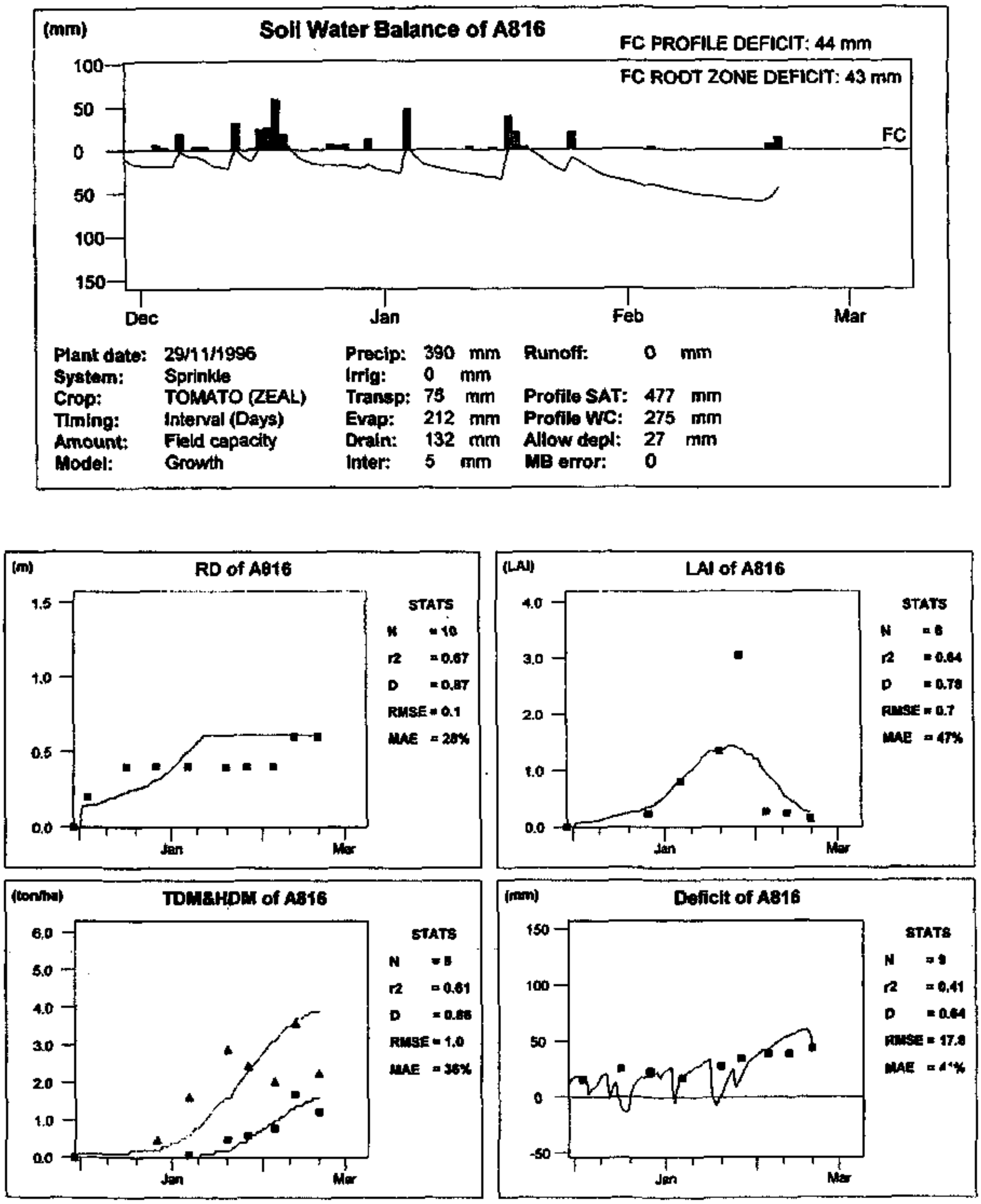


Figure 5.100

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Tomato (cv. Zeal)
Input data set: Roodeplaat field trial (Section 4.1)
Model type: Crop growth

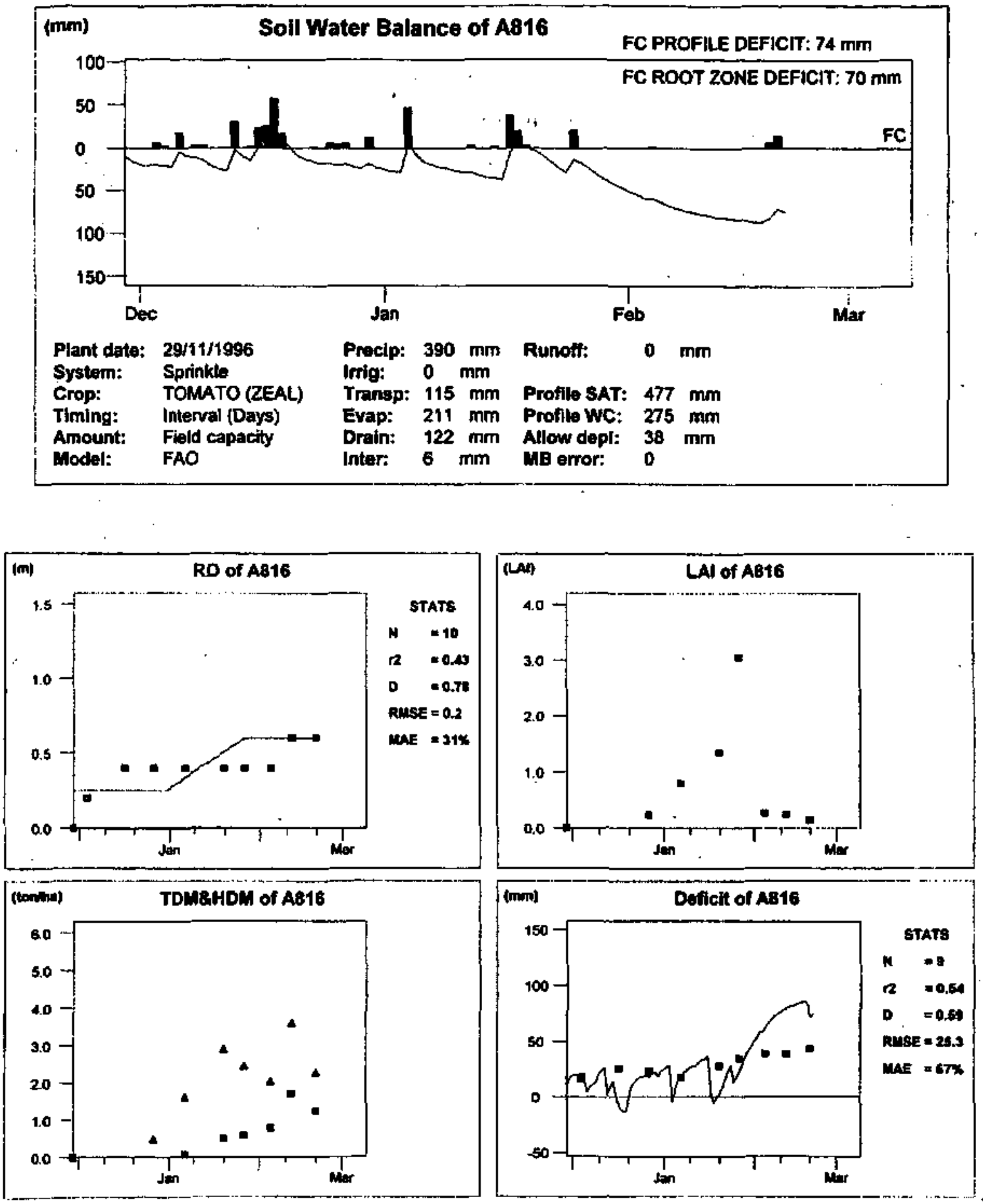


Figure 5.101

Soil water balance output graph, simulated (solid line) and measured (symbols) root depth (RD), leaf area index (LAI), total above ground (TDM) and harvestable dry matter (HDM), as well as soil water deficit.

Crop: Tomato (cv. Zeal)
Input data set: Roodeplaat field trial (Section 4.1)
Model type: FAO

5.3 Tree crops

5.3.1 Apple

The data used in this Section is unpublished data supplied by Ms T Volschenk (Agricultural Research Council - Infruitec, Stellenbosch). Her open cooperation in this respect is greatly appreciated. The interpretation of the raw data was done by the authors, so any gremlins which could have crept in cannot be laid at Infruitec's door!

Brief description of lay-out and objectives of the Infruitec trial:

The data was collected during the 1996/97 season in an irrigation trial investigating the effect of water stress during specific phenological phases associated with producing apples (*Malus domestica*). The trial was conducted on the ARC's experimental farm in Elgin using the cultivar Golden Delicious (scion) on Merton 793 rootstock. The orchard had been established in June 1985 in a hedgerow planting pattern (4.5 X 2.5 m) with the rows orientated in an East-West direction. The micro-spitter irrigation system wetted a 3 m band under the tree row (i.e. 67% area) with the litres applied per irrigation being converted to mm over the whole area. Daily hourly maximum and minimum temperatures (°C), average daily wind speed (m s^{-1}), total daily solar radiation (MJ m^{-2}) and daily precipitation (mm) were recorded by the experimental station's automatic weather station (32.19' S, 19.34' E, altitude 305 m). The soil could be regarded as a loam (25% clay, 28% silt and 47% sand) having a large proportion of loose stone (up to 60%).

The trial orchard was divided into three blocks (replications) which were further sub-divided into treatment plots of 4 trees in a row. The treatments were aimed at keeping the tree's water requirements satisfied until the specific phenological phase, where effects of water stress were to be investigated, was reached. Once the required phenological stage had been reached, varying water stress treatments were applied. Examples of treatments applied are as follows:

Treat No	Treatment
2	Irrigate at 100kPa during phase I and at 50kPa during Phase II, III and IV
7	" " " " " II " " " " " I, III and IV
12	" " " " " III " " " " " I, II and IV
17	" " " " " IV " " " " " I, II and III

The phenological phases are:

Phase I : Cell division period (bud, blossom till 40 days after full bloom; monitor full bloom date), i.e. from 1 October to 11 December 1996 (71 days).

Phase II: Vegetative growth and cell enlargement period (40 days from full bloom till ~ 4 weeks prior harvest), i.e. from 12 December 1996 to 5 February 1997 (56 days).

Phase III: Ripening till harvest period (estimated that Golden Delicious will be ripe ~ 132 days after full bloom), i.e. from 6 February to 18 March 1997 (41 days).

Phase IV: Post harvest period (Harvest till end April), from i.e. 7 February to 30 April 1997 (43 days).

Volumetric soil water content (θ) was monitored to a depth of 0.9 m with a neutron water meter (NWM) which had been calibrated for the site. Three NWM probe access tubes were used per monitoring site. These tubes were located under the drip of the tree in the following way: two were in the tree line at 0.5 and 1.0 m from the tree trunk; the third was located by taking an angle of 45° from the tree line at a point 1 m from the tree trunk. Thus θ was monitored only in the tree row region and the interrow region was ignored. The actual methodology used to convert NWM readings to θ is unclear to the authors. Evidently the method has been in use for some time and is generally accepted as being accurate. However, considering the high proportion of stones (60 %) in the 0.9 m profile, the possibility that the recorded θ are on the high side must not be disregarded.

For the purpose of the current data interpretation, volumetric soil water content at field capacity (θ_{fc}) was taken as θ recorded three to four days after a substantial rainfall. By using this approach, the average θ_{fc} of the treatment plots was determined to be 223 mm with a standard error of ± 52 mm. The range of θ_{fc} was 150 - 360 mm. The profile soil water deficit (SWD) for a particular day was determined by subtracting the recorded θ for that day from that site's θ_{fc}.

Since it was possible to achieve Infruitec's objective of the trial by only monitoring specific treatments during the critical stages under consideration, coupled to a man-power constraint, no specific plot of trees were monitored continuously throughout the growing season.

At various stages during the season, a daily average crop evapotranspiration (ET) was determined by the Infruitec personnel on the basis of the change in θ over a period of days (n) using the following equation:

$$ET = (\theta_i - \theta_{i+n})/n \quad (25)$$

Where θ_i is the θ for day "i" and θ_{i+n} is the θ recorded "n" days later.

Fractional interception (FI) of solar radiation was estimated as follows:

$$FI = Wc/R_h \quad (26)$$

where Wc is the width of the hedgerow canopy (m) and R_h is the hedgerow spacing (distance, in metres, from trunk to trunk across the interrow). FI was found to be 0.53, 0.64 and 0.56 for 6 December 1996, 19 February 1997 and 16 April 1997 respectively.

Data interpretation:

The weather data (daily maximum and minimum temperature, total solar radiation and average daily wind speed) were imported into the weather database of SWB for the Elgin weather station. This data was used to calculate daily ETo values.

The next step was to determine Kcb values for each FAO stage. This was done by using ET values as determined by the Infruitec personnel and ETo values calculated with the SWB model, using the following equation:

$$Kc = ET / ETo \qquad (27)$$

The Kc values, where available, were averaged over the respective days and plotted against days of season to give an indication of the possible locus of the Kcb line. The final value of Kcb for the FAO late-season stage was taken to be close to zero (0.05 in this case) since by the end of the season (30 April 1997) it can be expected that leaf senescence had reached an advanced stage and water loss from the leaf canopy would be minimal. First approximation values of Kcb were then estimated for periods corresponding to the phenological phases I to IV. A simulation was run and the SWB predicted soil water deficits were graphically compared to those determined by field measurements using the NWM. By means of a series of comparisons with slight step-wise changes to period lengths and Kcb values, a "best fit" Kcb curve was established (Figure 5.102).

The final simulations where predicted and measured values are compared are presented in Figures 5.103-5.107.

Since Infruitec had a different objective to ours, two problems were encountered, *viz*:

i) No treatment plot had been continuously monitored over the whole season; and

ii) Large differences in θ_{fc} of treatment plots restricted the ability to make θ comparisons across phases.

In an attempt to overcome these problems the following approaches were followed:

i) A "composite field" was generated by selecting, within a phase, treatment plots which had $\theta_{fc} \approx 200$ mm and using the average of these treatments θ's as a measure of the "composite field's" θ for that phase. Thus for each phase θ_{fc} of the "field" was ≈ 200 mm. The treatment plot combination per phase was as follows:

Phase	Dates	Treatment Plots
I	01/10/96 - 11/12/96	12, 13, 23, 33, 32 and 53
II	12/12/96 - 05/02/97	62, 63, 72, 73, 83, 92, 93 and 102
III	06/02/97 - 18/03/97	111, 113, 141 and 142
IV	19/03/97 - 30/04/97	172, 173, 182, 183, 202 and 203

In this manner it was possible to run a simulation over the whole season based on a comparable θ_{fc}. It was necessary to implement the "update" option of SWB (Section 6.2.6) on two dates, i.e. 07/02/97 and 20/03/97. This simulation is presented in Figure 5.103.

ii) During phase I and II single plots having θ_{fc}'s of ≈ 200 mm were simulated. During phase III and IV there were no plots with an $\theta_{fc} \approx 200$ mm so two plots were selected to give an average $\theta_{fc} \approx 200$ mm. The plot selection for this comparison was as follows:

Phase	Dates	Treatment Plots
I	01/10/96 - 11/12/96	23
II	12/12/96 - 05/02/97	73
III	06/02/97 - 18/03/97	Average of 121 and 122
IV	19/03/97 - 30/04/97	Average of 172 and 173

At the beginning of each phase the SWB "update" option (Section 6.2.6) was implemented to insure that the initial θ was correct. The simulations for these comparisons are presented in Figures 5.104-5.107.

Conclusions:

In spite of the problems associated with the lack of continuity of measurements of θ of specific treatment plots throughout the season, coupled to the very large differences in profile water holding characteristics of the treatment plots, this data set has been useful in showing that the FAO option in the SWB model can use climatic data to make a reasonable prediction of apple tree water use. As indicated in Figures 5.103, 5.104, 5.105 and 5.107, there is acceptable agreement between the measured and predicted SWD values for the phenological phases I, II and IV.

During phase III, the model predicted higher crop water use (i.e. increased SWD) than that indicated by the smaller measured SWD values (Figures 5.103 and 5.106). For the sake of clarity, the "update" option was implemented in the middle of phase III (indicated by the "*" in Figures 5.103 and 5.106) to bring the predicted line closer to the measured values so that the trends could be compared. When the model's prediction of ETo for this period is compared to the pan evaporation values for this site, one cannot fault the ETo estimation. It is worth while to consider the predicted and measured change in SWD during the period from 17/02/97 to 10/03/97 as indicated in Figure 5.106. The measured SWD indicates that $\approx$ 20 mm water has been used in this 21 day period, i.e. $\approx$ 1 mm d^{-1}. The SWB prediction is $\approx$ 33 mm in 21 days, i.e. 1.6 mm d^{-1}. During the period from 20/02/97 to 07/03/97, ET measurements were being done and indicated a change in θ of 26.3 mm during the 15 day period. This is equivalent to an average loss of 1.7 mm d^{-1} which substantiates the SWB prediction! However, it must be realized that the data set was generated for a completely different purpose, coupled with the variability in the profile water characteristics, so the apparent error in the measured SWD could be an artifact associated with the variability in θ of the treatment plots. One must also not loose site of the fact that the treatment blocks are relatively small (4 trees in a row) and are surrounded with other trees most probably receiving irrigations so the possibility of water seepage from surrounding treatments could also be a factor. A further factor which could influence the measured SWD values is that measurements are taken from a limited portion of the orchard; the influence of the inter-row region is totally ignored. The SWB model predicts for the whole area.

It is seen that at the end of phase IV the predicted SWD is less than the measured SWD (Figures 5.103 and 5.107). This could be due to the assumption that the canopy would already be entering senescence and the final value of 0.05 for Kcb is too low or it could be that the late-season stage is longer than the 88 days used in this exercise.

These preliminary results indicate that according to the water use trends, shown by the measured and predicted values, the periods of the phenological phases and the FAO stages do not coincide. Where the phenological phases I, II, III and IV are 71, 56, 41 and 43 days respectively, the FAO initial, development, mid-season and late-season stages are of the order of 31, 56, 36 and 88 days.

The initial FAO crop parameters for Golden Delicious apples cultivated in Elgin are shown in Table B2 (Appendix B).

It must be mentioned that the Kcb value of 0.4 determined for the mid-season stage is surprisingly low when compared to the measured FI values of ≈ 0.6. Generally FI and Kcb are very similar.

One must realize that these are preliminary values and must be used with caution. Further data sets are required to validate these values.

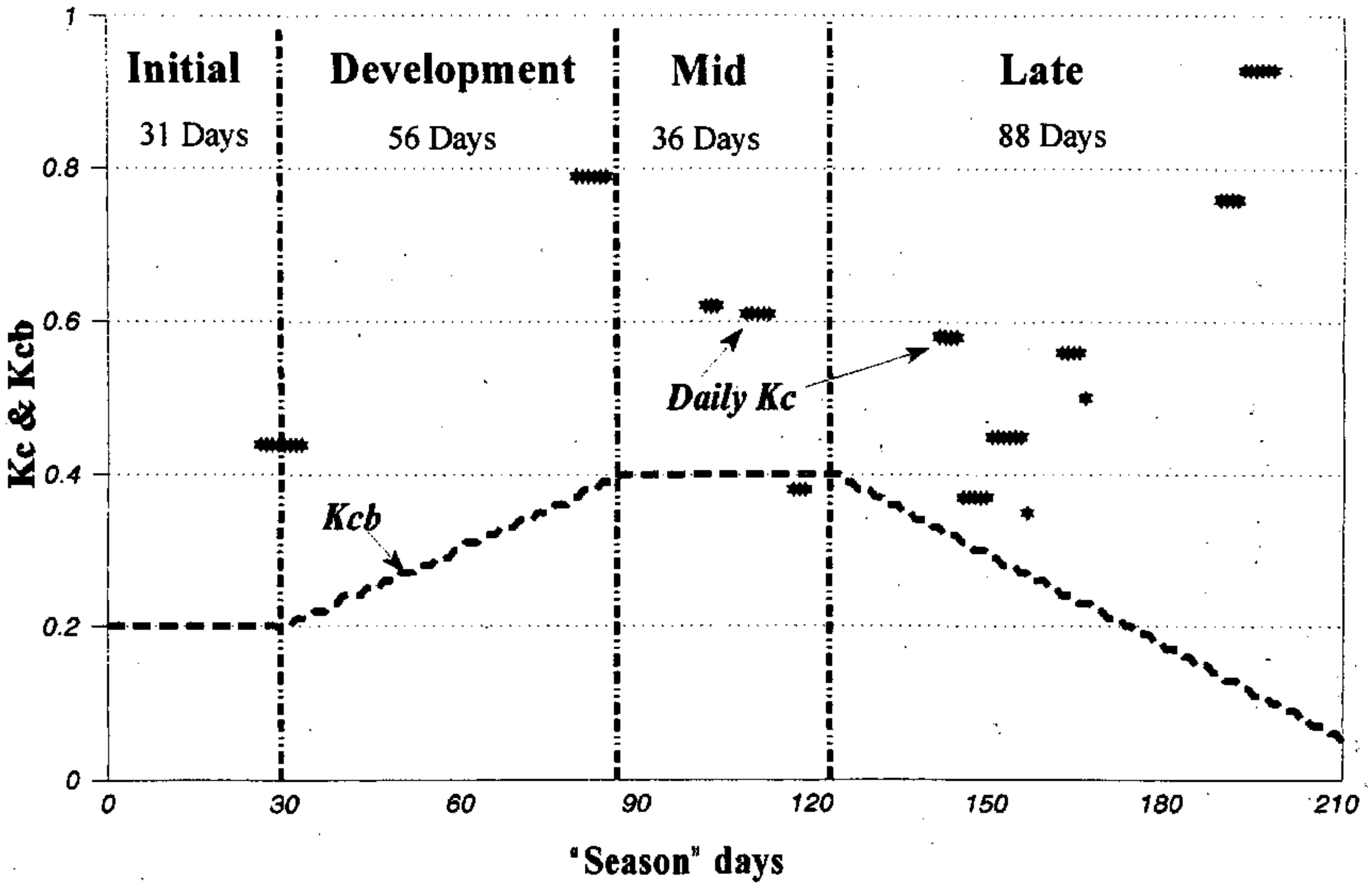


Figure 5.102
Daily FAO crop coefficient (Kc) and basal crop coefficient (Kcb), as well as FAO stages for 12 year Golden Delicious apple in Elgin (rootstock is Merton 793)

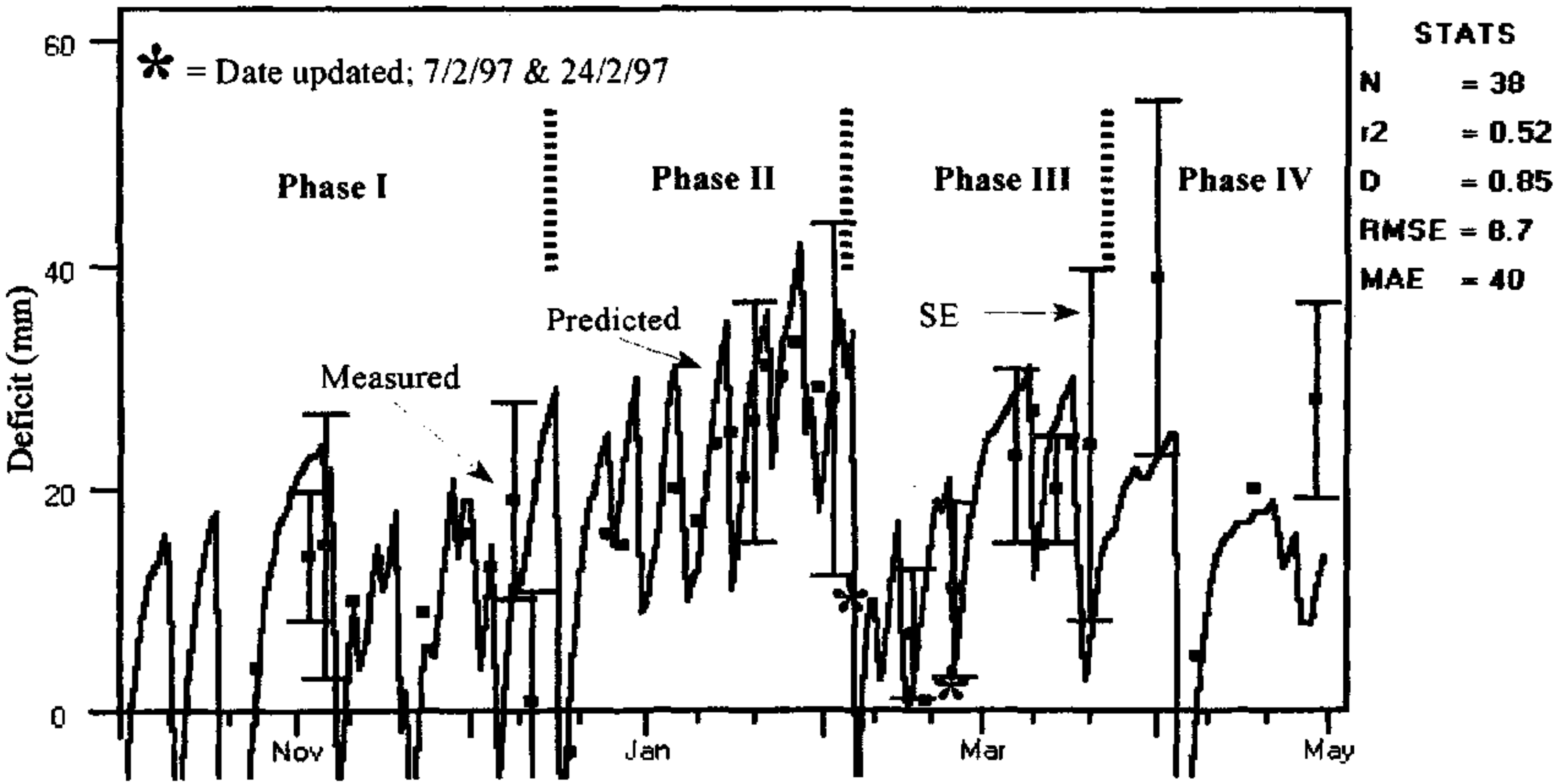


Figure 5.103

Predicted and measured soil water deficit for "composite field" over whole season.

Crop: 12 year Apple (cv. Golden Delicious, rootstock is Merton 793)

Input data set: Elgin (Infruitec)

Model type: FAO

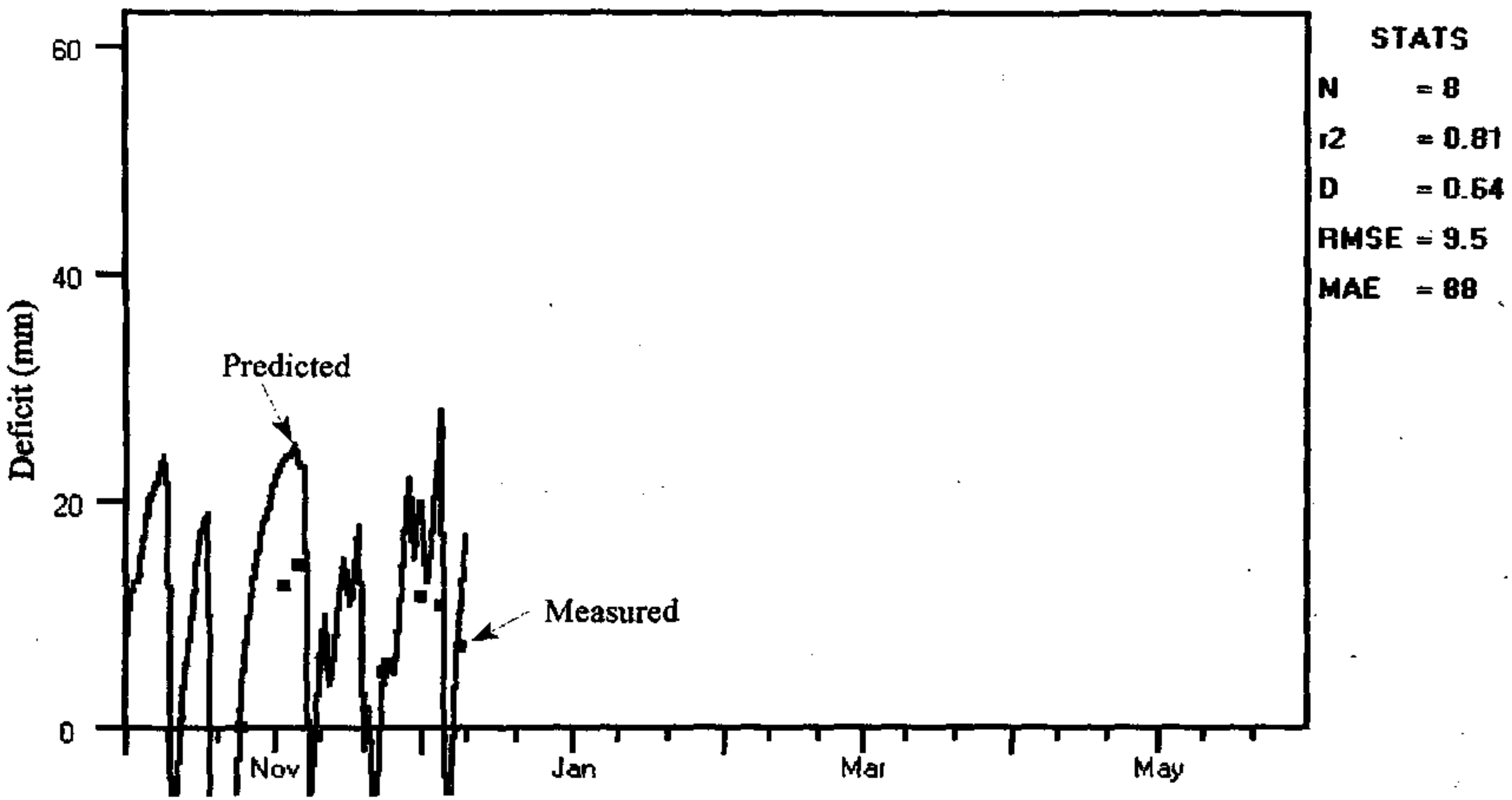


Figure 5.104

Predicted and measured soil water deficit for phase I over whole season.

Crop: 12 year Apple (cv. Golden Delicious, rootstock is Merton 793)

Input data set: Elgin (Infruitec)

Model type: FAO

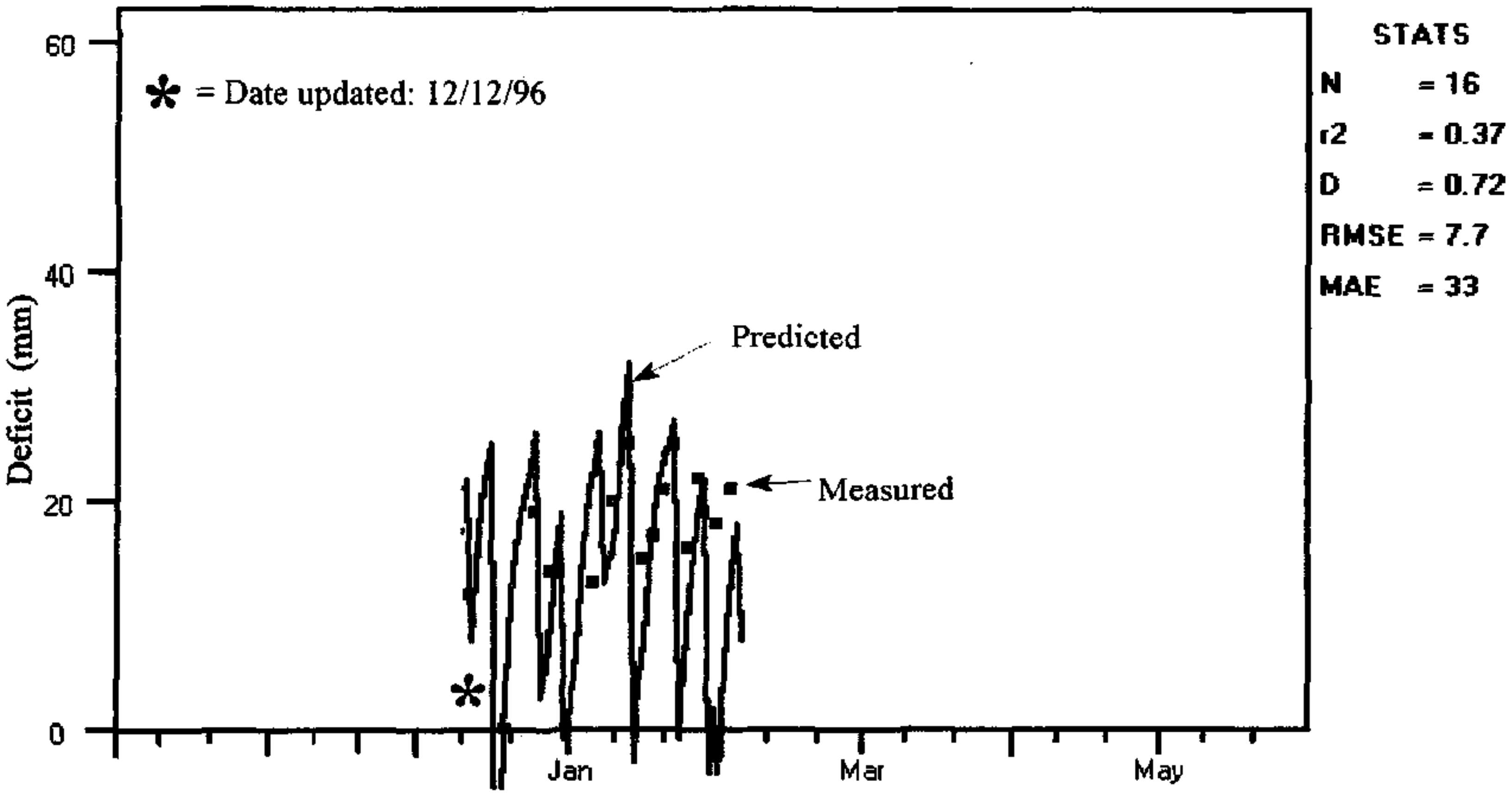


Figure 5.105
Predicted and measured soil water deficit for phase II over whole season.
Crop: 12 year Apple (cv. Golden Delicious, rootstock is Merton 793)
Input data set: Elgin (Infruitec)
Model type: FAO

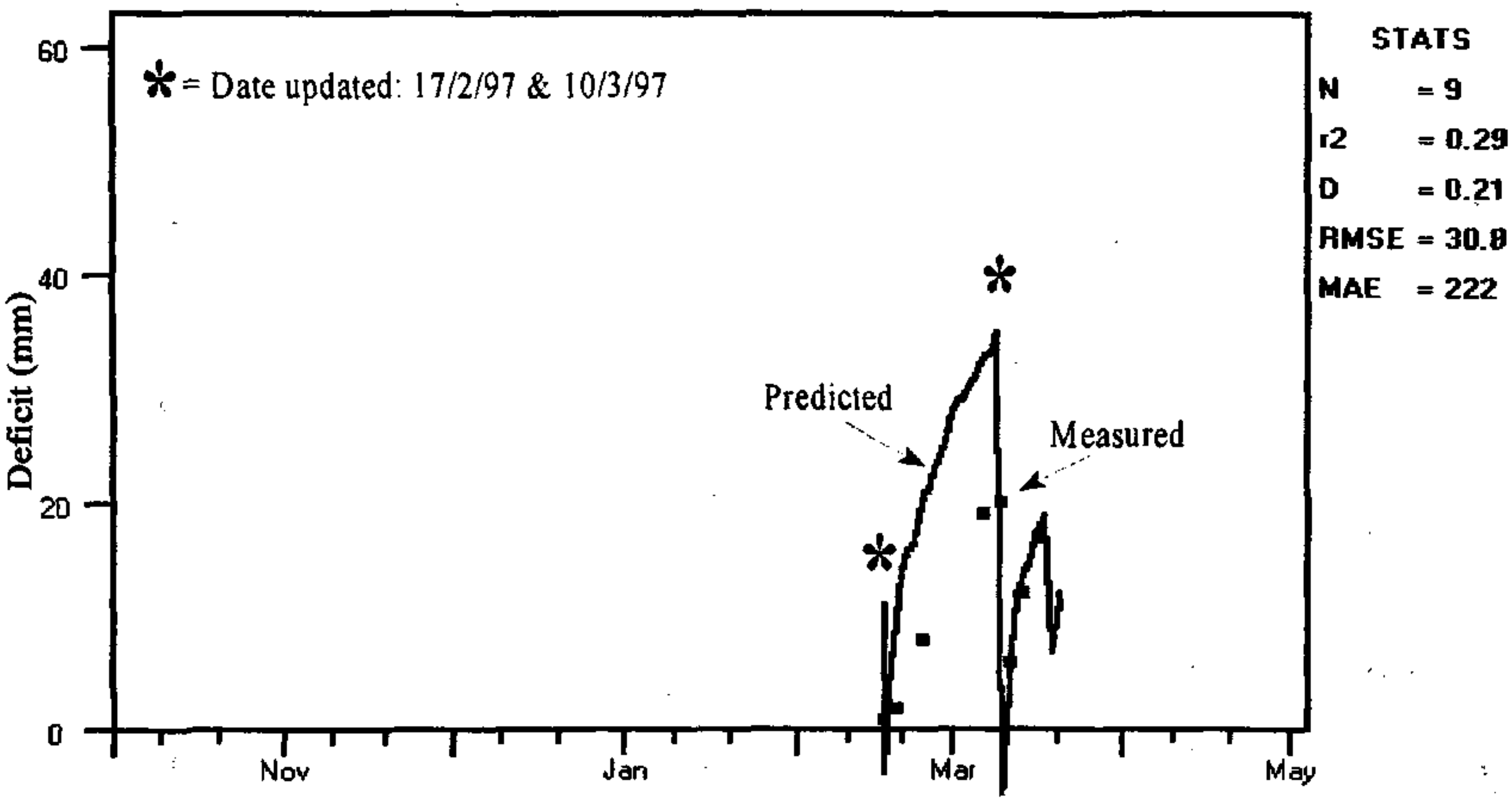


Figure 5.106

Predicted and measured soil water deficit for phase III over whole season.

Crop: 12 year Apple (cv. Golden Delicious, rootstock is Merton 793)

Input data set: Elgin (Infruitec)

Model type: FAO

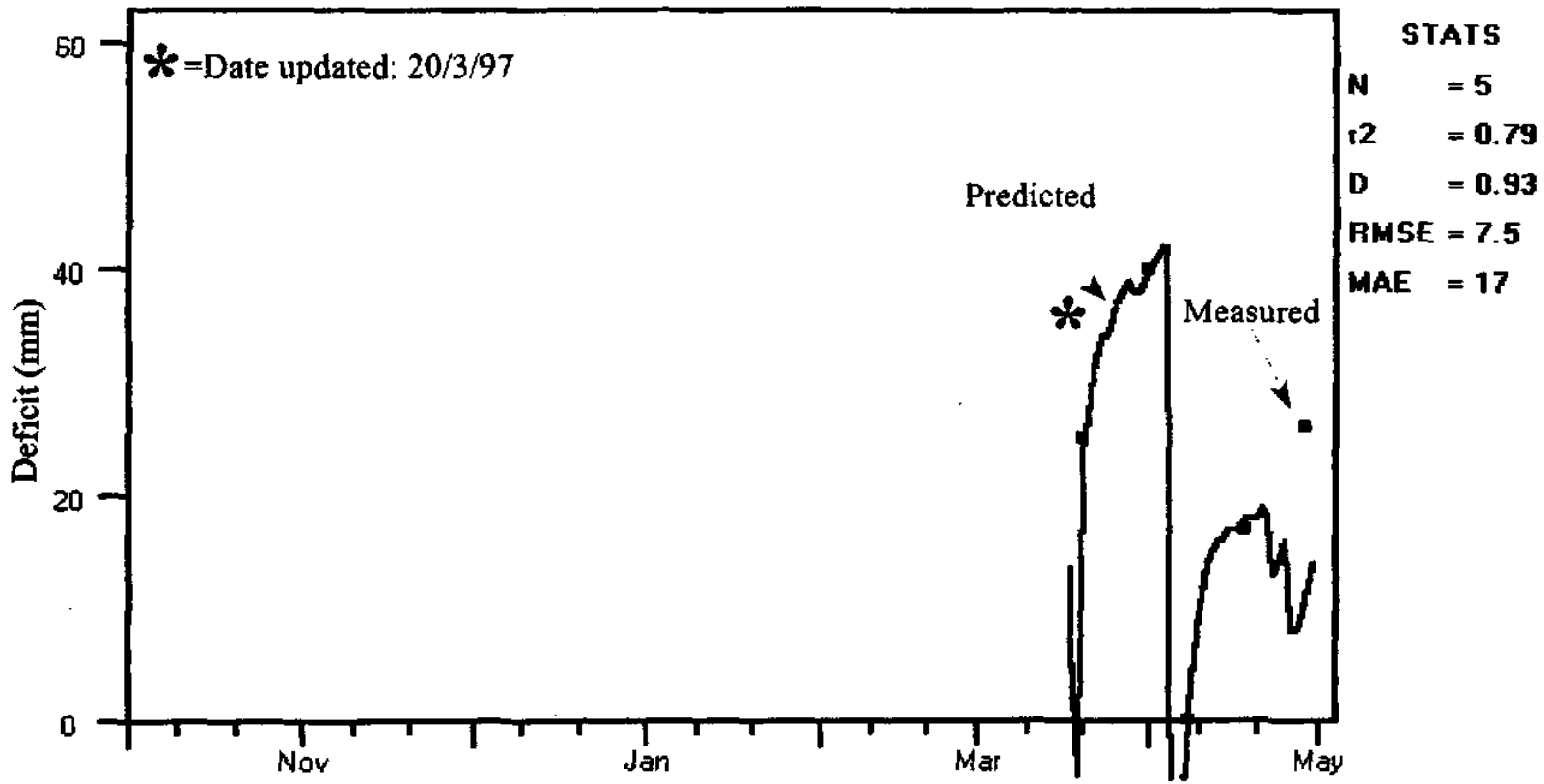


Figure 5.107

Predicted and measured soil water deficit for phase IV over whole season.

Crop: 12 year Apple (cv. Golden Delicious, rootstock is Merton 793)

Input data set: Elgin (Infruitec)

Model type: FAO

5.3.2 Citrus

The plant water dynamics data for this Section was supplied by Mr H.M. du Plessis (Water Research Commission) and was collected from the lysimeter facility at the Sundays River Experimental Farm near Addo during the period from 1976 to 1986. The climatic data was supplied by the Institute for Soil, Water and Climate, Pretoria. The authors are indebted to both parties for their cooperation.

Brief description of lay-out of Addo lysimeter facility

The Addo lysimeter facility is described in detail by Green and Bruwer (1979). Basically, there are three lysimeters constructed in a Valencia (*Citrus sinensis* L. cv. Osbeck) orchard in the Sundays River Valley Experimental Farm near Addo. The orchard has a 6.1 x 6.1 m planting pattern (i.e. 37.2 m^2 per tree). Each lysimeter has a surface area of 13.4 m^2 (3.66 x 3.66 m) which, according to Moreshet and Green (1979), approximates an irrigation basin equal to the drip of the tree. From the above, one can assume a canopy cover of 36% for the orchard.

During winter in 1972 a Valencia tree of the same age as the orchard (nine years) was transplanted into each lysimeter and soil was packed around the roots in layers in the same order and to the same bulk density as in the surrounding orchard (Green and Bruwer 1979). Moreshet and Green (1979) described a profile on the Experimental farm as an Oakleaf form of medium to fine sandy loam with a water holding capacity of 160 mm between 5 kPa and 1500 kPa in the top 100 cm of soil. Drainage of each lysimeter was facilitated by means of a coiled perforated pipe to which suction could be applied. The pipes were laid in a horizontal plane 1.7 m below the soil surface and embedded in coarse sand. This system proved adequate for removing the free water collected at the bottom of the lysimeter (1.8 m). This system closely simulated orchard soil water conditions in the top 1.2 m of soil where nearly all citrus roots are concentrated (Green and Bruwer, 1979).

Each lysimeter received a different irrigation regime. The tree in lysimeter "A" was subjected to a "long interval" between irrigations where the soil water deficit (SWD) reached the order of 100 to 150 mm before a heavy irrigation was applied to reduce the SWD to nil. Lysimeter "B" received a "short" interval between light irrigations; where it was attempted to keep the SWD close to 50 mm. The irrigation regime for lysimeter "C" fell between A and B; i.e. the irrigation interval and quantity applied were midway between A and B. In this treatment the SWD reached about 50 mm and was then irrigated back to nil.

Data interpretation

The climatic data files included daily precipitation (mm), daily maximum and minimum temperature (°C), daily average wind speed (m s^{-1}), as well as daily minimum and maximum relative humidity (%). These data sets were imported into SWB and used to calculate the required daily FAO reference evapotranspiration (ETo). From this basis, coupled to the precipitation and irrigation records, the daily soil water balance was determined for each lysimeter. The simulated soil water "Deficit" (mm) was then compared with the measured SWD (mm) for each lysimeter over a growing season (1 July to 30 June). The FAO crop parameters were used for the first simulation. Then, by comparing the simulated and measured values and making logical alterations to the crop parameters, it was possible to determine crop parameters for the Addo region. Once a set of crop parameters was established, it was then tested on another lysimeter data set during another year.

In this manner, it was possible to establish the following set of FAO crop parameters for Valencia trees:

PERIOD:	INITIAL	DEV	MID	LATE
Days	153	31	120	61
Kcb	0.5	---->	0.9	0.55
Root depth	1.2	---->	1.2	1.2
Height	3	---->	3	3

Stress day index: 0.95 Max transpiration: 9 mm/day
Potential at max transpiration: $-2000\ J\ kg^{-1}$ (Meyer and Green, 1981)

As can be seen in Figures 5.108a and 5.108b (long irrigation interval, 1976/77 season) and Figure 5.109 (very frequent irrigation, 1977/78 season), there is good agreement between simulated and measured values of soil water deficit.

It must be stressed that these crop parameters have been developed on the basis of the soil water balance and important factors such as yield and fruit size have not been considered. Thus it is very important to assess this yield and fruit size component.

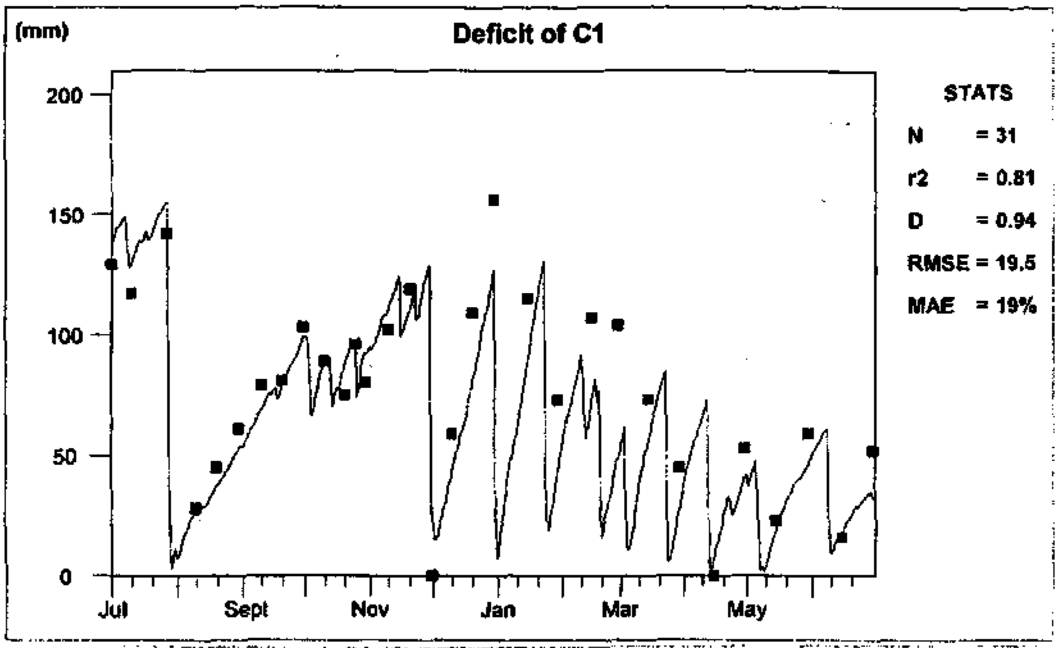


Figure 5.108a

Simulated (solid line) and measured (symbols) soil water deficit.

Crop: Orange (cv. Valencia)
Input data set: Addo (lysimeter data, 1976/77)
Model type: FAO

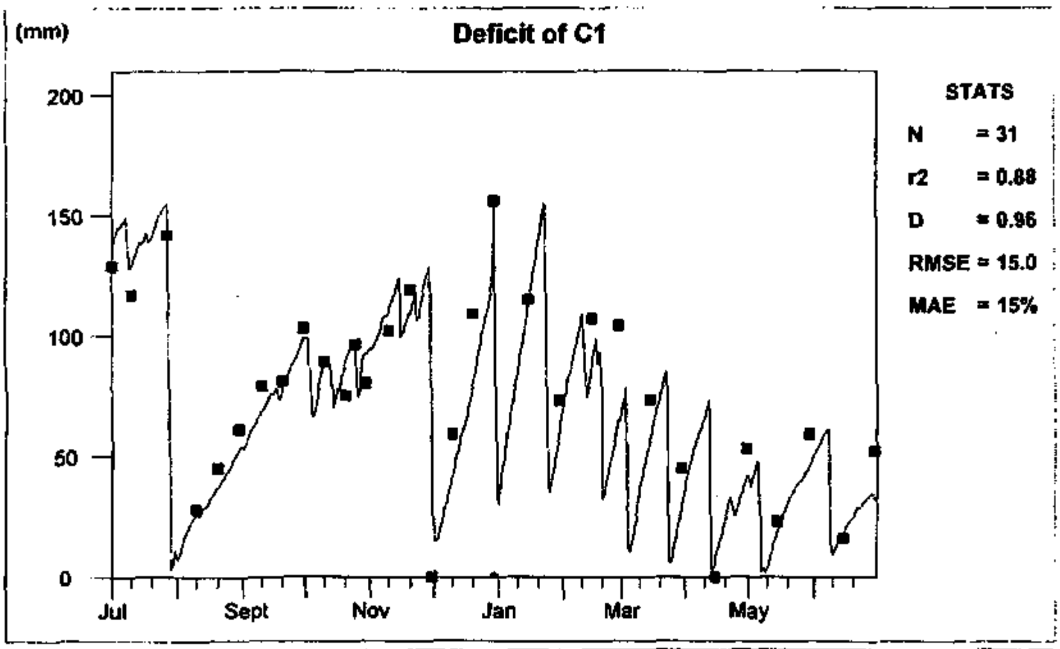


Figure 5.108b

Simulated (solid line) and measured (symbols) soil water deficit. The simulation was updated on 30/12/1976.

Crop: Orange (cv. Valencia)
Input data set: Addo (lysimeter data, 1976/77)
Model type: FAO

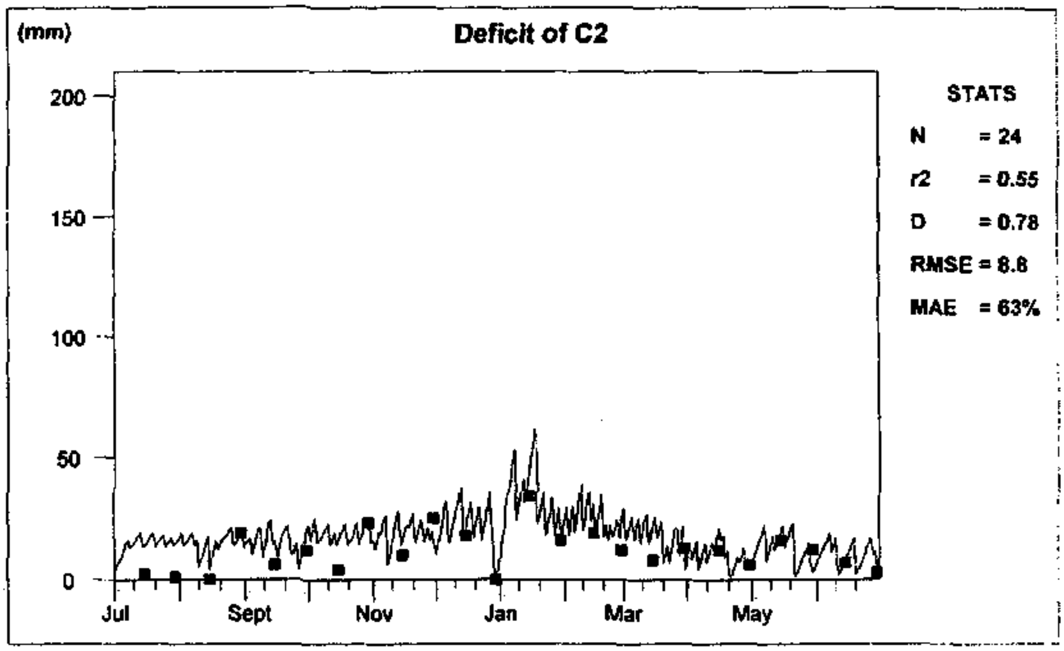


Figure 5.109
Simulated (solid line) and measured (symbols) soil water deficit.
Crop: Orange (cv. Valencia)
Input data set: Addo (lysimeter data, 1977/78)
Model type: FAO

5.3.3 Peach

Data sets for the calibration of SWB were obtained from the Hatfield trial (Section 4.2). The parameters required to run the FAO model were determined as described in Section 4.2.2. These are summarized in Table B2 (Appendix B).

During January and February 1997 (first leaf season), a strip of peach trees was water stressed. The comparison of soil water deficit simulated with SWB and that determined from measurements with the neutron water meter was good both for the stressed (Figure 5.110) and non-stressed treatment (Figure 5.111). Figure 5.112 shows measured and simulated soil water deficit for the second leaf season of peaches (1997/98 season).

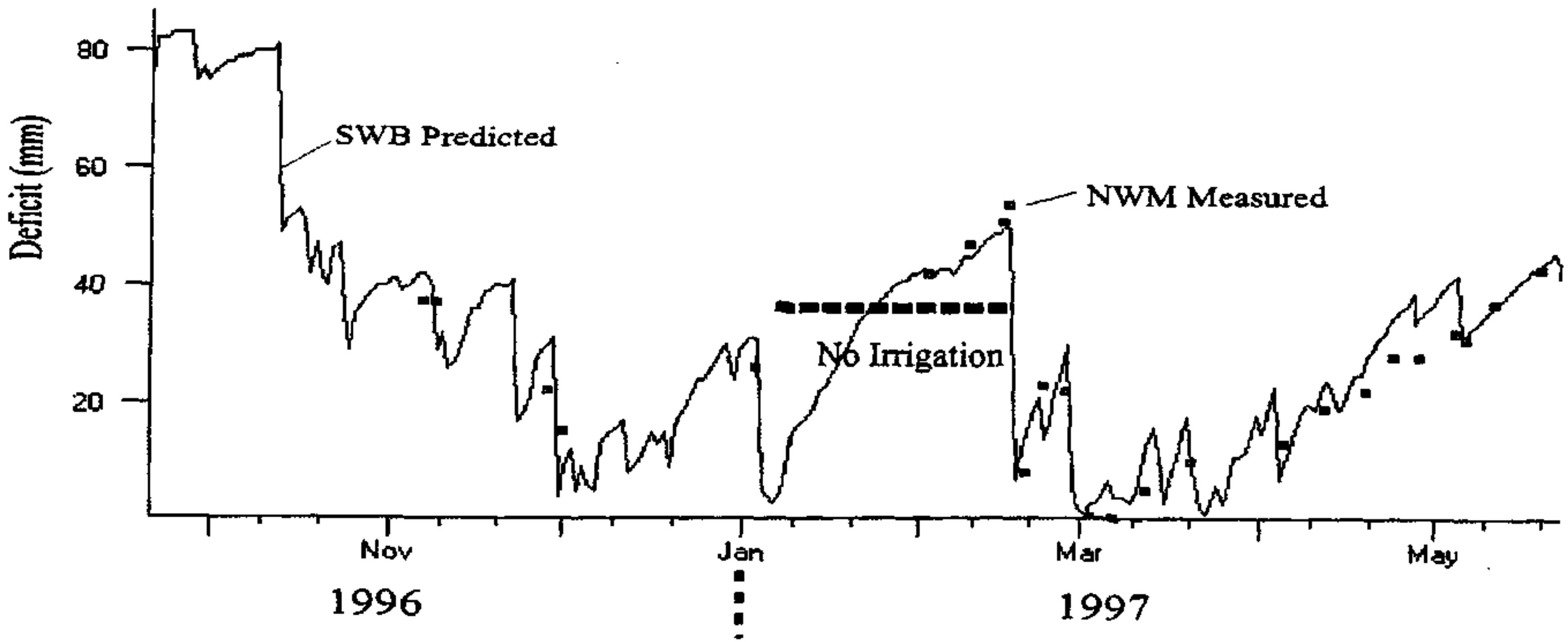


Figure 5.110

Simulated (solid line) and measured (symbols) soil water deficit of peaches for first leaf season (stress treatment).

Crop: Peach
Input data set: Hatfield field trial (Section 4.2)
Model type: FAO

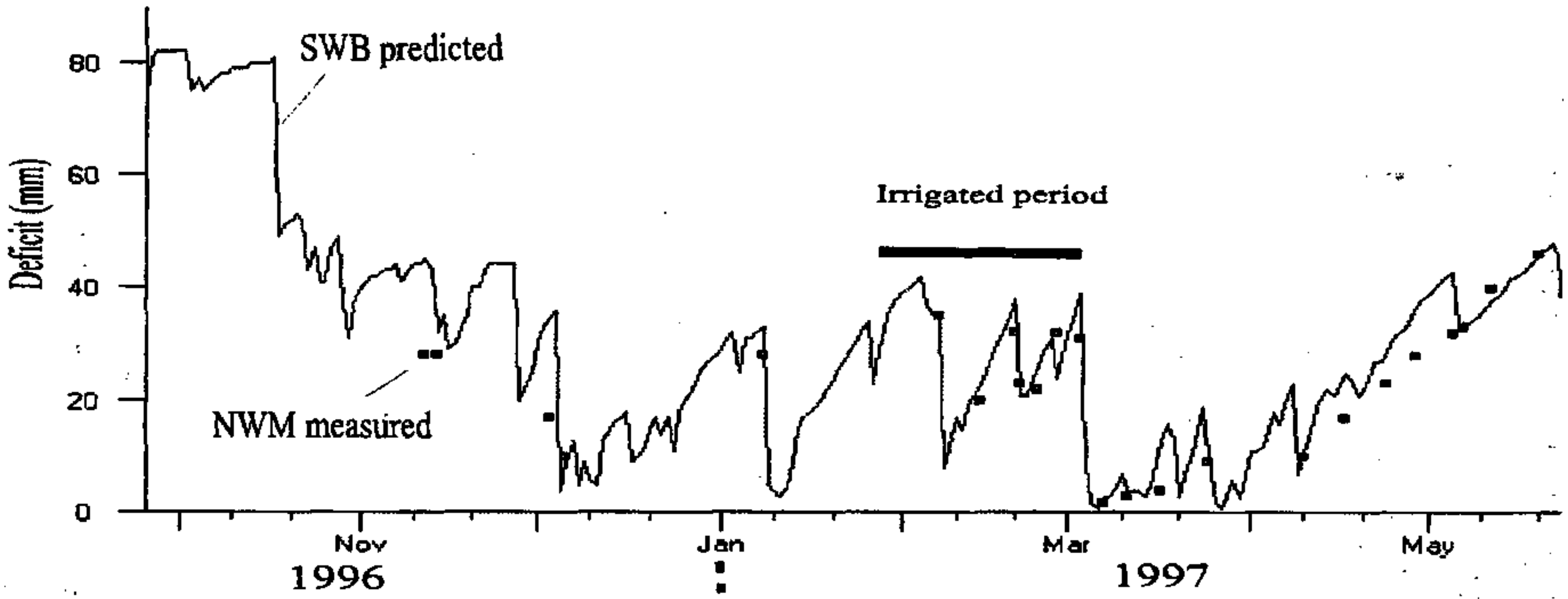


Figure 5.111
Simulated (solid line) and measured (symbols) soil water deficit of peaches for first leaf season (non-stressed treatment).

Crop: Peach
Input data set: Hatfield field trial (Section 4.2)
Model type: FAO

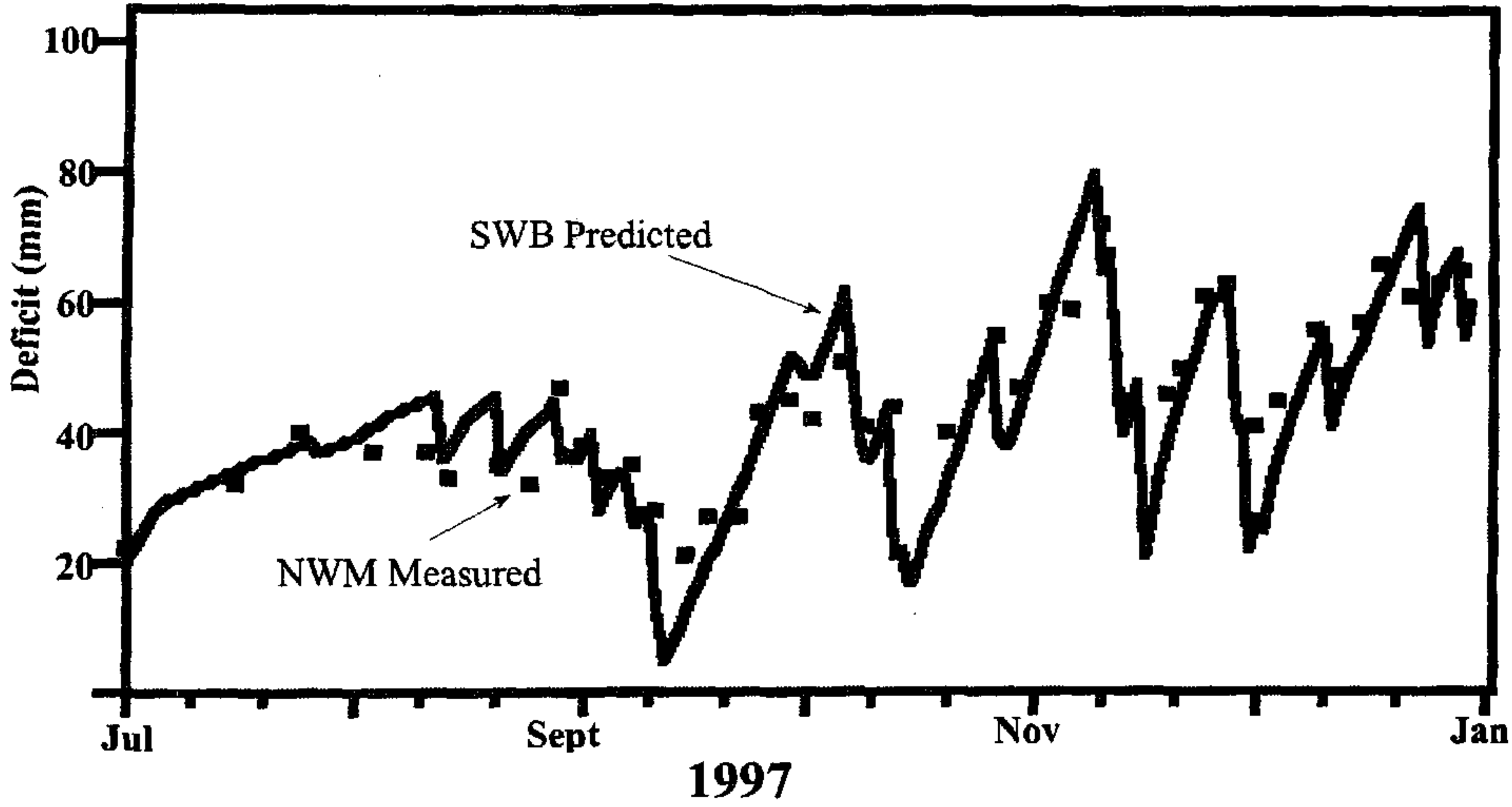


Figure 5.112
Simulated (solid line) and measured (symbols) soil water deficit of peaches for second leaf season.

Crop: Peach
Input data set: Hatfield field trial (Section 4.2)
Model type: FAO

CHAPTER 6

SWB FEATURES

6.1 User-friendly interface

The old DOS version of SWB was converted into the efficient 32 bit Delphi Windows 95 version. The user-friendly interface, on-line help tool, range and error checking, as well as comprehensive graphical output should allow the user to easily make real-time use of the output results.

Figure 6.1 represents the main menu of SWB as it appears on the screen.

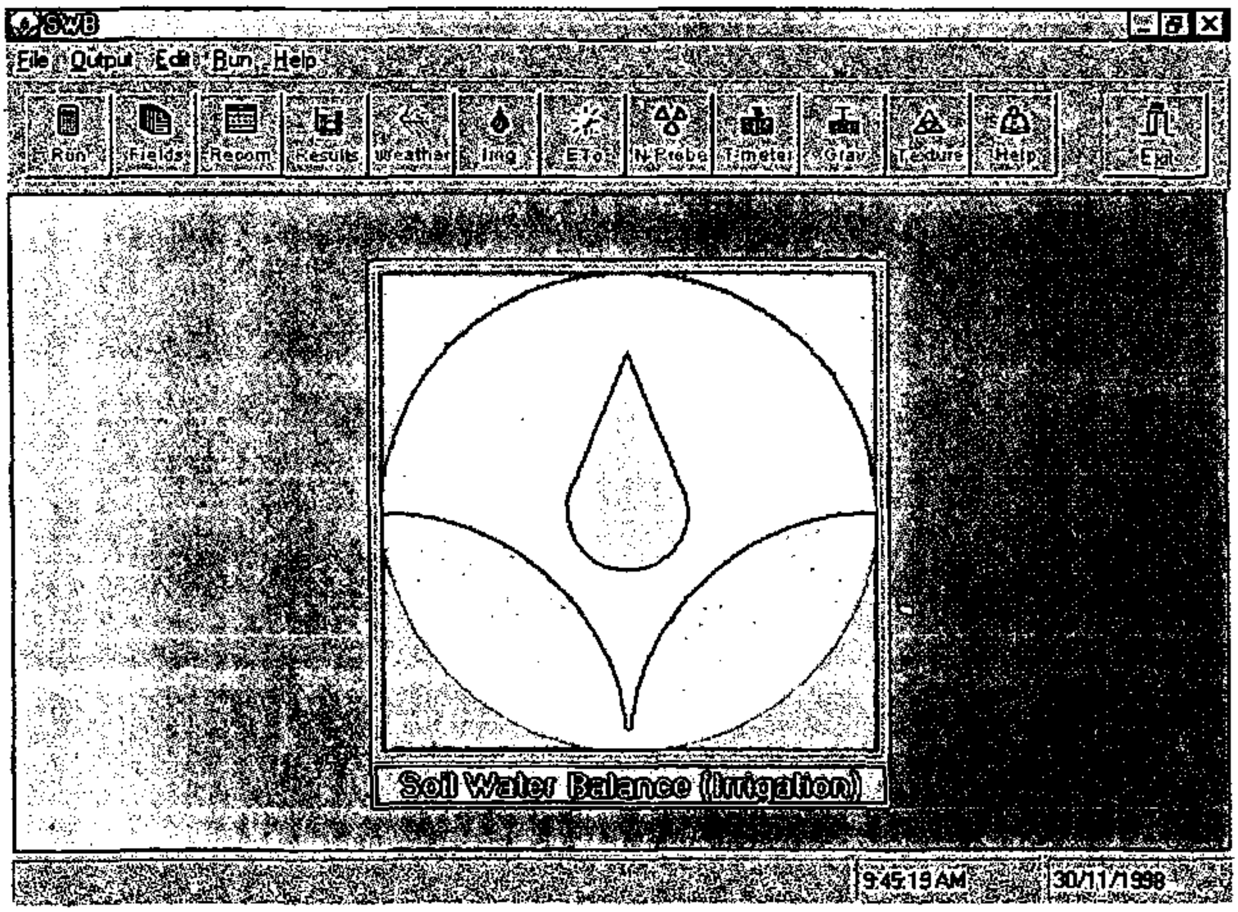


Figure 6.1

Main menu of SWB as it appears on the screen

SWB runs in two modes:

i) Irrigation mode does not allow editing of the crop parameters database. This feature was mainly included to prevent accidental overwriting of specific crop growth parameters and FAO crop factors.

ii) Scientific mode does allow editing of the crop parameters database. This feature was included to allow the user to add more crops to the database. In addition, by selecting the scientific mode, the user can run soil salinity and long-term simulations. Soil salinity and long-term simulations are not discussed in this report.

When first installed, SWB runs in irrigation mode. To swop mode, the user needs to double click on the bar below the logo in the main menu (Figure 6.1). A password needs to be typed in before SWB switches from irrigation to scientific mode.

Several options and icons can be selected in the main menu in order to enter input data, run simulations, print or create results and recommendations, as well as to use special features (Section 6.2).

Help files can be called by clicking on the help option or icon in the main menu (Figure 6.1). The help files are written in HelpScribble and they describe how to operate the model (enter input data, run simulations, and generate results and recommendations). They also describe most of the technical procedures used by SWB to estimate crop growth and calculate the soil water balance, as well as recommended ranges for input data and general information. The help files make extensive use of links and bitmaps with hotspots in order to access related topics. This should facilitate the operational and technical understanding of SWB. Context sensitive help can be accessed from any menu of SWB by pressing F1 on the keyboard. An example of the contents help topic is shown in Figure 6.2 as it appears on the screen.

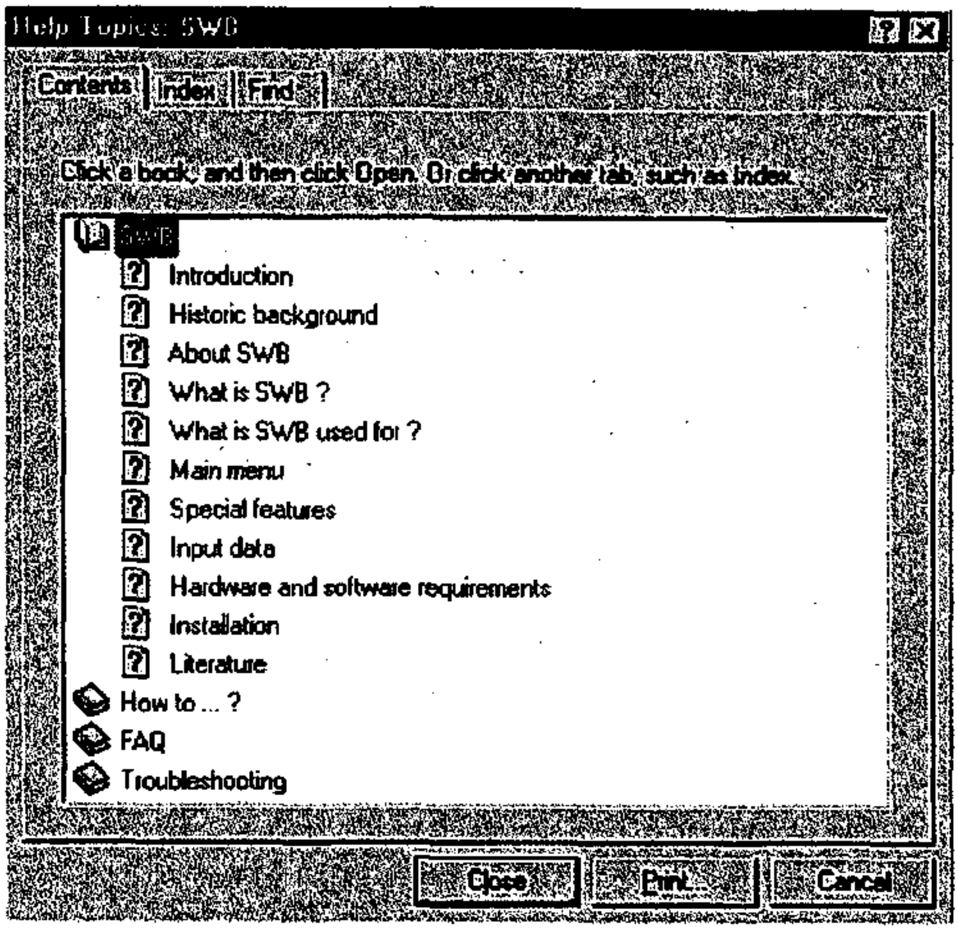


Figure 6.2

Contents help topic of SWB as it appears on the screen

SWB displays hints with ranges for input data, checks the ranges of input data, and generates error messages and warnings when operational errors are committed (e.g. input data out of range are entered). This should prevent accidental typing errors and errors in units. The example in Figure 6.3 shows the error message that pops up on the screen when a minimum temperature greater than the maximum temperature is entered for the same day in the weather database.

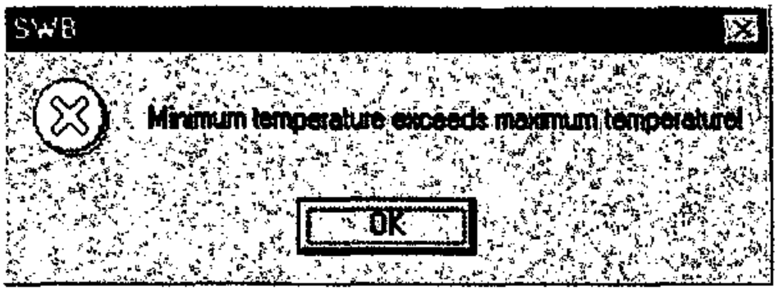


Figure 6.3

Error message that appears on the screen when a minimum temperature greater than the maximum temperature is entered for the same day in the weather database

SWB makes extensive use of graphics, in particular for the output. Besides the examples of graphs shown in the Figures in Chapter 5, SWB also generates printable graphs on which the following parameters are plotted for the simulated period:

i) Leaf area index;
ii) Root depth;
iii) Total above ground and harvestable dry matter;
iv) Fractional interception of total solar radiation;
v) Rainfall and irrigation;
vi) Evaporation;
vii) Transpiration;
viii) Drainage;
ix) Canopy interception;
x) Runoff;
xi) Potential evapotranspiration;
xii) Soil water deficit;
xiii) Profile soil water content;
xiv) Soil water content per layer;
xv) Crop height;
xvi) Basal crop coefficient;
xvii) FAO Penman-Monteith grass reference evapotranspiration;
xviii) Crop evapotranspiration; and
xix) Percentage of yield reduction predicted with the FAO model.

6.2 Special features

Several special features are included in SWB. These will be discussed in the following Sections.

6.2.1 ETo calculator

A stand-alone ETo calculator allows one to calculate the FAO Penman-Monteith grass reference evapotranspiration without running SWB. The procedure for the calculation of ETo with the ETo calculator is the same as that used for model predictions (Appendix A). Figure 6.4 shows the ETo calculator form as it appears on the screen. Input data are entered in the corresponding blocks, and ETo is calculated by clicking on the "Calc" icon.

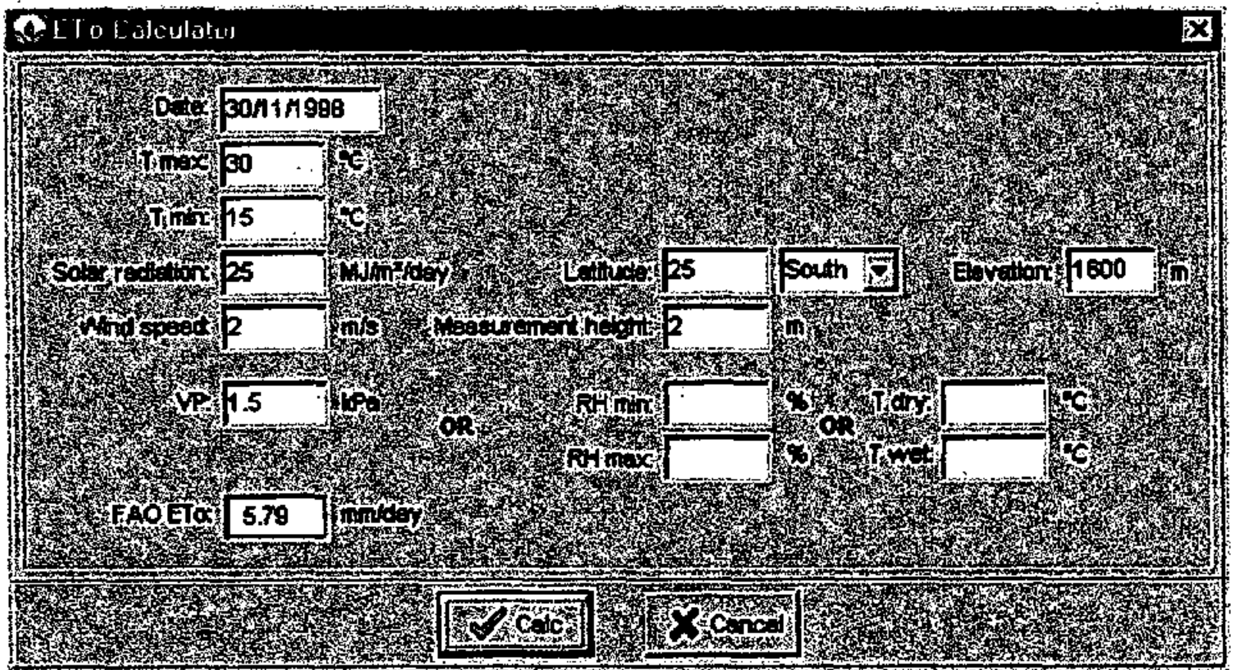


Figure 6.4

ETo calculator as it appears on the screen

6.2.2 Neutron probe scheduler

Soil water deficit can be calculated from measurements with the neutron water meter using the neutron probe scheduler as a stand-alone tool. The neutron probe scheduler form is shown in Figure 6.5 as it appears on the screen. Input data are entered in the corresponding cells. Volumetric soil water content and standard error of the measurement are calculated for a maximum of 11 soil layers (blue characters in Figure 6.5). Data from the soil database of SWB can be imported into the neutron probe scheduler form. Water content calculated in this form can be sent to the measured values database, or can be used to update simulations (Section 6.2.6).

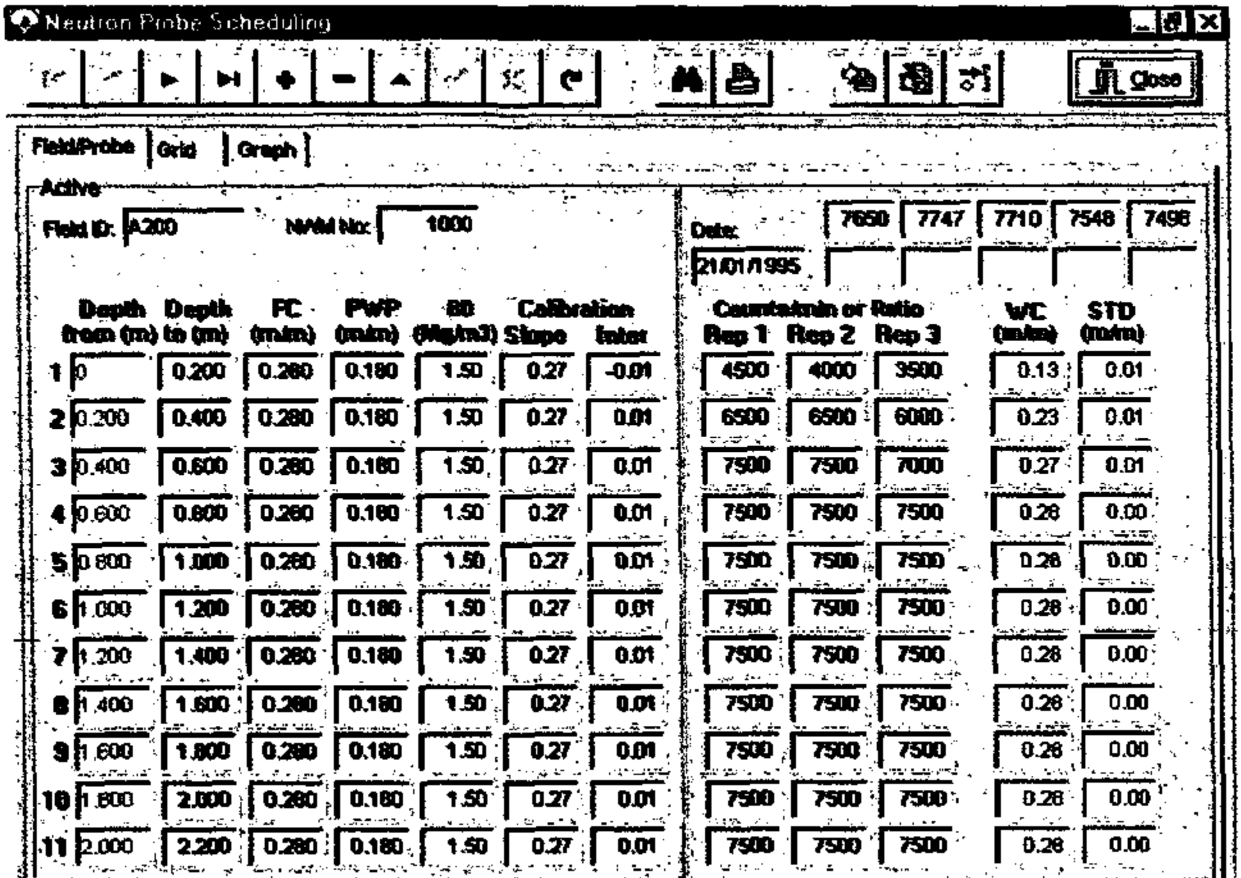


Figure 6.5

Neutron probe scheduler form as it appears on the screen

Volumetric soil water content calculated from neutron water meter measurements can also be displayed graphically (Figure 6.6). The horizontal bars represent the standard errors of the measurements and the calculated soil water deficit appears in the top right corner of the screen.

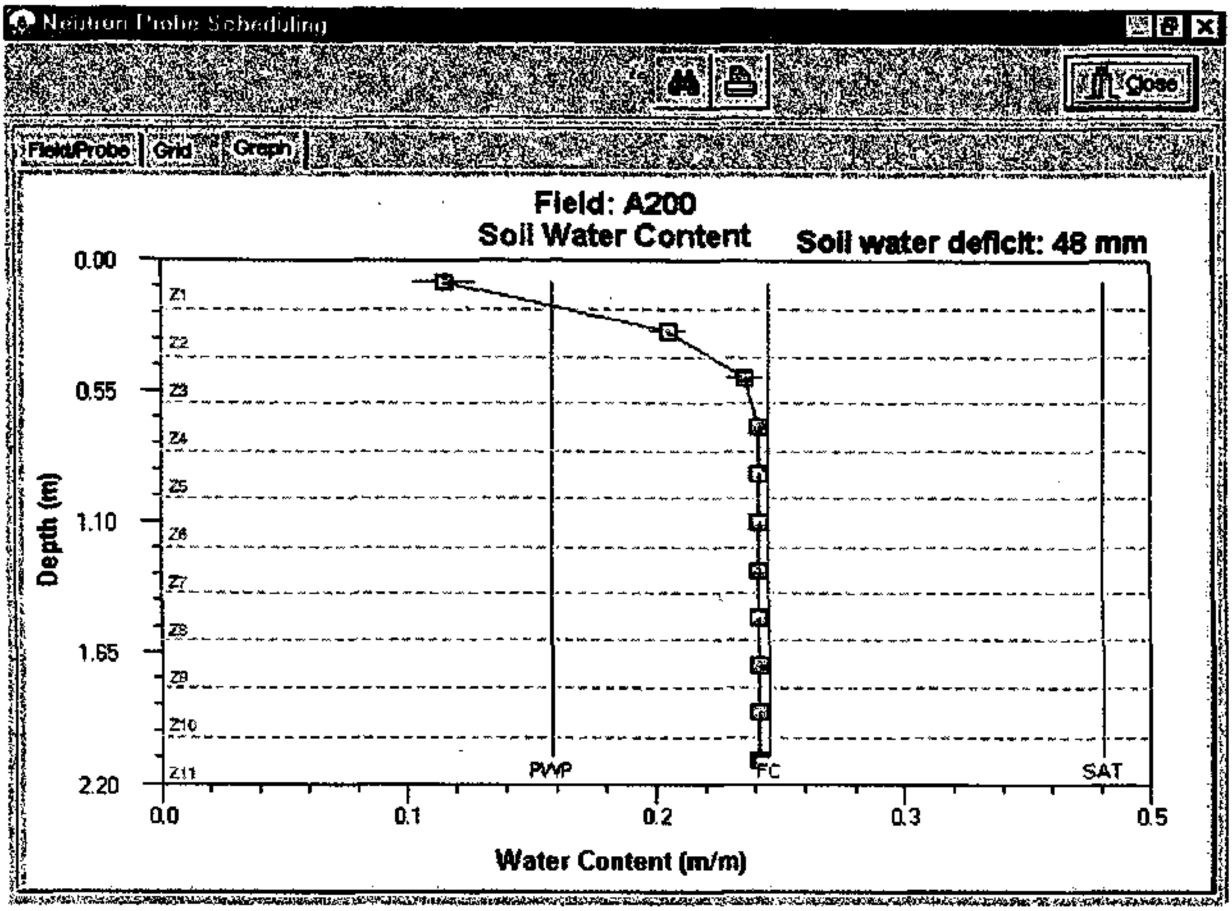


Figure 6.6

Example of graphical output of volumetric soil water content per soil layer calculated from neutron water meter measurements, as it appears on the screen. The horizontal bars represent the standard error of the measurement. Permanent wilting point (PWP), field capacity (FC) and saturation water content (SAT) are shown on the graph

6.2.3 Tensiometer scheduler

Soil water deficit can be calculated from measurements with tensiometers using the tensiometer scheduler as a stand-alone tool. The tensiometer scheduler form is shown in Figure 6.7 as it appears on the screen. Input data are entered in the corresponding cells. Volumetric soil water content and standard error of the measurement are calculated and displayed in the columns on the right side of the screen. Water content calculated in this form can be sent to the measured values database, or can be used to update simulations (Section 6.2.6). Volumetric soil water content and soil matric potential can be graphically displayed. The assumptions used to calculate soil water deficit from tensiometer measurements are explained in the help file.

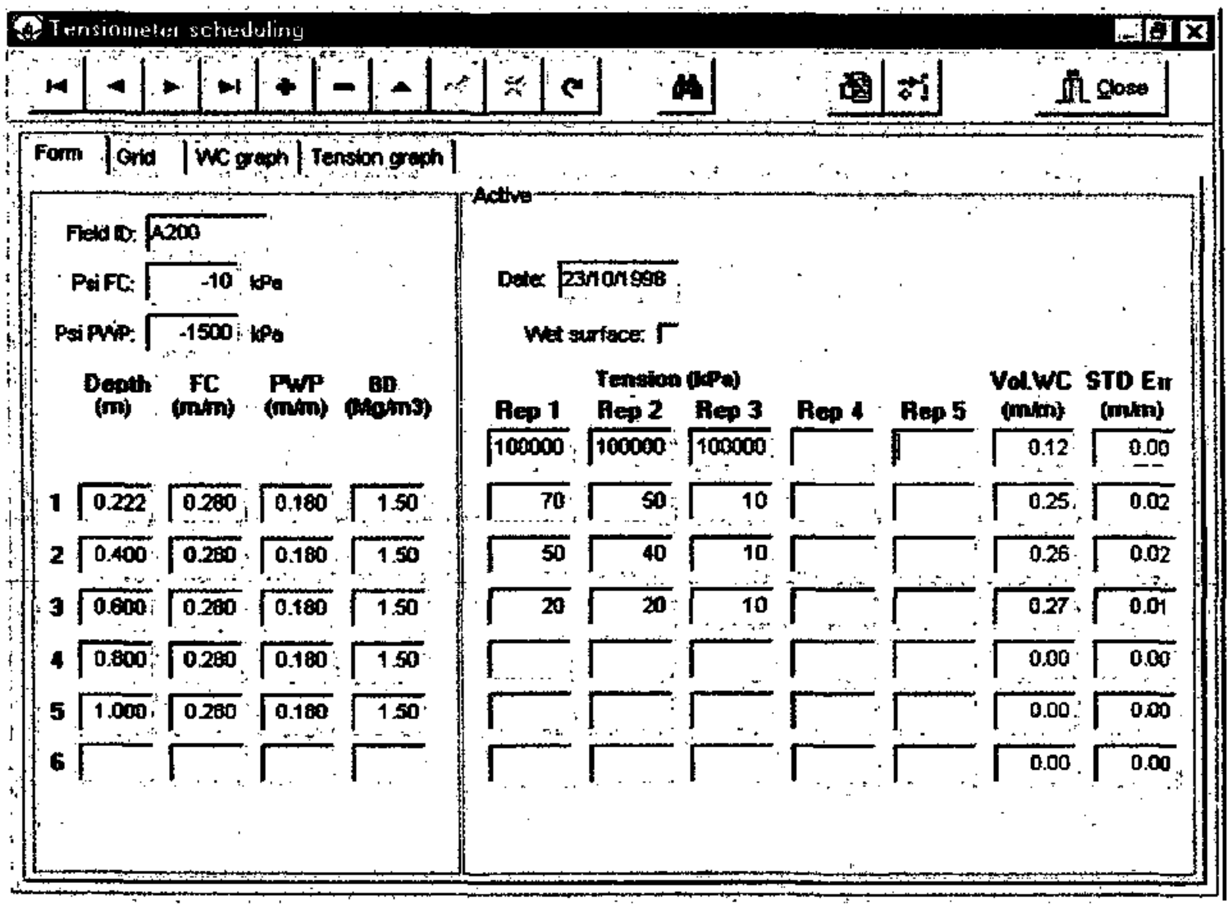


Figure 6.7

Tensiometer scheduler form as it appears on the screen

6.2.4 Gravimetric scheduler

Soil water deficit can be calculated from gravimetric measurements of soil water content using the gravimetric scheduler as a stand-alone tool. The gravimetric scheduler form is shown in Figure 6.8 as it appears on the screen. Input data are entered in the corresponding cells. Volumetric soil water content and standard error of the measurement are calculated and displayed in the columns on the right side of the screen. Water content calculated in this form can be sent to the measured values database, or can be used to update simulations (Section 6.2.6). Volumetric soil water content calculated from gravimetric measurements of soil water content can be displayed graphically.

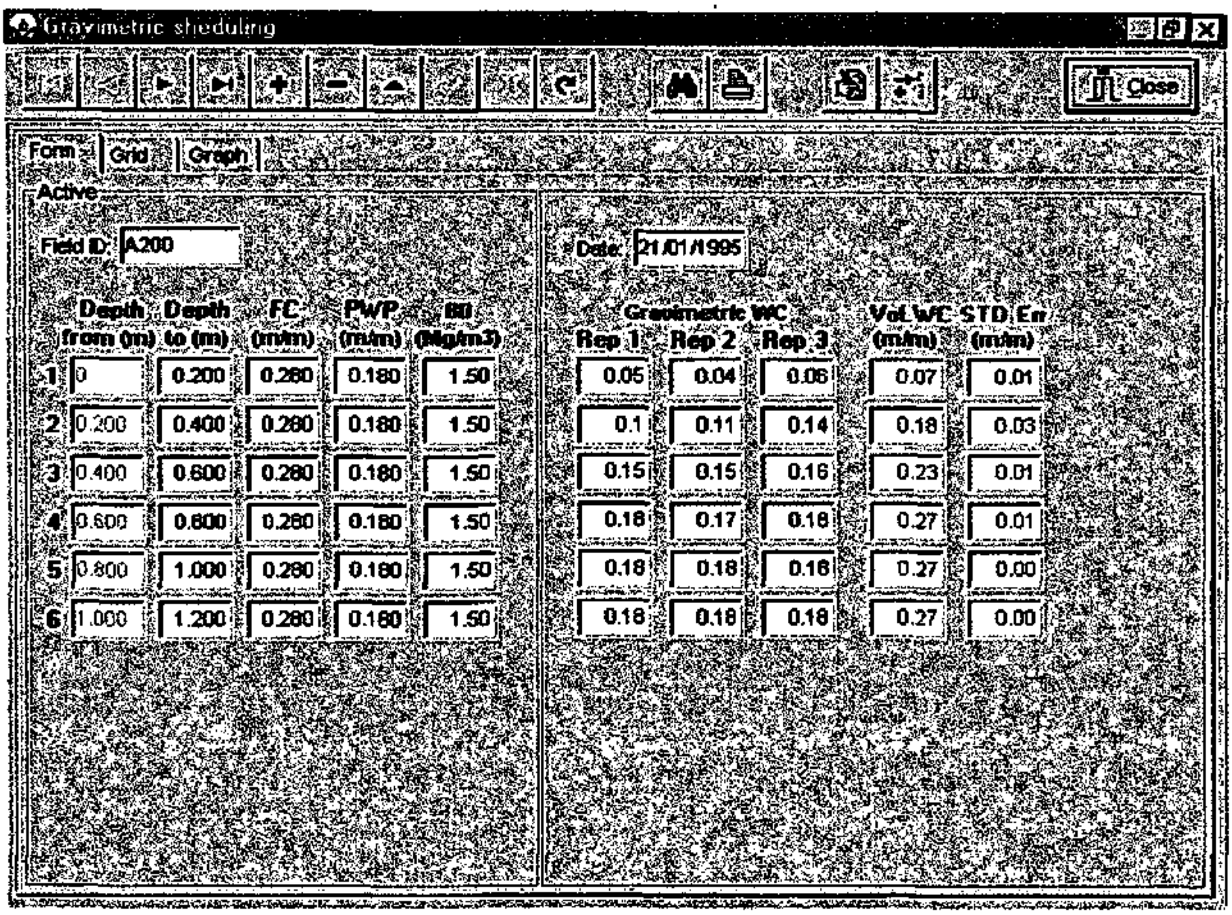


Figure 6.8

Gravimetric scheduler form as it appears on the screen

6.2.5 Field capacity and permanent wilting point calculator

Volumetric soil water content at field capacity and permanent wilting point are calculated from texture analysis (% silt and clay), using the empirical equations determined by Bennie et al. (1988) for soils in the Free State. The field capacity and permanent wilting point calculator form is shown in Figure 6.9 as it appears on the screen. The percentage of silt and clay is entered in the corresponding cells. Volumetric soil water content at field capacity and permanent wilting point calculated and displayed in the columns on the right side of the screen (blue characters in Figure 6.9).

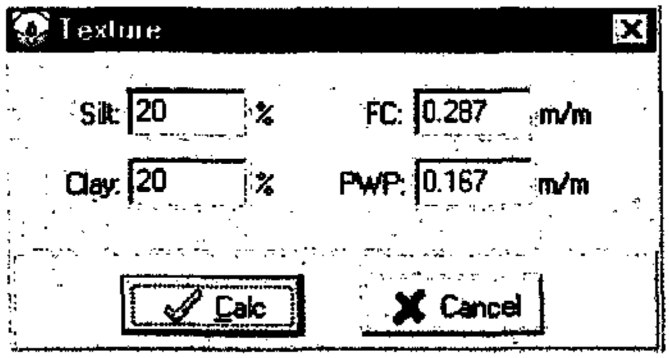


Figure 6.9

Field capacity and permanent wilting point calculator form as it appears on the screen

6.2.6 Update simulation

Computer models operated from offices are not supposed to completely substitute field measurements. They could, however, facilitate management by making field visits less frequent. SWB, as any other model, is very unlikely to simulate a value for a parameter which is exactly equal to the measurement. For this reason, the update simulation feature was included in the model. Simulated values of fractional interception and volumetric soil water content can be updated real-time with measured data.

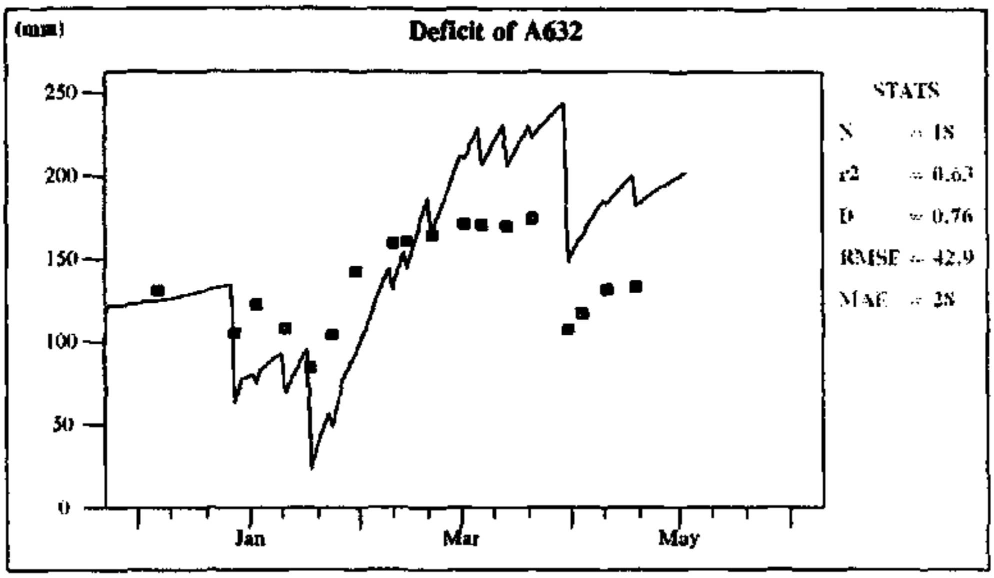
Figure 6.10 shows an example of updated simulation for peanuts, treatment L1VL (Bennie et al., 1996) (Section 5.1.2). The top graph represents the non-updated simulation of soil water deficit (solid line), as well as measured data (symbols). The bottom graph shows the updated simulation. Volumetric soil water content was updated on 02/03/95, as indicated with the arrow in the bottom graph. The parameters of the statistical analysis between measured and simulated data (Chapter 5) are shown in the top right corner of each graph.

In order to facilitate the estimation and update of fractional interception of radiation (canopy cover), a database of photos of crops at different canopy cover fractions was included in the help file. Measured values of fractional interception of radiation are reported for each photo. An example is shown in Figure 6.11.

6.2.7 Recommendations

Recommendations for irrigation scheduling are generated and can be printed by SWB. The following information of interest to the user is displayed in the recommendations table:

i) Field identification number;
ii) Date;
iii) Irrigated area;
iv) Irrigation system used;
v) Weather station linked to the particular field;
vi) Crop;
vii) Growth stage of the crop;
viii) Desired frequency of irrigation;
ix) Desired irrigation strategy;
x) Number of stress days during the growing season;
xi) Soil water deficit;
xii) Number of days till next irrigation for the particular field;
xiii) Recommended date of next irrigation for the particular field;
xiv) Recommended amount of irrigation for the particular field;
xv) Recommended volume of irrigation water for the particular field;
xvi) Recommended time of irrigation in hours and minutes;
xvii) Average ET rate in the last 5 days.



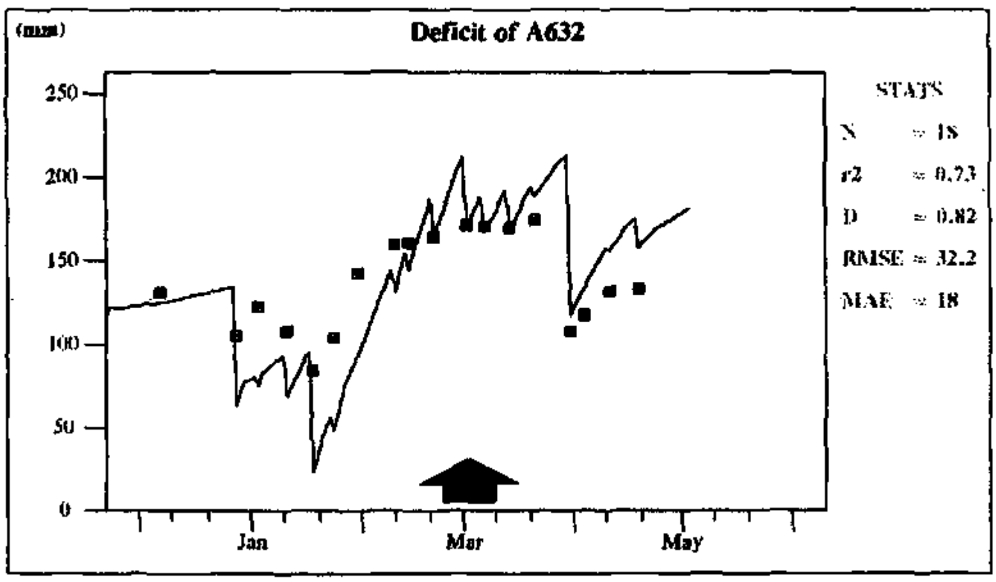


Figure 6.10

Non-updated (top graph) and updated simulation (bottom graph) of soil water deficit for peanuts, treatment L1VL (Bennie et al., 1996) (Section 5.1.2). The solid line represents predicted values, whilst symbols are measured data. Volumetric soil water content was updated on 02/03/95, as indicated with the arrow in the bottom graph

Figure 6.11

Example of a photo of chilli pepper included in the help file to facilitate the estimation and update of fractional interception of radiation (canopy cover).

The following information is supplied:
Fractional interception of radiation (canopy cover) = 0.40
Crop height = 45 cm
(Location: Roodeplaat, Pretoria; Season: summer 1996/97; Soil: clay loam)

6.2.8 Crop parameter database

A database of specific crop growth parameters and FAO crop factors is included in SWB. Specific crop growth parameters are shown in Table B1 (Appendix B), whilst parameters required to run the FAO model are given in Table B2 (Appendix B).

The database of specific crop growth parameters was built using data obtained from South African researchers (Section 3.3), from the Roodeplaat and Hatfield field trials (Chapter 4), as well as from the Kromdraai trial (Barnard et al., 1998). Specific crop growth parameters were measured, obtained from measured data by calibration or estimated. Cardinal temperatures for vegetables were taken from Knott (1988), and Campbell and Norman (1998). Differences in cultivars could affect thermal time requirements for crop phenological stages and canopy development.

The database of FAO crop factors was also built using data obtained from South African researchers (Section 3.3), as well as from the Roodeplaat and Hatfield field trials (Chapter 4). The database was completed using parameters recommended in the FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996) for crops with no field measurements available. Parameters which are not available in the FAO literature, were estimated. For some crops, FAO parameters for species with similar canopy structure and growth periods were included in the SWB database. For those crops, the FAO literature was cited in the footnote of Table B2. If stress factors for different growth stages were not available, these were assumed to be 0.5. If allowable depletion levels for different growth stages were not available, these were assumed to be 50%. Potential yield is expected to vary depending on location and crop management. Caution should be exercised against blind acceptance of the FAO parameters as local conditions, management and cultivars are likely to influence crop growth periods and basal crop coefficients.

6.2.9 Address database

An address database can be used to keep record of the users of SWB. Figure 6.12 shows the address database form as it appears on the screen. Data of SWB users are entered in the corresponding cells and stored in the address database.

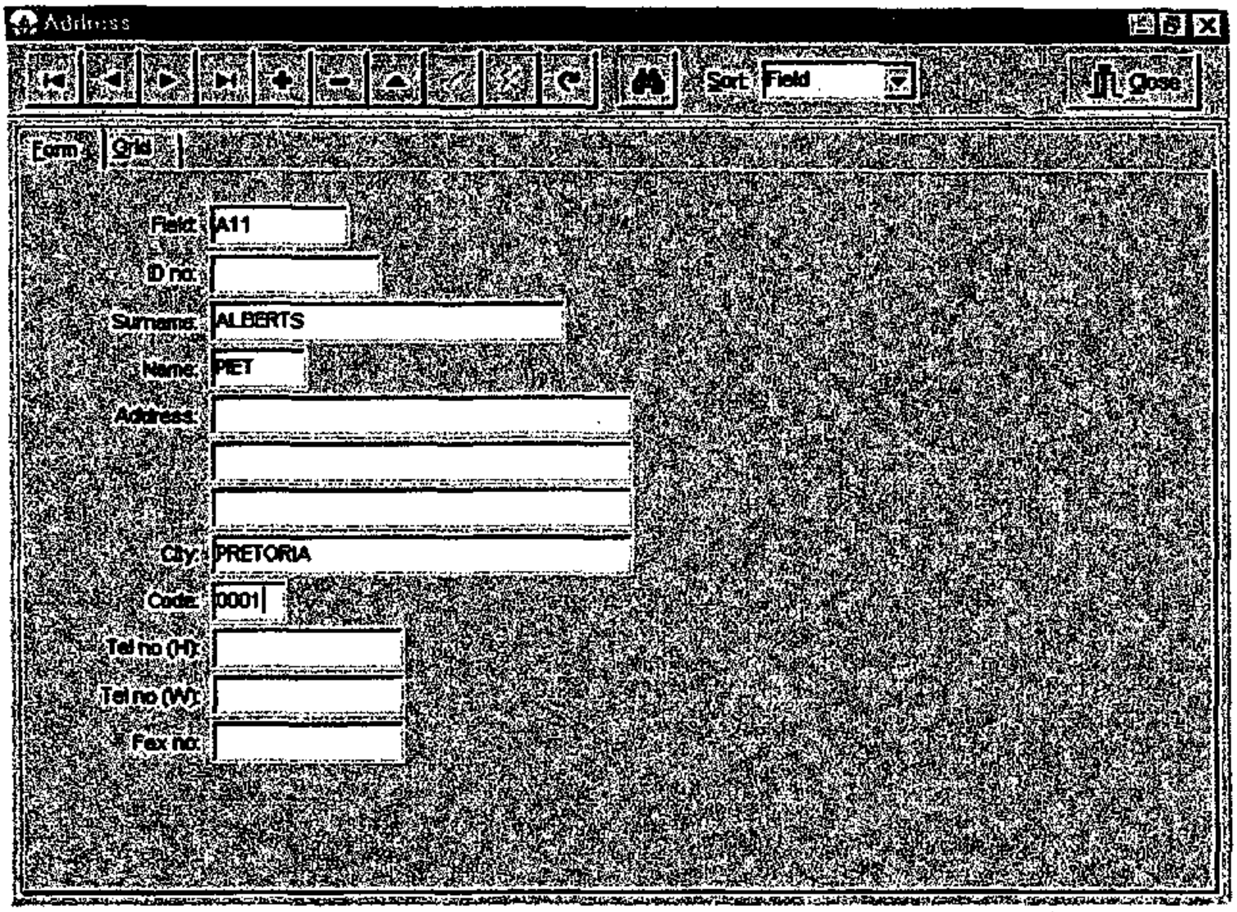


Figure 6.12

Address database form as it appears on the screen

6.2.10 Import weather data

Weather data can be imported into SWB from comma delimited, tab delimited or space delimited files. Figure 6.13 shows the import weather data form as it appears on the screen. By selecting the detail form (Figure 6.13), the order in which the data appear in the file can be specified, so standardization of data files is not important. Ranges of the imported weather data can also be set up by the user in the detail form. While importing weather data, SWB checks for data out of range. These can be displayed by selecting the out of range form (Figure 6.13).

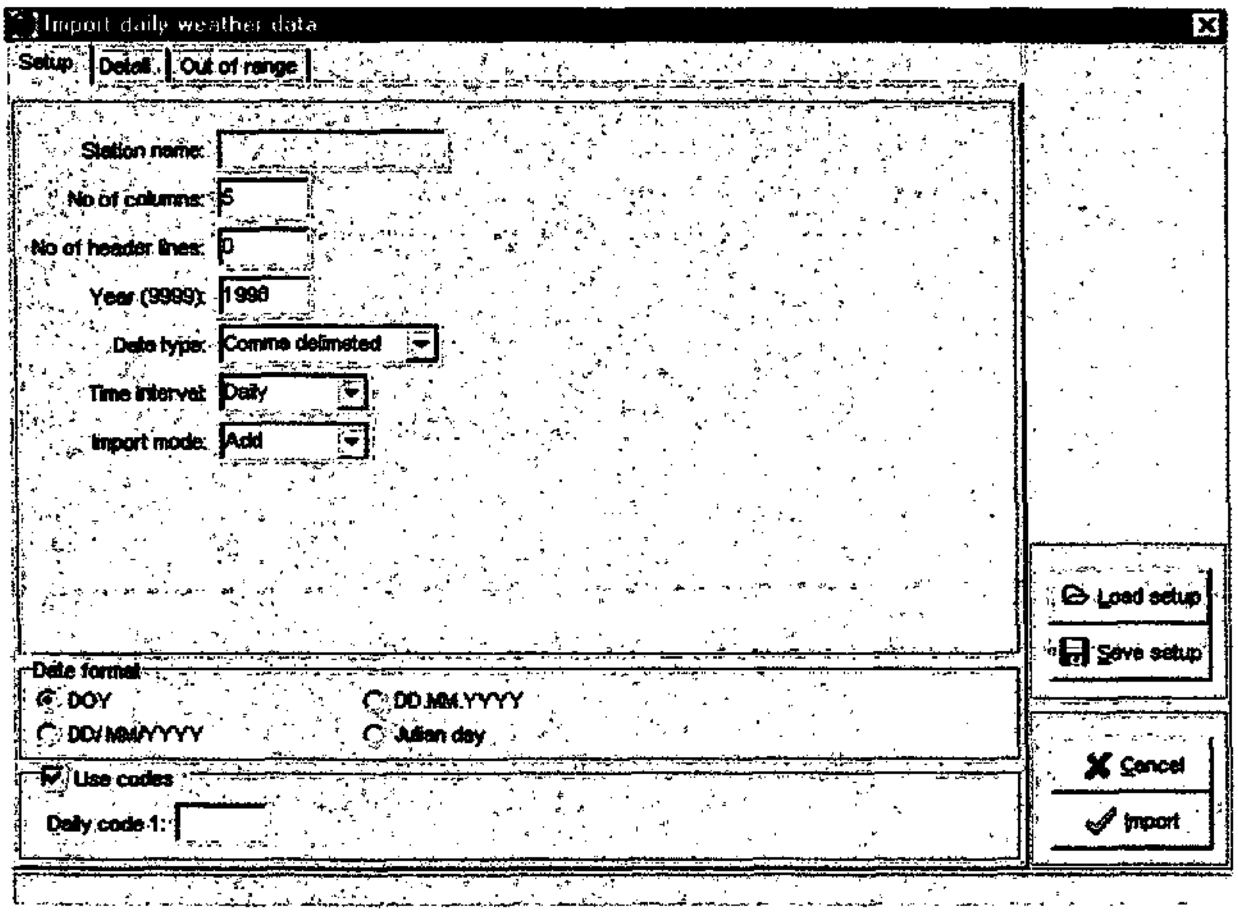


Figure 6.13

Import weather data form as it appears on the screen

CHAPTER 7

TECHNOLOGY TRANSFER ACTIONS

SWB (Version 1.0) is available for use with Windows 95 on an IBM-PC or compatible computer. The minimum requirement is 16 Mb RAM . The time required to complete a seasonal simulation is 3 to 5 s on a Pentium 166. The program is supplied in executable code on 3.5-inch disks or CD, including a comprehensive user's guide and technical manual. Copies of the program are available through John G. Annandale, Dept. Plant Production and Soil Science, Univ. of Pretoria, 0001 Hatfield, South Africa (e-mail address: annan@scientia.up.ac.za).

The cost of the CD and user's guide and technical manual is R500, if SWB is used for commercial purposes. Bona fide researchers and government extension officers are charged R100 to cover duplication costs. A register of SWB users is done by the Dept. Plant Production and Soil Science, Univ. of Pretoria.

The source code of the model is available from Dr N Benadé. All data presented in this report are stored in the databases of SWB.

SWB is mainly used for real-time irrigation scheduling. The main target group includes commercial farmers as well as irrigation officers and consultants. Small-scale commercial farmers are also potential users, as well as small-scale subsistence farmers, provided they are advised by irrigation officers.

Other applications of SWB are:

- i) Crop growth and water use under soil salinity conditions (no toxic ion effect is included in the model);
- ii) Long-term simulations of water and salt balance with generated weather data; and
- iii) Irrigation planning, if historic weather data are entered in the model.

SWB is already used by several irrigation consultants and commercial farmers.

Dr JM Steyn (Agricultural Research Council - Roodeplaat Vegetable and Ornamental Plant Institute - Potato Programme) uses SWB as an irrigation scheduling tool for potatoes in the Northern Province. This is part of a scheduling service run by the Agricultural Research Council (Roodeplaat) on a trial basis.

Omnia approached the research team to address their agriculturalists on using SWB.

The research group has been approached to assist Prof N Botha (University of Pretoria) to present short courses on the use of SWB for his technology transfer project sponsored by the Water Research Commission. Infruitec (Agricultural Research Council - Stellenbosch) was also assisted with their Water Research Commission project.

SWB was used for modelling crop growth and water use under irrigation with lime-treated acid mine drainage in the Water Research Commission project carried out by Barnard et al. (1998). Long-term simulations of water and salt balance with generated weather data were also made with SWB in order to predict the long-term effect of irrigation with lime-treated acid mine drainage on soil and water resources. SWB will be used to schedule pivot irrigations for several crops, in the Water Research Commission project entitled "Modelling and monitoring crop production, soil properties and drainage water under centre pivot irrigation with gypsiferous mine water".

The following papers and posters were presented at conferences:

1) MHLAULI NC, JOVANOVIC NZ, FERREIRA DI and ANNANDALE JG (1997) Crop water use efficiency of six vegetable species. *First All Africa Crop Science Congress.* Jan 1997, Pretoria, South Africa.

2) ANNANDALE JG, BENADÉ N, JOVANOVIC NZ and VAN DER WESTHUIZEN AJ (1997) The Soil Water Balance (SWB) irrigation scheduling model. *First All Africa Crop Science Congress.* Jan 1997, Pretoria, South Africa.

3) DU SAUTOY N, ANNANDALE JG, JOVANOVIC NZ, VAN DER MERWE LL and DE BEER JM (1997) Water balance studies on deciduous fruit trees in Gauteng; preliminary results. *First All Africa Crop Science Congress.* Jan 1997, Pretoria, South Africa.

4) MHLAULI NC, JOVANOVIC NZ, FERREIRA DI and ANNANDALE JG (1997) Crop water use efficiency of spinach. *7th Congress of the Southern African Society for Horticultural Sciences.* June 1997, Nelspruit, South Africa.

5) DU SAUTOY N, JOVANOVIC NZ and ANNANDALE JG (1997) Modelling peach water use for irrigation scheduling. *7th Congress of the Southern African Society for Horticultural Sciences.* June 1997, Nelspruit, South Africa.

6) JOVANOVIC NZ AND ANNANDALE JG (1998) Facilitating irrigation scheduling of several vegetable species by means of the Soil Water Balance (SWB) model. *Joint Congress, Soils and Crops Towards 2000.* Jan 1998, Alpine Heath, KwaZulu-Natal, South Africa.

7) DU SAUTOY N, JOVANOVIC NZ and ANNANDALE JG (1998) Modelling fruit tree water use for irrigation scheduling. *Joint Congress, Soils and Crops Towards 2000.* Jan 1998, Alpine Heath, KwaZulu-Natal, South Africa.

8) ANNANDALE JG, BENADÉ N, JOVANOVIC NZ and DU SAUTOY N (1998) SWB, a user friendly irrigation scheduling model. *Joint Congress, Soils and Crops Towards 2000.* Jan 1998, Alpine Heath, KwaZulu-Natal, South Africa.

9) THACKRAH A, WALKER S, PEENSE L, JOVANOVIC NZ and ANNANDALE JG (1999) Modelling irrigation requirements of vegetable crops at Roodeplaat. *8th Congress of the Southern African Society for Horticultural Sciences.* Jan 1999, Stellenbosch, South

Africa.

Paper No. 8 won the Soil Science Society silver medal as the best paper on implementable technology at the Joint Congress; Soils and Crops Towards 2000, January 1998, Alpine Heath, KwaZulu-Natal, South Africa.

The following papers were published:

1) JOVANOVIC NZ and ANNANDALE JG (1998) Measurement of radiant interception of crop canopies with the LAI-2000 plant canopy analyzer. *S. A. Plant Soil* **15**(1), 6-13.

2) JOVANOVIC NZ and ANNANDALE JG (1999) An FAO type crop factor modification to SWB for inclusion of crops with limited data: Examples for vegetable crops. *Water SA*. In press.

3) JOVANOVIC NZ, ANNANDALE JG and MHLAULI NC (1999) Field water balance and SWB parameter determination of six winter vegetable species. *Water SA*. In press.

SWB was presented during the South African Irrigation Institute conference held in Blydepoort (May 1997), during the "Oklahoma Mesonet" workshop held at the Institute of Soil, Climate and Water (Pretoria) in February 1998, as well as during the workshop on "Crop modelling and irrigation scheduling" held in Pietersburg on 24-25 March 1998.

SWB was also presented at the Gardenex show in Johannesburg (April 1998), Nampo show in Bothaville (May 1998), OTK Farmers' day in Bethal (3 February 1999), and South African Irrigation Institute regional meeting in Pretoria (17 March 1999).

SWB v. 1.0 was officially launched on 15 September 1998 at the University of Pretoria.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Discussion of results

The revised objectives of the project have to a large degree been achieved.

An extensive literature search was done in order to collect independent data sets required to determine crop parameters and validate the model. Difficulties were encountered in obtaining useable data sets. In some cases, available data sets were incomplete, in others potential collaborators were reluctant to make data available. Useful data sets obtained from South African researchers and organizations are summarized in Table 5.1. These were used to validate the model.

Data obtained from two field trials (Roodeplaat and Hatfield) were used to generate crop parameters for vegetables and peach trees, and to calibrate SWB.

In order to include more crops in the database, an FAO-type model has been developed for the estimation of crop water requirements both under supply- and demand-limited conditions. This allowed use of the FAO crop factor database available in FAO publications. In particular, tree crops were critical as growth analysis data for tree crops are seldom available. A database of FAO crop factors was included in SWB. It is important, however, to bear in mind that the crop factor approach requires canopy cover adjustment to accommodate stress conditions.

Several important irrigated crops were included in the SWB crop parameter database (Table 5.1). Data sets were not obtained for cotton and some relevant irrigated fruit tree crops. It was also not possible to set up time-consuming and expensive field trials. Specific crop growth parameters are therefore not available for these crops, but FAO crop factors were included in SWB. The user will therefore be able to schedule irrigations by making use of the FAO-based model.

The database of specific crop growth parameters and FAO crop factors is summarized in Tables B1 and B2 (Appendix B).

Simulations were carried out for agronomic, vegetable and tree crops, using both the crop growth and FAO-type model. Model calibration and validation was carried out using a statistical analysis between measured and simulated data. SWB calculates parameters of the statistical analysis and displays standard errors of measured data on output graphs. This allows an efficient, quantitative evaluation of model accuracy.

Reasonable predictions of soil water deficit, root depth, leaf area index, total above ground and harvestable dry matter were obtained with SWB. Differences in crop water use and growth were observed for different cultivars. The crop growth model proved to be suitable for deficit irrigation simulations. Soil water deficit predicted with the FAO-type model was generally higher than that calculated with the crop growth model under water stress conditions, as the FAO model does not account for smaller canopy size. Caution should be exercised against blind acceptance of the FAO parameters as local conditions, management and cultivars are likely to influence crop growth periods and basal crop coefficients. They should, however, give a reasonable first estimate of the behaviour of the system.

The following improvements to SWB have been made:

i) Conversion of the old DOS version of the model to the efficient 32 bit Delphi Windows 95 version.

ii) "Marriage" of the mechanistic soil water balance model to the FAO basal crop coefficient approach. This brought with it the advantage of immediate inclusion of several new crops into SWB's crop database. The parameters are available from international research on updating FAO 24 (Doorenbos and Pruitt, 1992). This provided a means of making the model useable whilst more detailed data is being sought or generated through field trials for the growth model option. The fact that basal crop coefficients have been used allow us to still separate evaporation and transpiration. Maximum transpiration and the leaf water potential at this maximum rate are retained so that the mechanistic supply- and demand-limited water uptake calculation can still be utilized. These two parameters can be fairly easily estimated from one's experience with the crop.

iii) The standardized FAO Penman-Monteith grass reference evapotranspiration (Smith, 1992b; Smith et al., 1996) has now replaced the G.S. Campbell (Washington State University) modified Priestley-Taylor approach used in the past. Crop height has been added to calculate a weather and surface roughness modified PET from the grass reference ETo. Height increase is assumed to be a linear function of thermal time for the growth model and of time in days during the development stage for the FAO model. Standardized options for estimating missing weather data have also been included (Smith, 1992b; Smith et al., 1996).

iv) A subroutine for the estimation of yield with the FAO model under conditions of water stress, was included in SWB. The procedure recommended by the FAO was used as a basis (Smith, 1992a).

v) The problem of the effect of the irrigation system on canopy interception and uneven surface wetting was also addressed. No interception is calculated unless rain or sprinkle irrigation occurs. The whole soil surface is wetted by rain and sprinkle or flood irrigation, but for micro- or drip irrigation only a fraction of the surface is wetted. The model keeps track of canopy size to determine evaporation from the wetted and non-wetted surfaces separately.

vi) A subroutine for the calculation of non-instantaneous drainage has been included in the model. A drainage factor (input value) allows a certain fraction of the soil water above field capacity to drain daily.

SWB was developed as a daily time step, generic crop, water balance model for real-time irrigation scheduling. Particular attention was given to the development of a user-friendly interface with a context sensitive on-line help tool, range and error checking, as well as comprehensive graphical output. This should allow the user to easily make real-time use of the output results. A comprehensive user's guide and technical manual is supplied with the model.

Special features like updating simulations, importing weather data and displaying printable recommendations should facilitate the application of the model in practice. A database of photos of crops was included in the help files in order to facilitate the estimation of canopy cover, when measurements are not available.

Stand-alone tools like the ETo calculator, the field capacity and permanent wilting point calculator, as well as the neutron probe, tensiometer and gravimetric schedulers, have been developed and can be used for irrigation scheduling.

8.2 Needs for further research

Further research needs concern the introduction of specific crop growth parameters for cotton and some important tree crops. Crop growth parameters refinement should be ongoing.

Further validation of the model is required for some crops. In particular, the simulation of specific physiological responses of some crops, like peanuts, needs to be included in SWB. Differences in cultivars could affect thermal time requirements for crop phenological stages and canopy development. Crop parameters for cultivars of different maturity groups should therefore be determined.

Specific requirements for some crops can be included in SWB. For example, irrigation scheduling of factory tomato and tobacco for yield and quality optimization can be modelled. Future research should also include the modification of SWB to accommodate day length sensitive crops, such as potatoes. An alternative is to merge existing specific crop growth models like CANEGRO into SWB. This could improve crop growth and soil water balance predictions, while maintaining the user-friendly interface of SWB, but specific crop growth models generally require more inputs.

Very few useable data sets were found for tree crops. Trees are generally grown in wide rows and irrigated with micro- or drip irrigation systems. A two-dimensional soil water balance and energy interception model is therefore needed in order to predict water requirements of trees accurately.

Deficit irrigation strategies can be accurately simulated with the mechanistic crop growth model. An economic subroutine can therefore be included in SWB in order to facilitate economic optimization of target yields and irrigation strategies.

SWB can be further developed for other applications besides irrigation scheduling of crops. For example, irrigation is often used for protection against wind erosion. Inclusion of a nitrogen balance will also assist irrigators quantifying possible N leaching and crop N requirements. Other useful additions include taking electricity tariffs (ruralflex) into account when recommending irrigations. Due to the fact that weather data is already in the database, disease, insect and frost warnings can also be added to make the tool even more valuable to the producer. GIS integration of SWB, FARMS and WAS is being carried out in another project sponsored by the Water Research Commission.

Agricultural development can be enhanced by making seasonal rather than real-time estimates with SWB available to farmers that do not own an automatic weather station and computer.

The model needs to be used extensively in the field now so that users can give valuable feedback as to it's user-friendliness and accuracy.

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APPENDIX A

THEORETICAL OVERVIEW OF SWB

1. Weather unit

1.1 Introduction

The aim of this Section is to calculate potential evapotranspiration (PET) from available meteorological input data (Smith, Allen and Pereira, 1996; Smith, 1992b). Daily Penman-Monteith grass reference evapotranspiration (ETo) and PET are calculated in the **Weather unit** and used in the **Soil unit** to compute actual transpiration (T) and evaporation (E).

The **Weather unit** includes the procedure for initializing weather parameters, and five functions where the following parameters are calculated:

i)	R_a	-	Extraterrestrial radiation (MJ m^{-2} day^{-1});
ii)	VPD	-	Vapour pressure deficit (kPa);
iii)	R_n	-	Net radiation (MJ m^{-2} day^{-1});
iv)	ETo	-	FAO reference evapotranspiration (mm day^{-1}); and
v)	PET	-	Potential evapotranspiration (mm day^{-1}).

An additional **Weather day step** function is performed on a daily basis (Figure A1).

The procedure **Initialize weather** converts the weather station latitude (Lat) from degrees into radians, and calculates atmospheric pressure (P_a) from altitude, as follows:

$$P_a = P_0 \left[(T_0 - \alpha \text{ Alt}) / T_0 \right]^{g/(\alpha Rg)}$$

(Burman, Jensen and Allen, 1987)

Alt	-	Altitude (m)
P_0	-	Standard atmospheric pressure at sea level (101.3 kPa)
T_0	-	Standard temperature at sea level (293 K)
g	-	Gravitational acceleration (9.8 m s^{-2})
Rg	-	Specific gas constant for dry air (286.9 J kg^{-1} K^{-1})
α	-	Adiabatic lapse rate (K m^{-1})

The adiabatic lapse rate is assumed to be 0.0065 K m^{-1} for saturated air. Alt is an input parameter linked to a particular weather station.

The functions for calculating R_a, VPD, R_n, ETo, PET and weather day step will be treated separately in the following Sections.

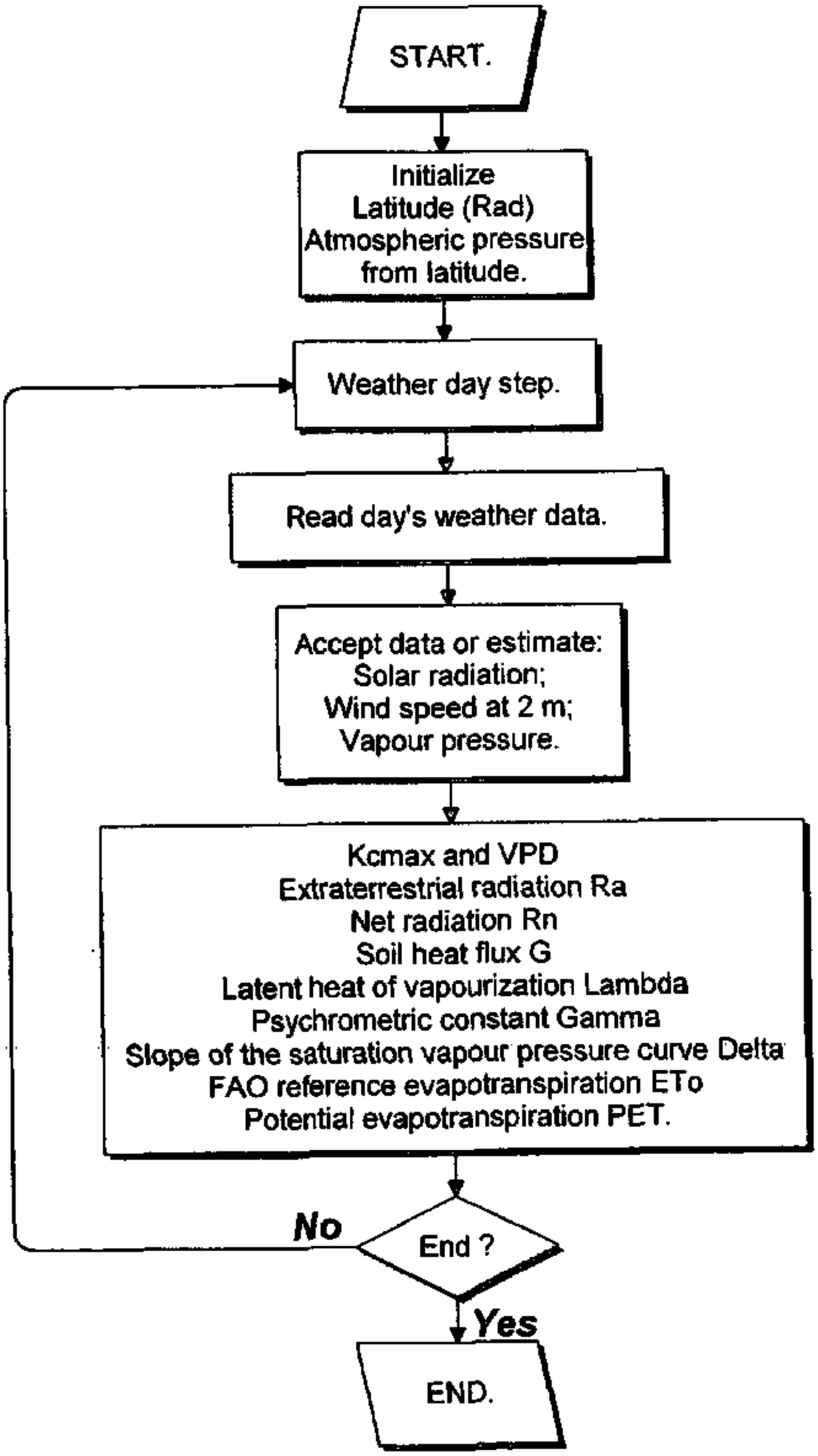


Figure A1
Flow diagram of the weather unit of SWB

1.2 Extraterrestrial radiation

Potential solar radiation is calculated as a function of Lat (input value) and day of year (DOY), as follows:

$$R_a = 118.08\ D_{rel} / \pi\ [\omega_s \sin(Lat)\sin(Dec) + \sin(\omega_s)\cos(Lat)\cos(Dec)]$$

R_a is in MJ m^{-2} day^{-1}, whilst the constant 118.08 represents the solar constant in MJ m^{-2} day^{-1}. D_{rel} is the relative distance of the earth from the sun, a function of DOY:

$$D_{rel} = 1 + 0.033 \cos(2\pi\ DOY / 365)$$

ω_s is sunset hour angle (rad), a function of latitude and solar declination (Dec):

$$\omega_s = \arccos[-\tan(Lat) \tan(Dec)]$$

For the Southern hemisphere, solar declination is calculated as follows:

$$Dec = -\ 0.409 \sin(2\pi / 365\ DOY - 1.39)$$

(Duffie and Beckman, 1980)

whilst for the Northern hemisphere the sign of the equation is changed.

1.3 Vapour pressure deficit

Vapour pressure deficit is calculated adopting the following equation:

$$VPD = [e_s(T_{max}) + e_s(T_{min})] / 2 - e_a$$

where e_s is saturated vapour pressure (kPa), a function of maximum (T_{max}) and minimum air temperature (T_{min}), and e_a is the actual vapour pressure (kPa).

Saturated vapour pressure is estimated from air temperature (T_a), as follows:

$$e_s = 0.611 \exp[17.27\ T_a / (T_a + 237.3)] \qquad \text{(Tetens, 1930)}$$

Actual vapour pressure is an input variable. If not available, it is calculated from measured minimum (RH_{min}) and maximum relative humidity (RH_{max}), and if that is not available, from measured wet bulb (T_w) and dry bulb temperature (T_d).

Vapour pressure can be calculated as a function of percent relative humidity as follows:

$$e_a = [e_s(T_{min})\ RH_{max} / 100 + e_s(T_{max})\ RH_{min} / 100] / 2$$

and from psychrometer readings with

$$e_a = e_s(T_w) - 0.0008\ (T_d - T_w)\ P_a \qquad \text{(Bosen, 1958)}$$

If not available for use in Kc_{max} (FAO maximum crop coefficient), RH_{min} is calculated as a function of T_{max} and T_{min} for use in the weather modified PET calculation:

$$RH_{min} = e_s(T_{min}) / e_s(T_{max})$$

If no atmospheric vapour measurements are available, SWB assumes T_{min} reaches dew point, and e_a is set to $e_s(T_{min})$.

VPD is used in the calculation of ETo and water limited dry matter production.

1.4 Net radiation

In this Section, the R_n value is calculated to be used for computing the Penman-Monteith reference evapotranspiration, as follows:

$$R_n = R_{ns} - R_{nl}$$

R_{ns} - Short-wave net radiation (MJ m^{-2} day^{-1})
R_{nl} - Long-wave net radiation (MJ m^{-2} day^{-1})

Assuming the albedo of the reference crop is 0.23, R_{ns} is:

$$R_{ns} = 0.77\ R_s$$

R_s - Solar radiation (MJ m^{-2} day^{-1})

R_s is an input value in MJ m^{-2} day^{-1}. In the absence of measured data, SWB calculates R_s after Allen (1995), as follows:

$$R_s = 0.17\ P_a / P_0\ (T_{max} - T_{min})^{0.5}\ R_a$$

T_{max} and T_{min} are in °C and they represent the minimum required input data for calculating R_s. Kelvin air temperatures are used to calculate net terrestrial radiation:

$$R_{nl} = f_c\ \epsilon\ \sigma\ (T_{max}^4 + T_{min}^4) / 2$$

with f_c, the cloudiness factor

$$f_c = 1.35\ R_s / R_{so} - 0.35 \qquad \text{(Doorenbos and Pruitt, 1992)}$$

R_{so} is the short-wave radiation during bright sunshine (MJ m^{-2} day^{-1}):

$$R_{so} = 0.75\ R_a$$

The factor "0.75" represents the maximum clear sky transmissivity of the atmosphere. ϵ is the clear sky emissivity of the earth's surface:

$$\epsilon = 0.34 - 0.14\ e_a^{0.5}$$ (Doorenbos and Pruitt, 1992)

and σ is the Stefan-Boltzmann constant (4.9×10^{-9} MJ m^{-2} K^{-4}).

1.5 FAO *reference evapotranspiration*

The Penman-Monteith ETo is calculated according to the FAO procedure, as recommended by Smith et al. (1996). The following equation is adopted:

$$ETo = [0.408\Delta(R_n - G) + \gamma 900 / (T_{avg} + 273) U_2 VPD] / [\Delta + \gamma(1 + 0.34 U_2)]$$

with Δ the slope of the saturation vapour pressure curve in kPa °C^{-1}

$$\Delta = 4098\ e_s / (T_a + 237.3)^2$$

and G the soil heat flux (MJ m^{-2} day^{-1}) calculated from today's (DOY) and yesterday's (DOY-1) average air temperatures (T_{avg})

$$G = 0.38\ [T_{avg}(DOY) - T_{avg}(DOY-1)]$$

(Wright and Jensen, 1972)

where

$$T_{avg} = (T_{max} + T_{min}) / 2$$

γ is the psychrometer constant (kPa °C^{-1}) calculated as

$$\gamma = 0.00163\ P_a / \lambda$$

with λ the latent heat of vaporization (MJ kg^{-1})

$$\lambda = 2.501 - 2.361 \times 10^{-3}\ T_{avg}$$

U_2 is wind speed measured at 2 m height (m s^{-1}).

U_2 is a weather data input value. If it is not available, SWB assumes an average U_2 of 2 m s^{-1}. Smith et al. (1996) recommended an average U_2 of 3 m s^{-1} for windy, and 1 m s^{-1} for low wind conditions. If wind speed (U) is not measured at 2 m height, the logarithmic wind speed profile function is applied to calculate U_2, as follows:

$$U_2 = U\ 4.87 / \ln(67.8\ H_U - 5.42)$$

(Allen, Jensen, Wright and Burman, 1989)

H_U - Height at which wind speed is measured (cm)

1.6 Potential evapotranspiration

Potential evapotranspiration is used to determine actual transpiration and evaporation in the **Soil unit**. Crop PET is calculated as a function of the reference evapotranspiration and Kc_{max}, as follows:

$$PET = ETo\ Kc_{max}$$

Kc_{max} represents the maximum value for the FAO crop coefficient (Kc) following rain or irrigation. It is calculated according to the procedure recommended by Allen, Smith, Pruitt and Pereira (1996), and identified as the maximum of the following two calculations:

$$Kc_{max} = 1.2+[0.04(U_2\text{-}2)\text{-}0.004(RH_{min}\text{-}45)]\ (Hc / 3)^{0.3}$$

$$Kc_{max} = Kcb + 0.05$$

Hc - Crop height (m)
Kcb - FAO basal crop coefficient

The upper limit of Kc_{max} is set at 1.45. The calculation of Hc and Kcb is shown in the **Crop unit**.

1.7 Weather day step

The **Weather day step** function is executed on a daily basis until the present day, or until crop maturity. This function identifies the day of year and reads precipitation (P) and irrigation (I) input data. It remembers the average air temperature of the previous day (T_{avg}(DOY-1)), used to estimate soil heat flux in Section 1.5 (FAO reference evapotranspiration).

The **Weather day step** function reads the following variables:

- FAO basal crop coefficient, Kcb;
- Crop height, Hc;
- Maximum daily temperature, T_{max};
- Minimum daily temperature, T_{min};
- Incoming solar radiation, R_s;
- Actual vapour pressure, e_a;
- Wind speed measured at 2 m height, U_2;
- Height at which wind speed is measured, H_U;

- Daily minimum relative humidity, RH_{min};
- Daily maximum relative humidity, RH_{max};
- Dry bulb temperature, T_d; and
- Wet bulb temperature, T_w.

Kcb and Hc are calculated in the **Crop unit.** $\mathbf{T_{max}}$ **and** $\mathbf{T_{min}}$ **are essential input values.** H_U input value is needed if U is not measured at 2 m height. If measured input data are not available, SWB calculates R_s, e_a, U_2 and RH_{min}, as described in the previous Sections.

2. Soil unit

2.1 Introduction

The aim of this Section is to simulate the dynamics of water movement in the soil profile in order to determine soil water availability to the crop. Water movement is simulated with a cascading model. This divides the soil profile into a number of layers. Each layer has its own physical properties:

- Soil matric potential, Ψ_m (J kg^{-1});
- Volumetric soil water content, θ;
- Volumetric soil water content at field capacity, θ_{fc};
- Volumetric soil water content at permanent wilting point, θ_{pwp};
- Campbell's "a" and "b" parameters of the log-log water retention function; and
- Bulk density, ρ_b (Mg m^{-3}).

θ_{fc}, θ_{pwp}, ρ_b and initial θ are input values. Soil water movement is calculated in the **Soil unit** and includes three procedures:

i) Calculation of soil layer thickness (dz);
ii) Soil parameters initialization; and
iii) Soil day step calculation.

In addition, two separate functions are used to calculate:

i) Soil water storage; and
ii) Allowable depletion.

SWB firstly calculates the thickness of each soil layer (i), using the following equation:

$$dz_i = z_i - z_{i-1}$$

z - Layer depth (m)

Layer depth (distance between the lower boundary of the layer and the soil surface) is an input value.

In the procedure that initializes soil water parameters, SWB reads input values of initial θ, θ_{fc}, θ_{pwp} and ρ_b for each of the layers. For uniform profiles only one set of layer values needs to be entered. Volumetric soil water content at saturation (θ_{sat}) is calculated using the following equation:

$$\theta_{sat} = 1 - \rho_b / 2.65$$

where 2.65 represents the average density of soil particles.

Campbell's "a" and "b" coefficients of the water retention function are calculated for each layer, as follows (Campbell, 1985):

$$b = \ln(\Psi_{pwp} / \Psi_{fc}) / \ln(\theta_{fc} / \theta_{pwp})$$

$$a = \exp(\ln(-\Psi_{pwp}) + b \ln(\theta_{pwp}))$$

Ψ_{pwp} - Soil matric potential at permanent wilting point (J kg^{-1})
Ψ_{fc} - Soil matric potential at field capacity (J kg^{-1})

Ψ_{pwp} and Ψ_{fc} are input parameters. Hillel (1982) recommended values of -1500 J kg^{-1} for Ψ_{pwp} and -10 J kg^{-1} for Ψ_{fc}.

Volumetric water content at permanent wilting point is then recalculated as the lower limit of crop water uptake for a specific plant:

$$\theta_{pwp} = \exp(-\ln(-3\ \Psi_{lm} / (2\ a)) / b)$$

Ψ_{lm} - Leaf water potential at maximum transpiration rate (J kg^{-1})

Ψ_{lm} is a crop specific parameter.

Air dry volumetric soil water content (θ_{ad}) is calculated as follows (Campbell and Stockle, 1993):

$$\theta_{ad} = 0.3\ \theta_{pwp}$$

θ_{ad} is used to set the lower limit of water loss through evaporation from the soil surface. As SWB assumes evaporation occurs from the top soil layer, θ_{ad} is only calculated for this layer.

The soil day step procedure is performed on a daily basis. It includes five more procedures which are performed in the following order (Figure A2):

i) Amount of precipitation intercepted by the canopy, I_c;
ii) Runoff, R;
iii) Infiltration and redistribution;
iv) Evaporation; and
v) Transpiration.

SWB provides options to determine the soil water balance if either sprinkler/flood or localized irrigations are performed. In the case of sprinkler/flood irrigation, the model simulates even wetting of the soil surface. When irrigations are performed with drip or micro-irrigators, SWB calculates the soil water balance for both irrigated and non-irrigated surface layers. The irrigated fraction of the surface (f_i, portion of wetted area) is chosen in the input field table.

SWB simulates one-dimensional water movement in the soil for both sprinkler/flood and localized irrigation. The calculation of the soil water balance components is discussed in the following Sections.

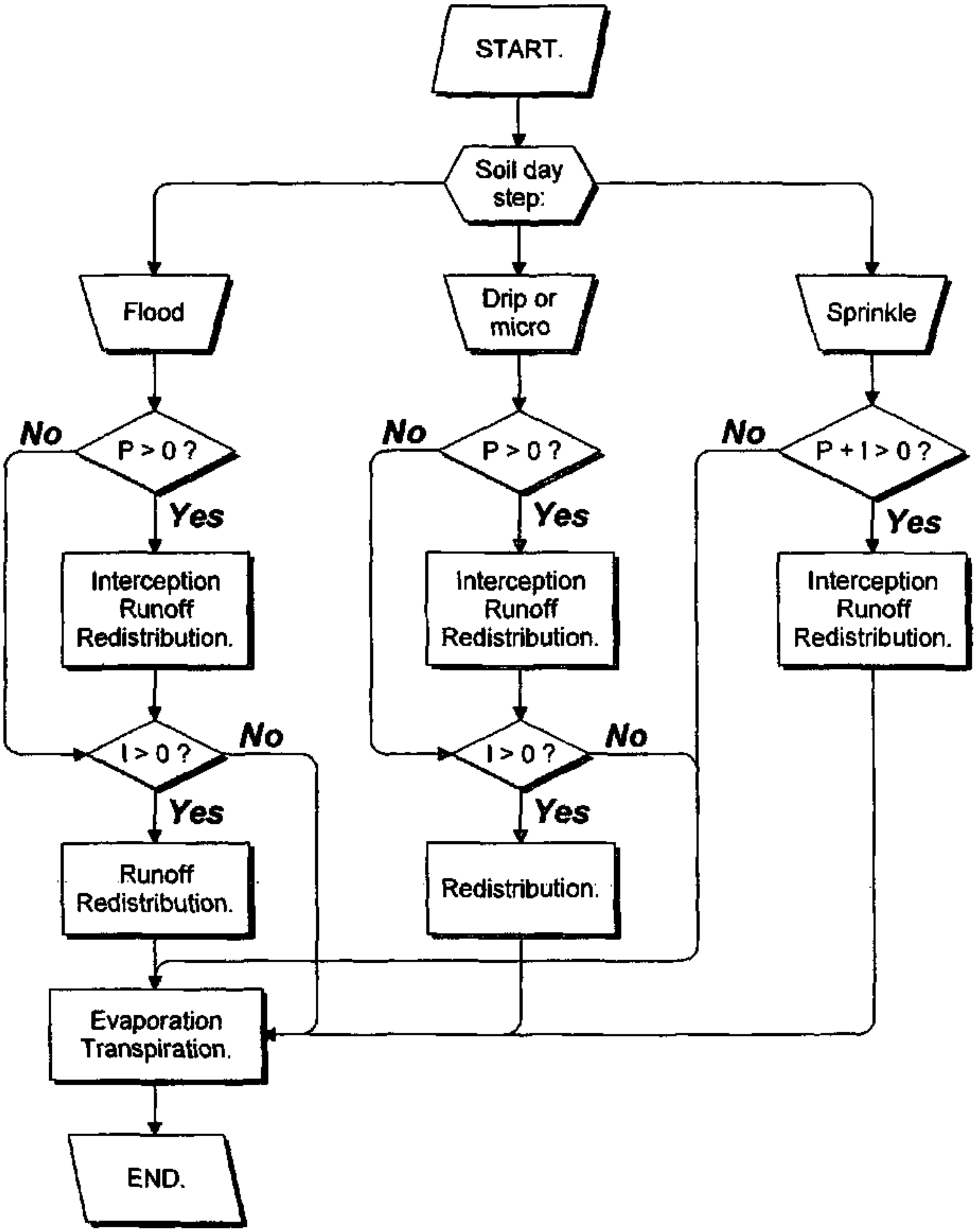


Figure A2
Flow diagram of the soil unit of SWB

2.2 Interception

Amount of rainfall and irrigation are two of the required inputs of SWB. Interception of precipitation and irrigation (P + I) by the crop canopy is calculated only on days when rainfall and/or sprinkler irrigation occur.

The amount of water intercepted by the canopy is assumed to be equal to the interception of radiation by the canopy, including both photosynthetically active and senesced leaves (FI_{evap}), multiplied by a canopy storage parameter. The FI_{evap} calculation is shown in the **Crop unit**, whilst canopy storage is a crop specific parameter. The amount of precipitation penetrating the canopy and reaching the soil surface is reduced by the amount of water intercepted by the canopy.

If the amount of precipitation is lower than potential interception, it is assumed that all precipitation is intercepted by the canopy, and no rainfall and/or sprinkler irrigation water reaches the soil surface.

2.3 Runoff

Runoff is calculated on days when rainfall and/or sprinkler/flood irrigation occur. R is calculated adopting a semi-empirical algorithm based on the assumption that once precipitation is greater or equal to a value representing initial infiltration and surface storage, R increases with increasing precipitation.

Runoff is assumed to be 0 if

$$P + I \leq 0.2\ S$$

S - Runoff curve number (mm)

S is an input parameter giving an indication of the storage of surface. If rain plus irrigation exceeds 20% of S, runoff is calculated according to the following relation:

$$R = (P + I - 0.2\ S)^2 / (P + I + 0.8\ S)$$

(Stewart, Woolhiser, Wischmeier, Caro and Frere, 1976)

Surface runoff is then subtracted from the rainfall and/or irrigation water allowing the remainder to infiltrate into the soil.

2.4 Infiltration and redistribution

Infiltration and redistribution of water in the soil profile are calculated on days when rainfall, irrigation or drainage (Dr) occur. The model distributes water from rainfall, irrigation and drainage by filling soil layers to saturation, starting from the top of the profile and moving downwards. In the case of drip- or micro-irrigated fields, the top soil layer water redistribution is calculated for both irrigated and non-irrigated portions of the ground for rainfall, and only for the irrigated portion for irrigations.

SWB updates soil layer water content on a daily basis. Layer soil water deficit (SWD) is calculated as a function of θ using the following expression:

$$SWD = (\theta_{fc} - \theta)\ \rho_w\, dz$$

ρ_w - Density of water (1000 kg m^{-3})

If the amount of water penetrating a soil layer is larger than $\theta_{sat} - \theta$ for that layer, θ is set to θ_{sat}. The amount of water penetrating the deeper layer (D_i) is then reduced by "$(\theta_{sat} - \theta)\ \rho_w\, dz$". If the amount of water penetrating a soil layer is smaller than $\theta_{sat} - \theta$ for that layer, θ is increased by "$D_i / \rho_w\, dz$" and D_i is set to 0 for the next soil layer.

Drainage is calculated when θ exceeds θ_{fc} for the particular layer using the following equation:

$$Dr = Df\,(\theta - \theta_{fc})\ \rho_w\, dz + D_i$$

where Df is a drainage factor (soil input parameter).

2.5 Evaporation

The actual partitioning between evaporation and transpiration depends on the available energy reaching the crop canopy and soil surface and the resistances to water transport (Ritchie, 1972; Norman and Campbell, 1983).

Water loss by evaporation is assumed to occur only from the top soil layer.

The expression for potential evaporation (PE) is given by:

$$PE = (1 - FI_{evap})\ PET \qquad \text{(Reddy, 1983)}$$

PET is calculated in the **Weather unit**, whilst FI_{evap} in the **Crop unit**.

Evaporation proceeds at the potential rate until θ_{pwp} is reached (atmospheric evaporative demand-limited). If water content decreases in the top soil layer below θ_{pwp}, then evaporation becomes supply-limited (Campbell, 1985):

$$E = PE\ ((\theta - \theta_{ad}) / (\theta_{pwp} - \theta_{ad}))^2$$

According to this equation, actual evaporation from the soil surface decreases by reducing the layers water content.

Water content in the top soil layer is reduced by the amount of water evaporated from the soil surface, on a daily basis.

If the calculated θ is below θ_{ad}, θ is assumed to be equal to θ_{ad}. E is then calculated as follows:

$$E = (\theta - \theta_{ad})\ \rho_w\ dz$$

Two possible cases are simulated when drip/micro-irrigations are performed:

i) If the canopy cover fraction (FI_{evap}) is larger than the irrigated surface fraction (f_I), evaporation is simulated only from the non-irrigated portion of the ground; and
ii) If $FI_{evap} < f_I$, evaporation from the irrigated, non-shaded area is added to the evaporation from the non-irrigated surface layer.

2.6 Transpiration

Water loss by transpiration is calculated on days when root depth (RD) and fractional interception of radiation by photosynthetically active leaves (FI_{transp}) are greater than 0. SWB assumes that layer water uptake is weighted by root density when soil water potential is uniform. No root water uptake is calculated for the uppermost soil layer which is reserved for evaporation.

Soil matric potential is calculated daily as a function of the actual soil water content, using the following equation (Campbell, 1985):

$$\Psi_m = a\ \theta^{-b}$$

By plotting Ψ_m and θ on a log-log scale and fitting a straight line to the data, it is possible to derive Campbell's "a" and "b" values from the intercept and the slope of the relationship.

Reduction in Ψ_m closes stomata and decreases transpiration and dry matter production. Transpiration is therefore computed as a function of Ψ_m. The following equation is applied to each layer in the soil profile, in order to calculate water loss by transpiration as a fraction of soil volume:

$$Loss = (FI_{transp}\ Tr_{max}\ f\ (\Psi_x - \Psi_m) / (0.67\ \Psi_{lm})) / (\rho_w\ dz)$$

Tr_{max}	-	Maximum transpiration rate (mm day^{-1})
f	-	Layer root fraction
Ψ_x	-	Xylem water potential (J kg^{-1})

Tr_{max} is a crop specific parameter. The factor "f" is computed for each soil layer, according to the following expression:

$$f = dz\,(2\,(RD-z) + dz) / RD^2$$

(Campbell and Diaz, 1988)

In the layer where z is larger than RD, the factor "f" is calculated as follows:

$$f = ((RD - z + dz) / RD)^2$$

Ψ_x is calculated using the expression:

$$\Psi_x = \Psi_{lm}\,(\Psi_{avg}^* + 0.67\,T^*)$$

where

$$\Psi_{avg}^* = \Psi_{avg} / \Psi_{lm}$$

Ψ_{avg} - Root weighted average soil matric potential (J kg^{-1})

$$\Psi_{avg} = \Sigma\, f_i\, \Psi_{mi}$$

The subscript "i" indicates the soil layer.

T^* is the dimensionless actual water uptake. T^* is chosen as the minimum between the dimensionless root uptake rate (U^*) and the maximum dimensionless loss rate (E^*):

$$U^* = 1 - 0.67\,\Psi_{avg}^*$$

$$E^* = PET / Tr_{max}$$

The factor "0.67" takes into account the resistances which water flow encounters in the path from the soil toward the leaf. The major resistances are in the endodermis, where water enters the root steele and in the leaf, at the bundle sheath. For typical plants growing in moist soil, the potential drop across the endodermis is 60-70% of the total (Campbell, 1985). In this model, root resistance is assumed to be two thirds of total plant resistance, with leaf resistance the remaining third. Xylem resistance is assumed to be negligible as water flows in cell walls and xylem vessels without crossing membranes. Soil resistance is also considered negligible.

Water uptake is calculated only when

$$\Psi_{avg}^* = \Psi_{avg} / \Psi_{lm} < 1.5$$

If the ratio between root weighted average soil matric potential and leaf water potential at maximum transpiration rate exceeds 1.5, actual crop transpiration is assumed to be 0. Under this condition, the xylem water potential is equal to the root weighted average soil matric potential ($\Psi_x = \Psi_{avg}$) and no water flow through the plant occurs.

Actual water content is reduced in each soil layer by the amount of water absorbed by the roots. The lower limit of θ is θ_{pwp}. If the difference between actual water content and water loss by transpiration is smaller than the water content at permanent wilting point (θ - Loss < θ_{pwp}), θ is set equal to θ_{pwp} and the water taken up by the roots is:

$$\text{Loss} = \theta - \theta_{pwp}$$

Finally, water losses by transpiration are converted into mm units and cumulated for each soil layer to determine daily T in mm.

A dimensionless daily water stress index (SI) is calculated as follows:

$$SI = T / (FI_{transp}\ PET)$$

PET is calculated in the **Weather unit**, whilst FI_{transp} in the **Crop unit**. SI is used to simulate partitioning of daily dry matter production to different plant organs under water stress conditions **(Crop unit)**.

2.7 *Soil water storage*

Soil water storage is calculated on a daily basis as the sum of the water content in mm in each soil layer. This is subtracted from profile water content at field capacity to determine profile deficit. In the case of drip/micro-irrigation, root zone deficit is calculated only for the fraction of irrigated ground.

2.8 Allowable depletion

Allowable depletion level (ADL) in the root zone is calculated on a daily basis. ADL is calculated in mm for each soil layer where the root system is present, as follows:

$$ADL = (\theta_{fc} - \theta_{pwp})\ \rho_w\ dz$$

Soil layer ADL values are cumulated to calculate ADL in the root zone. For the layer not completely explored by roots, ADL is calculated as follows:

$$ADL = -\ (z - RD)\ (\theta_{fc} - \theta_{pwp})\ \rho_w$$

In this way, ADL is reduced by the amount of available water ((θ_{fc} - θ_{pwp}) ρ_w dz) below the root zone. SWB uses allowable depletion in the soil water balance graph to guide irrigation timing.

3. Crop unit

3.1 Introduction

The aim of this Section is to simulate crop growth. The **Crop unit** includes three procedures:

i) Initialization;
ii) Planting; and
iii) Day step calculation.

Crop initialization sets initial values of several crop parameters to zero. Crop height requires a starting value > 0 and this is set to 0.001 m.

The procedure for crop planting is initiated once a valid planting date has been identified. Top dry matter (TDM) is set to TDM at emergence (crop specific parameter). For most crops, TDM at emergence is estimated to be equivalent to seed mass density. Initial root dry matter (RDM) is calculated as:

$$RDM = f_r \, TDM / (1 - f_r)$$

f_r - Fraction of dry matter partitioned to the roots (crop specific parameter).

Initial leaf area index (LAI) is calculated as follows:

$$LAI = SLA \, TDM$$

SLA - Specific leaf area ($m^2 \, kg^{-1}$)

SLA is a crop parameter which describes the leaf morphology of a specific crop.

The crop day step procedure is performed on a daily basis (Figure A3). It includes the following calculations:

i) Growing day degrees (GDD);
ii) Fractional interception of radiation (FI);
iii) Crop height (Hc);
iv) Dry matter production increment (DM_i);
v) Harvestable dry matter increment (HDM_i);
vi) Partitioning of DM_i into plant organs;
vii) Partitioning of DM_i under conditions of water stress;
viii) Leaf area index (LAI); and
ix) Rooting depth (RD).

The simulation of crop growth is discussed in the following Sections.

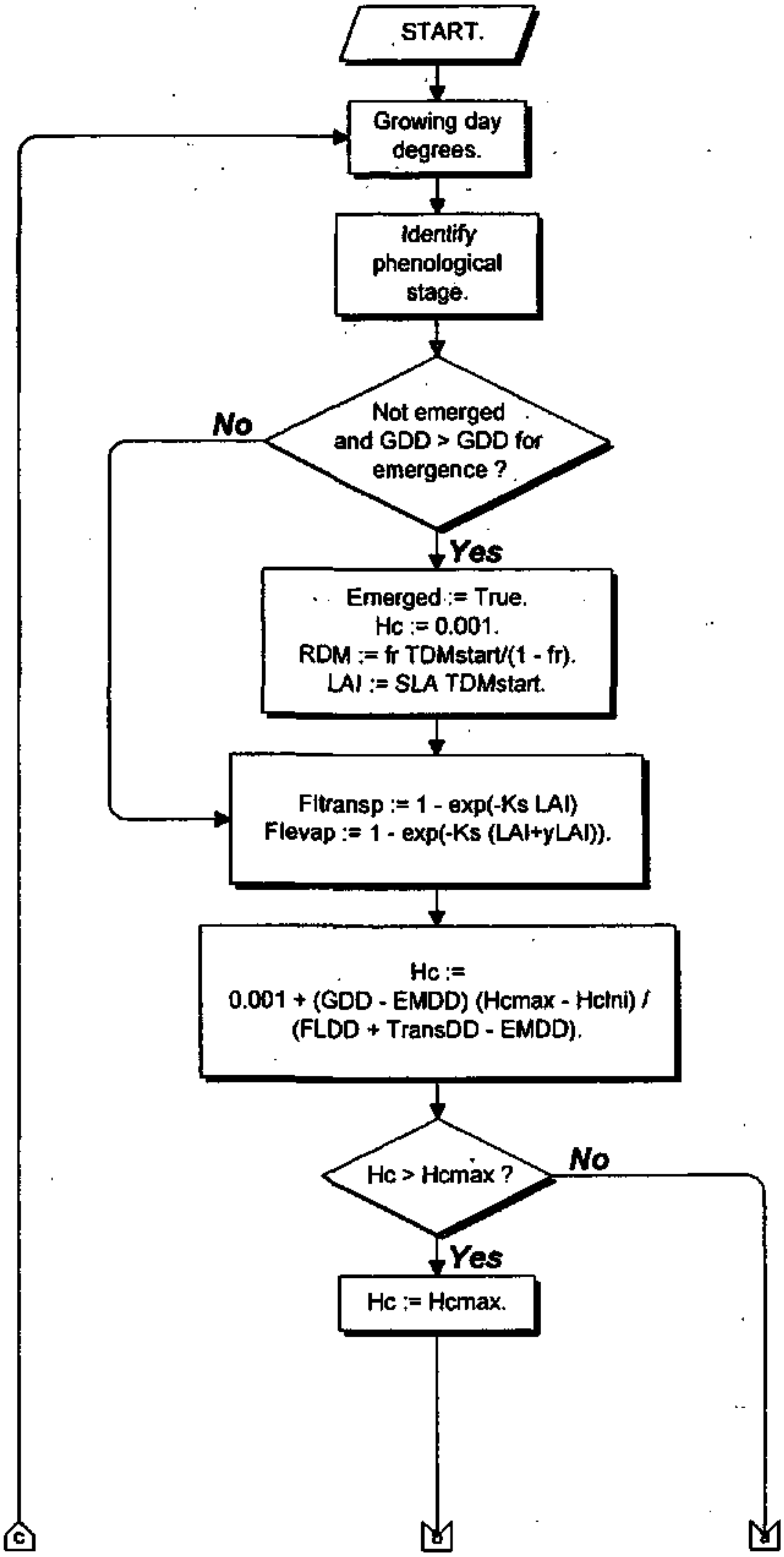


Figure A3
Flow diagram of the crop growth model

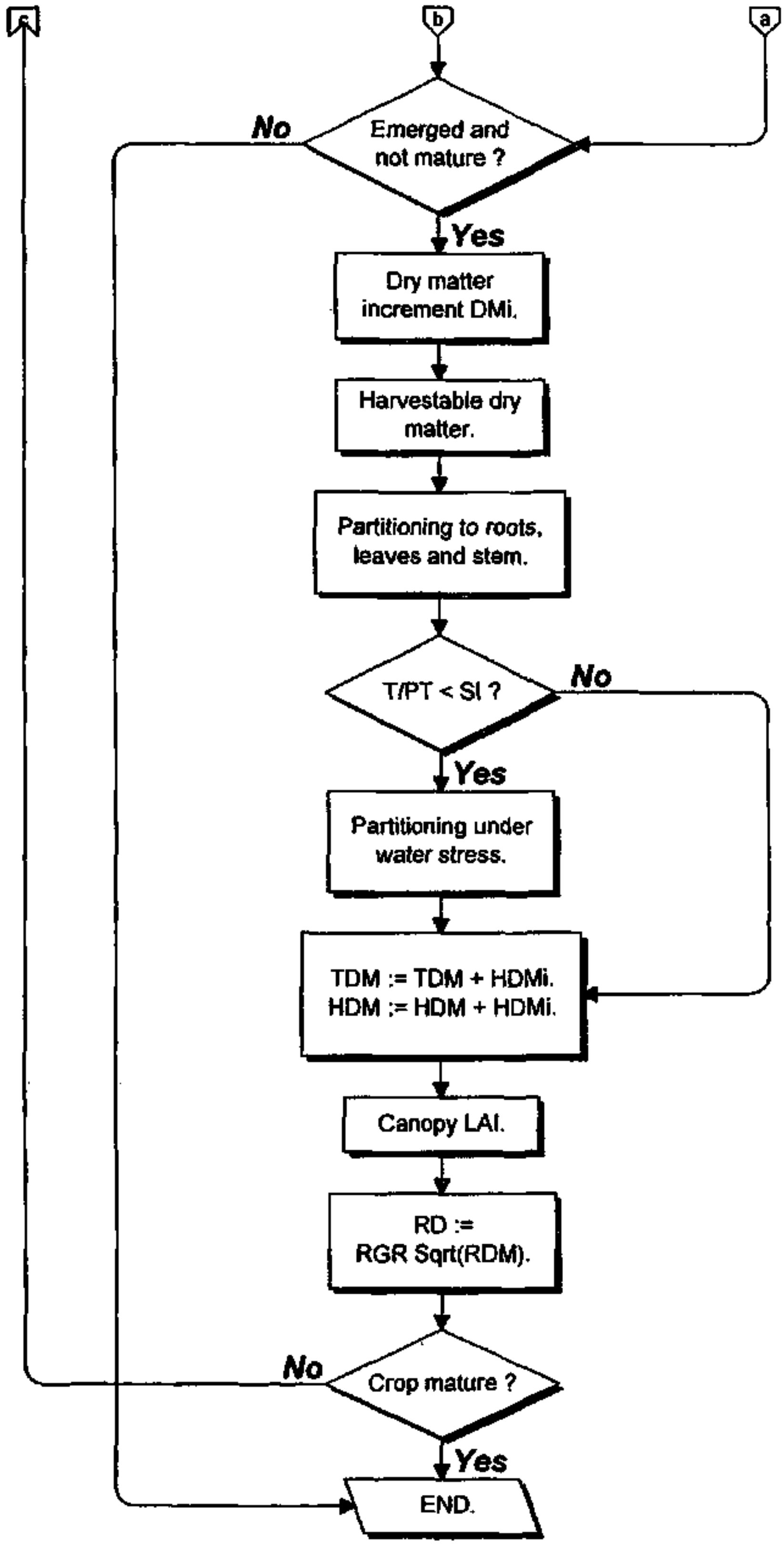


Figure A3
Flow diagram of the crop growth model (continued)

3.2 Growing day degrees

Crop development is simulated using thermal time, an approach suggested by Monteith (1977). The calculation of growing day degrees (GDD) starts after crop planting. GDD are accumulated daily using the following expression:

$$GDD = GDD + GDD_i$$

GDD_i - Growing day degrees increment

Growing day degrees increment is calculated as follows:

$$GDD_i = T_{avg} - T_b$$

T_b - Base temperature (°C)

T_b is a crop specific parameter.

When the average daily temperature is below the base temperature, GDD_i is set to 0.

If $T_{avg} > T_{cutoff}$, then:

$$GDD_i = T_{cutoff} - T_b$$

where T_{cutoff} is an optimal temperature for crop development in °C (crop specific parameter).

The succession of phenological stages is simulated using day degree requirements for emergence (EMDD), completion of vegetative growth (FLDD), transition period between vegetative and reproductive growth (TransDD) and maturity (MTDD).

3.3 Fractional interception of radiation

Fractional interception of radiation is used to determine the portion of radiation available for crop transpiration and evaporation from the soil surface. The two parameters calculated in this Section are:

$$FI_{transp} = 1 - e^{(-K\,LAI)}$$

$$FI_{evap} = 1 - e^{(-K\,(LAI + yLAI))}$$

K - Canopy radiation extinction coefficient (crop specific parameter)
yLAI - Leaf area index of senesced (yellowed) leaves

FI_{transp} is the amount of radiation intercepted by the canopy and used for photosynthesis and transpiration. The amount of radiation penetrating the canopy and used for evaporation from the soil surface is given by "1 - FI_{evap}".

3.4 Crop height

Crop height is used in the calculation of potential evapotranspiration in the **Weather unit**.

Hc is assumed to be 0.001 until emergence. After emergence, it increases linearly until the end of the transition period between vegetative and reproductive growth, when it reaches its maximum (Hc_{max}, crop specific parameter). SWB calculates Hc daily, using the following equation:

$$Hc = 0.001 + (GDD - EMDD)\,(Hc_{max} - 0.001) / (FLDD + TransDD - EMDD)$$

After the transition period between vegetative and reproductive stage has been completed, crop height remains equal to Hc_{max}.

3.5 Daily dry matter production increment

SWB calculates DM_i on a daily basis, after crop emergence and before the crop reaches maturity. DM_i is calculated as either transpiration- or radiation-limited.

Transpiration-limited DM_i (kg m^{-2}) is predicted using the following relationship (Tanner and Sinclair, 1983):

$$DM_i = DWR\,(T / VPD)$$

DWR - Dry matter-water ratio (Pa)

VPD is in Pa and T in mm.

Under conditions of radiation-limited crop growth, DM_i is calculated using the equation recommended by Monteith (1977):

$$DM_i = E_c\, T_f\, FI_{transp}\, R_s$$

E_c - Radiation conversion efficiency (kg MJ^{-1})
T_f - Temperature factor for radiation-limited crop growth

where

$$T_f = (T_{avg} - T_b) / (T_{lo} - T_b)$$

T_{lo} - Temperature of optimum light-limited growth (°C)

The upper limit of T_f is set at 1, when $T_{avg} > T_{lo}$.

Daily dry matter increment is chosen as the minimum of the transpiration- and radiation-limited DM_i.

3.6 Daily harvestable dry matter increment

SWB assumes that, after flowering, DM_i is firstly partitioned to reproductive sinks, then to the other plant organs. The calculation of daily harvestable dry matter increment is therefore the first in the series of calculations carried out to determine dry matter partitioning to plant organs.

On the day when flowering stage commences, initial harvestable dry matter (HDM) of the crop is calculated as follows:

$$HDM = Transl\ SDM$$

Transl - Factor determining translocation of dry matter from stem to grain
SDM - Stem dry matter (kg m^{-2})

Transl is a crop specific parameter.

During the flowering stage, the following equation is used to calculate the daily harvestable dry matter increment:

$$HDM_i = rpf\ DM_i$$

rpf - Reproductive partitioning fraction

where

$$rpf = (GDD - FLDD) / TransDD$$

FLDD and TransDD are crop specific parameters. The upper limit of rpf is set to 1 (all dry matter produced is partitioned to the reproductive portion). If the crop has not flowered, rpf is set to 0. Once the HDM calculation has been completed, SWB subtracts HDM_i from DM_i.

3.7 Partitioning of dry matter into other plant organs

SWB assumes that DM_i is firstly partitioned into roots, then into leaves and finally into the stem.

Daily dry matter increment for roots (RDM_i) is calculated as follows:

$$RDM_i = f_r\, DM_i$$

f_r is set to 0 once root depth has reached a maximum value. Maximum rooting depth (RD_{max}) is a crop specific parameter.

Canopy dry matter daily increment (CDM_i) is then calculated:

$$CDM_i = (1 - f_r)\, DM_i$$

Daily increment of leaf dry matter (LDM_i) is calculated as follows:

$$LDM_i = f_l\, CDM_i$$

f_l - Fraction of top dry matter partitioned into leaves

f_l is calculated as a function of canopy dry matter (CDM):

$$f_l = 1 / (1 + PART\ CDM)^2$$

PART is the stem-leaf partitioning factor (crop specific parameter).

The daily increment of stem dry matter (SDM_i) is then calculated as follows:

$$SDM_i = CDM_i - LDM_i$$

HDM_i is finally added to CDM_i in order to include grain dry matter into CDM.

3.8 Partitioning of dry matter under conditions of water stress

Assimilate partitioning is affected by water stress. Water stress conditions are simulated when the calculated daily water stress index is lower than the threshold (crop specific parameter). SI is calculated in the **Soil unit** as the ratio between actual and potential transpiration.

Under conditions of water stress, a half of the daily leaf dry matter increment is partitioned into roots, the other half into the stem:

$$RDM_i = RDM_i + LDM_i / 2$$

$$SDM_i = SDM_i + LDM_i / 2$$

$$CDM_i = CDM_i - LDM_i / 2$$

If the root system has already reached the maximum depth ($f_r = 0$), the daily leaf dry matter increment is fully partitioned into the stem:

$$SDM_i = SDM_i + LDM_i$$

and LDM_i becomes 0 and one stress day is accumulated.

3.9 Leaf area index

Once emergence has taken place, LAI daily increments (LAI_i) are calculated using the following relationship:

$$LAI_i = LDM_i\ SLA$$

LAI is then calculated by cumulating LAI_i values. It represents the "green leaf" or photosynthetically active canopy, which contributes to transpiration and dry matter production.

Leaf senescence is also accounted for in SWB. This is done by tracking each individual day's LAI age ($LAIage_i$). The age (in d °C) of each day's leaf area increment is kept track of from the day it was generated. Once the LAI_i reaches a maximum age (crop specific parameter), it is classified as leaf area of "yellow/dead leaves" ($yLAI_i$) as it stops contributing to photosynthesis and dry matter production. The green LAI value is then reduced by $yLAI_i$. Leaf area index of senesced leaves (yLAI) is increased by $yLAI_i$, so as to estimate shading of the soil for the evaporation calculation **(Soil unit)**.

A water stress factor (wsf) is used to simulate premature leaf senescence under water stress conditions. When SI is lower than the threshold value, wsf is calculated as follows:

$$wsf = 1 / SI$$

Ageing of leaves is speeded up by multiplying the daily thermal time increment by wsf:

$$LAIage_i = wsf\ GDD_i$$

The upper limit of wsf is set to 2, indicating that the ageing of leaves under water stress conditions can be at most twice as fast as that under well-watered conditions.

3.10 Rooting depth

Rooting depth is calculated with the following equation:

$$RD = RGR\ RDM^{0.5}$$

RGR - Root growth rate ($m^2\ kg^{-0.5}$)

RGR is a crop specific parameter. RD is used in the calculation of transpiration **(Soil unit)**.

4. FAO model

The calculation of crop growth with SWB can only be performed if the afore mentioned crop specific growth parameters are known. If growth parameters for a specific crop are not included in the SWB database, the model allows one to run the soil water balance simulation using an additional database of FAO crop coefficients (Allen et al., 1996).

The FAO approach for crop water use simulations can be selected as an option. The following crop specific parameters are required:

- Length of initial (IniStage), development (DevStage), mid-season (MidStage) and late-season stage (LateStage) of the crop, in days;
- FAO basal crop coefficient for:
  - Initial stage (K_{cb}Ini),
  - Mid-season stage (K_{cb}Mid), and
  - Late-season stage (K_{cb}Late);
- FAO stress factor (Ky) for initial, development, mid-season and late-season stage;
- Potential yield (Y_{pot}) in t ha^{-1};
- Crop height at initial (H_cIni) and mid-season stage (Hc_{max});
- Root depth at initial (RDIni) and mid-season stage (RD_{max});
- Maximum transpiration rate (Tr_{max}); and
- Leaf water potential at maximum transpiration (Ψ_{lm}).

The FAO approach does not calculate dry matter accumulation and canopy LAI. It is, however, used to determine FI_{transp}, FI_{evap} and RD whose values are then used in the soil water balance calculation (**Soil unit**), and Hc whose value is used in the Penman-Monteith calculation of PET (**Weather unit**). The calculation of FI_{transp}, FI_{evap}, RD and Hc using the FAO approach is carried out in the **Crop unit**.

The FAO approach, if selected, is run on a daily basis after crop planting (Figure A4).

Crop developmental stages (initial, development, mid-season and late-season) are identified from days after planting (DAP).

During the initial stage, Kcb is assumed to be equal to K_{cb}Ini. Hc is assumed to be equal to H_cIni, whilst RD is equal to RDIni.

At the beginning of the development stage, the FAO basal crop coefficient is equal to K_{cb}Ini. During the development stage, Kcb linearly increases reaching a value equal to K_{cb}Mid at the end of the stage (Doorenbos and Pruitt, 1992). The following equation is applied to calculate Kcb for the development stage, on a daily basis:

$$Kcb = Kcb + K_{cb}UpGrad\ (DAP - IniStage)$$

where K_{cb}UpGrad (gradient of FAO basal crop coefficient increase during the development stage) is:

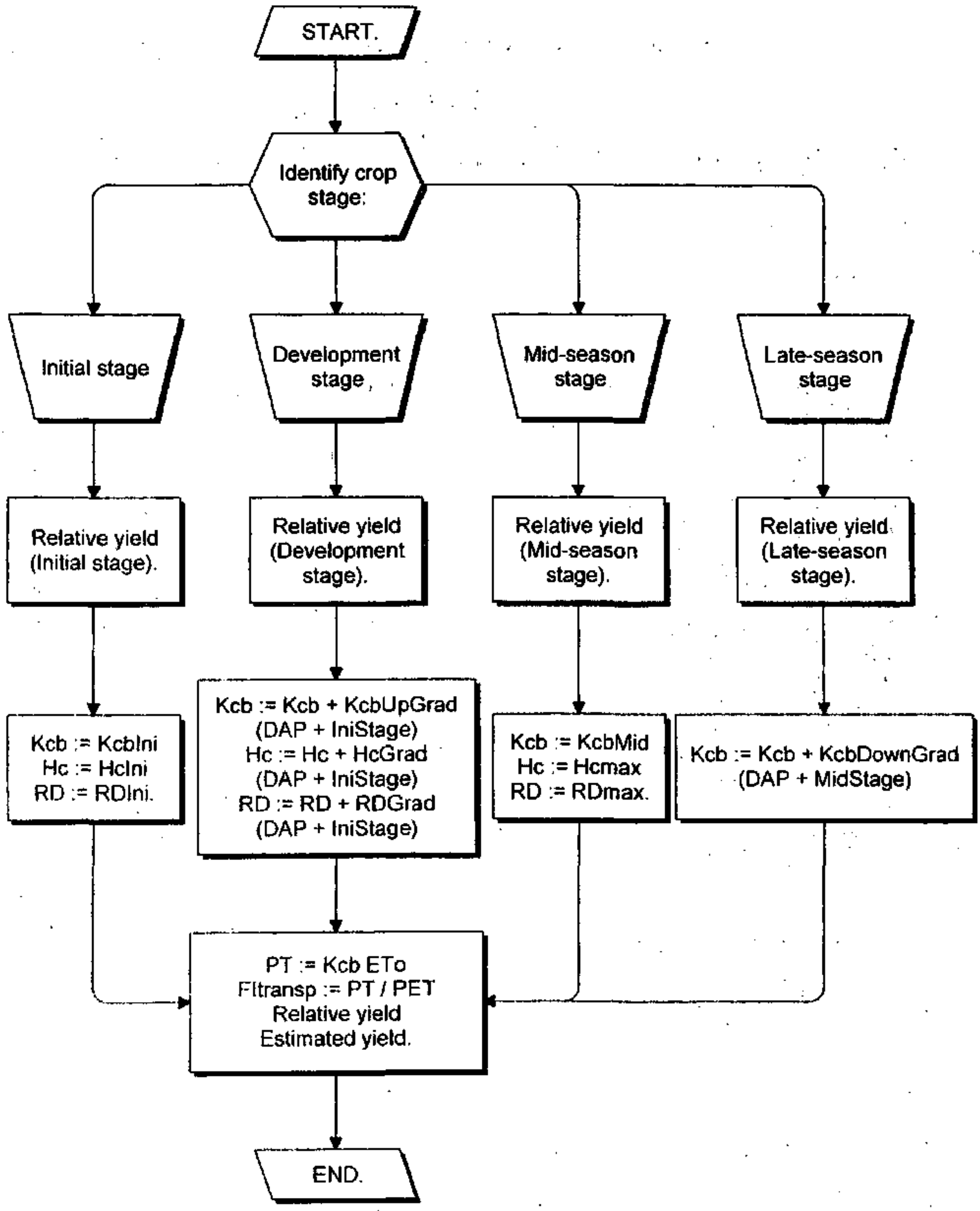


Figure A4
Flow diagram of the FAO model

$$K_{cb}UpGrad = (K_{cb}Mid - K_{cb}Ini) / DevStage$$

Similarly, Hc is calculated adopting the following equation:

$$Hc = Hc + H_cGrad\ (DAP - IniStage)$$

where H_cGrad (gradient of crop height increase during the development stage) is:

$$H_cGrad = (Hc_{max} - H_cIni) / DevStage$$

RD is calculated as follows:

$$RD = RD + RDGrad\ (DAP - IniStage)$$

where RDGrad (gradient of root depth increase during the development stage) is:

$$RDGrad = (RD_{max} - RDIni) / DevStage$$

During the mid-season stage, Kcb is assumed to be equal to K_{cb}Mid, crop height equal to Hc_{max} and RD equal to RD_{max}.

At the beginning of the late-season stage, the FAO basal crop coefficient is equal to K_{cb}Mid. During the late-season stage, Kcb linearly decreases reaching a value equal to K_{cb}Late at the end of the stage. The following equation is applied to calculate Kcb for the late-season stage, on a daily basis:

$$Kcb = Kcb + K_{cb}DownGrad\ (DAP - MidStage)$$

where K_{cb}DownGrad (gradient of FAO basal crop coefficient decrease during the late-season stage) is:

$$K_{cb}DownGrad = (K_{cb}Late - K_{cb}Mid) / LateStage$$

RD and Hc remain at their maximum value during the late-season stage.

Values of PET calculated in the **Weather unit** are used to determine FI_{transp} which is assumed equal to FI_{evap}, as follows:

$$FI_{transp} = FI_{evap} = PT / PET$$

PT - Potential transpiration (mm)

FI_{transp} and FI_{evap} are used in the **Soil unit** to determine actual T and E.

A subroutine for the estimation of yield with the FAO model under conditions of water stress, was included in SWB. The procedure recommended by the FAO was used to compile this procedure (Smith, 1992a). The estimated crop yield (Y) is calculated as follows:

$$Y = Y_{pot} (1 - Y_{red} / 100)$$

where

Y_{pot}	-	Potential yield (t ha^{-1})
Y_{red}	-	Percentage yield reduction (%)

Y_{pot} is a specific crop input parameter. Y_{red} is calculated as follows:

$$Y_{red} = 100 (1 - Y_{rel(Init)} Y_{rel(Dev)} Y_{rel(Mid)} Y_{rel(Late)})$$

where

$Y_{rel(Init)}$	-	Relative yield for initial stage
$Y_{rel(Dev)}$	-	Relative yield for development stage
$Y_{rel(Mid)}$	-	Relative yield for mid-season stage
$Y_{rel(Late)}$	-	Relative yield for late-season stage

Relative yield for each stage (Y_{rel}) is calculated as a function of Ky for that particular stage and the SI:

$$Y_{rel} = 1 - Ky (1 - SI_1 SI_2 ... SI_{n-1} SI_n / n)$$

Ky for each stage and the duration of the stage in days (n) are crop specific input parameters. The subscript of SI indicates the day of the stage. SWB calculates SI on a daily basis as follows:

$$SI = T / (FI_{evap} PET)$$

SI therefore represents the relative transpiration of the crop (ratio of actual and potential crop transpiration). The CROPWAT model of the FAO (Smith, 1992a) uses the ratio of actual and potential evapotranspiration instead of SI, as it does not calculate soil water supply-limited root uptake.

SWB calculates and outputs estimated yield (Y) and Y_{red} on a daily basis, assuming that no water stress (SI = 1) will occur from that particular day until the end of the growing season.

APPENDIX B

SPECIFIC CROP GROWTH PARAMETERS AND FAO CROP FACTORS

TABLE B1
SPECIFIC CROP GROWTH PARAMETERS INCLUDED IN THE SWB DATABASE

Crop	Babala 1) (cv. SA standard)	Beetroot 2) (cv. Crimson Globe)	Bush beans 2) (cv. Bronco)	Bush beans 2) (cv. Provider)	Cabbage 2) (cv. Grand Slam)
Canopy radiation extinction coefficient	0.49	0.93	0.792	0.792	0.83
Corrected dry matter-water ratio (Pa)	7	9	6	2.5	9
Radiation conversion efficiency (kg MJ^{-1})	0.0015	0.0016	0.00122	0.00117	0.0016
Base temperature (°C)	10	4.4	10	10	4.4
Temperature for optimum crop growth (°C)	25	15	18.3	18.3	15
Cutoff temperature (°C)	30	23.9	26.2	26.6	23.9
Emergence day degress (d °C)	50	100	80	50	0
Day degrees at end of vegetative growth (d °C)	1000	800	300	400	600
Day degrees for maturity (d °C)	1650	1509	700	800	1234
Transition period day degrees (d °C)	10	10	400	200	10
Day degrees for leaf senescence (d °C)	1100	1509	250	300	1234
Maximum crop height (m)	2.5	0.4	0.5	0.5	0.3
Maximum root depth (m)	0.6	0.8	0.6	0.4	0.8
Fraction of total dry matter translocated to heads	0.05	0.5	0.05	0.05	0.5
Canopy storage (mm)	1	1	1	1	1
Leaf water potential at maximum transpiration (kPa)	-1500	-1500	-1500	-1500	-1500
Maximum transpiration (mm d^{-1})	9	9	9	9	9
Specific leaf area (m^2 kg^{-1})	17	10.09	12.2	16.8	6.93
Leaf-stem partition parameter (m^2 kg^{-1})	1.3	1.44	0.57	1.01	0.44
Total dry matter at emergence (kg m^{-2})	0.0019	0.0019	0.0019	0.0019	0.007
Fraction of total dry matter partitioned to roots	0.05	0.2	0.2	0.2	0.2
Root growth rate (m^2 $kg^{-0.5}$)	4	5	4	4	4
Stress index	0.95	0.95	0.95	0.95	0.95

1) Irrigation with lime-treated acid mine drainage (Barnard et al., 1998)
2) Roodeplaat trial (Section 4.1)

TABLE B1
SPECIFIC CROP GROWTH PARAMETERS INCLUDED IN THE SWB DATABASE (Continued)

Crop	Carrots 1) (cv. Kuroda)	Chilli pepper 1) (cv. Super Cayenne)	Cocksfoot 2) (cv. Hera)	Cowpeas 3) (cv. Dr Saunders)	Crownvetch 2) (cv. Penngift)
Canopy radiation extinction coefficient	1.31	0.42	0.8	0.53	0.8
Corrected dry matter-water ratio (Pa)	7	4.5	2	3.5	4.4
Radiation conversion efficiency (kg MJ^{-1})	0.0008	0.00163	0.0015	0.0009	0.0015
Base temperature (°C)	7.2	11	4	10	4
Temperature for optimum crop growth (°C)	15	22.5	15	25	15
Cutoff temperature (°C)	23.9	26.6	25	30	25
Emergence day degress (d °C)	100	0	0	50	0
Day degrees at end of vegetative growth (d °C)	600	350	2500	900	2500
Day degrees for maturity (d °C)	1067	900	2500	1700	2500
Transition period day degrees (d °C)	10	550	10	200	10
Day degrees for leaf senescence (d °C)	1067	350	2500	700	2500
Maximum crop height (m)	0.3	0.6	0.3	0.5	0.3
Maximum root depth (m)	0.8	0.6	0.6	0.3	0.8
Fraction of total dry matter translocated to heads	0.5	0.05	0.05	0.005	0.05
Canopy storage (mm)	1	1	1	1	1
Leaf water potential at maximum transpiration (kPa)	-1500	-1500	-1500	-1500	-1500
Maximum transpiration (mm d^{-1})	9	9	9	9	9
Specific leaf area (m^2 kg^{-1})	14.28	11.2	9	18	15
Leaf-stem partition parameter (m^2 kg^{-1})	3.08	1.04	0.1	1	0.5
Total dry matter at emergence (kg m^{-2})	0.0007	0.0019	0.05	0.0019	0.05
Fraction of total dry matter partitioned to roots	0.2	0.2	0.01	0.05	0.01
Root growth rate (m^2 $kg^{-0.5}$)	3	6	25	4	25
Stress index	0.95	0.95	0.95	0.95	0.95

1) Roodeplaat trial (Section 4.1)
2) Irrigation with lime-treated acid mine drainage (Barnard et al., 1998); day degrees for flowering, maturity and leaf senescence are high to allow a long season with several harvests
3) Irrigation with lime-treated acid mine drainage (Barnard et al., 1998)

TABLE B1
SPECIFIC CROP GROWTH PARAMETERS INCLUDED IN THE SWB DATABASE (Continued)

Crop	Eggplant 1) (cv. Black Beauty)	Eragrostis 2) (cv. Ermelo)	Fescue 3) (cv. A.U. Triumph)	Green pepper 1) (cv. King Arthur)	Kikuyu 2)
Canopy radiation extinction coefficient	0.735	0.8	0.8	0.345	0.8
Corrected dry matter-water ratio (Pa)	2.4	4	2.3	4.5	3.5
Radiation conversion efficiency (kg MJ^{-1})	0.0009	0.0015	0.0015	0.0015	0.0015
Base temperature (°C)	11	10	4	18.3	10
Temperature for optimum crop growth (°C)	25.3	20	15	22.5	20
Cutoff temperature (°C)	35	30	25	26.6	30
Emergence day degress (d °C)	0	0	0	0	0
Day degrees at end of vegetative growth (d °C)	350	700	2500	350	700
Day degrees for maturity (d °C)	900	1500	2500	900	1500
Transition period day degrees (d °C)	550	10	10	550	10
Day degrees for leaf senescence (d °C)	350	700	2500	350	700
Maximum crop height (m)	0.6	0.3	0.3	0.5	0.3
Maximum root depth (m)	0.6	1.4	0.6	0.6	1.4
Fraction of total dry matter translocated to heads	0.05	0.01	0.05	0.05	0.01
Canopy storage (mm)	1	1	1	1	1
Leaf water potential at maximum transpiration (kPa)	-1500	-1500	-1500	-1500	-1500
Maximum transpiration (mm d^{-1})	9	9	9	9	9
Specific leaf area (m^2 kg^{-1})	15.4	8	9	12.2	10
Leaf-stem partition parameter (m^2 kg^{-1})	0.981	0.1	0.1	1.07	0.3
Total dry matter at emergence (kg m^{-2})	0.0019	0.05	0.05	0.0019	0.05
Fraction of total dry matter partitioned to roots	0.2	0.05	0.01	0.2	0.05
Root growth rate (m^2 $kg^{-0.5}$)	6	4	25	6	4
Stress index	0.95	0.95	0.95	0.95	0.95

1) Roodeplaat trial (Section 4.1)
2) Irrigation with lime-treated acid mine drainage (Barnard et al., 1998)
3) Irrigation with lime-treated acid mine drainage (Barnard et al., 1998); day degrees for flowering, maturity and leaf senescence are high to allow a long season with several harvests

TABLE B1
SPECIFIC CROP GROWTH PARAMETERS INCLUDED IN THE SWB DATABASE (Continued)

Crop	Lettuce 1) (cv. Great Lakes)	Lucerne 2) (cv. Pan 4860)	Maize 3) (cv. SNK 2340)	Maize 4) (cv. PNR 6552)	Maize 5) (cv. PNR 6479, Ermelo)
Canopy radiation extinction coefficient	0.56	0.8	0.5	0.56	0.56
Corrected dry matter-water ratio (Pa)	3.5	2.2	4	9	9
Radiation conversion efficiency (kg MJ^{-1})	0.0014	0.0015	0.0012	0.0015	0.0015
Base temperature (°C)	7.2	4	10	10	10
Temperature for optimum crop growth (°C)	15	15	25	25	25
Cutoff temperature (°C)	23.9	30	30	30	30
Emergence day degress (d °C)	0	0	50	50	50
Day degrees at end of vegetative growth (d °C)	300	2500	900	900	900
Day degrees for maturity (d °C)	656	2500	1700	1445	1700
Transition period day degrees (d °C)	10	10	10	10	10
Day degrees for leaf senescence (d °C)	656	2500	900	600	900
Maximum crop height (m)	0.4	0.5	2.2	2.2	2.2
Maximum root depth (m)	0.6	0.8	0.6	1.8	1.2
Fraction of total dry matter translocated to heads	0.5	0.05	0.05	0.05	0.05
Canopy storage (mm)	1	1	1	1	1
Leaf water potential at maximum transpiration (kPa)	-1500	-1500	-2000	-2000	-2000
Maximum transpiration (mm d^{-1})	9	9	9	9	9
Specific leaf area (m^2 kg^{-1})	20.27	15	15	15	15
Leaf-stem partition parameter (m^2 kg^{-1})	8.28	0.6	0.8	0.8	0.8
Total dry matter at emergence (kg m^{-2})	0.001	0.05	0.0019	0.0019	0.0019
Fraction of total dry matter partitioned to roots	0.2	0.01	0.01	0.2	0.2
Root growth rate (m^2 $kg^{-0.5}$)	5	25	8	8	8
Stress index	0.95	0.95	0.95	0.95	0.95

1) Roodeplaat trial (Section 4.1)
2) Irrigation with lime-treated acid mine drainage (Barnard et al., 1998); day degrees for flowering, maturity and leaf senescence are high to allow a long season with several harvests
3) Irrigation with lime-treated acid mine drainage (Barnard et al., 1998)
4) Measured data obtained from Bennie et al. (1996)
5) Measured data obtained from Hensley et al. (1994)

TABLE B1
SPECIFIC CROP GROWTH PARAMETERS INCLUDED IN THE SWB DATABASE (Continued)

Crop	Maize 1) (cv. PNR 6479, Kroonstad)	Maize 1) (cv. PNR 473, Setlagole)	Marrow 2) (cv. Long White Bush)	Marrow 2) (cv. President)	Milkvetch 3) (cv. Windsor)
Canopy radiation extinction coefficient	0.56	0.56	0.5	0.58	0.8
Corrected dry matter-water ratio (Pa)	9	9	3	3	2.5
Radiation conversion efficiency (kg MJ^{-1})	0.0015	0.0015	0.0014	0.0014	0.0015
Base temperature (°C)	10	10	10	10	4
Temperature for optimum crop growth (°C)	25	25	21.1	21.1	15
Cutoff temperature (°C)	30	30	32.2	32.2	30
Emergence day degress (d °C)	50	50	0	0	0
Day degrees at end of vegetative growth (d °C)	900	900	250	400	2500
Day degrees for maturity (d °C)	1700	1700	1000	1000	2500
Transition period day degrees (d °C)	10	10	750	600	10
Day degrees for leaf senescence (d °C)	900	900	300	400	2500
Maximum crop height (m)	2.2	2.2	0.65	0.6	0.3
Maximum root depth (m)	1.4	2.1	0.8	1	0.8
Fraction of total dry matter translocated to heads	0.05	0.05	0.05	0.05	0.05
Canopy storage (mm)	1	1	1	1	1
Leaf water potential at maximum transpiration (kPa)	-2000	-2000	-1500	-1500	-1500
Maximum transpiration (mm d^{-1})	9	9	9	9	9
Specific leaf area (m^2 kg^{-1})	15	15	16.6	11.6	15
Leaf-stem partition parameter (m^2 kg^{-1})	0.8	0.8	1.3	1.18	0.5
Total dry matter at emergence (kg m^{-2})	0.0019	0.0019	0.005	0.005	0.05
Fraction of total dry matter partitioned to roots	0.2	0.2	0.2	0.2	0.01
Root growth rate (m^2 $kg^{-0.5}$)	8	8	4	4	25
Stress index	0.95	0.95	0.95	0.95	0.95

1) Measured data obtained from Hensley et al., (1994)
2) Roodeplaat trial (Section 4.1)
3) Irrigation with lime-treated acid mine drainage (Barnard et al., 1998); day degrees for flowering, maturity and leaf senescence are high to allow a long season with several harvests

TABLE B1
SPECIFIC CROP GROWTH PARAMETERS INCLUDED IN THE SWB DATABASE (Continued)

Crop	Oats 1) (cv. Overberg)	Onions 2) (cv. Mercedes)	Panicum 3) (cv. Gattom)	Peanuts 4) (cv. Harts)	Peas, dry 4) (cv. Orb)
Canopy radiation extinction coefficient	0.49	0.75	0.8	0.63	0.63
Corrected dry matter-water ratio (Pa)	4.5	7	4	4	3.5
Radiation conversion efficiency (kg MJ^{-1})	0.0019	0.0015	0.0015	0.0004	0.0015
Base temperature (°C)	4	7.2	10	4	4
Temperature for optimum crop growth (°C)	15	20	20	10	10
Cutoff temperature (°C)	25	29.4	30	30	30
Emergence day degress (d °C)	50	0	0	50	180
Day degrees at end of vegetative growth (d °C)	2000	450	700	1500	600
Day degrees for maturity (d °C)	2000	837	1500	2820	1300
Transition period day degrees (d °C)	10	10	10	1000	10
Day degrees for leaf senescence (d °C)	2000	837	700	1500	1300
Maximum crop height (m)	0.4	0.5	0.3	0.6	0.4
Maximum root depth (m)	0.7	0.8	1.4	1.8	1.2
Fraction of total dry matter translocated to heads	0.05	0.5	0.005	0.05	0.05
Canopy storage (mm)	1	1	1	1	1
Leaf water potential at maximum transpiration (kPa)	-1500	-1500	-1500	-800	-1500
Maximum transpiration (mm d^{-1})	9	9	9	9	9
Specific leaf area (m^2 kg^{-1})	12	8.11	7	19	19
Leaf-stem partition parameter (m^2 kg^{-1})	108	1.12	0.2	1.5	8
Total dry matter at emergence (kg m^{-2})	0.0019	0.007	0.05	0.0019	0.0019
Fraction of total dry matter partitioned to roots	0.05	0.2	0.05	0.2	0.2
Root growth rate (m^2 kg$^{-0.5}$)	4	7	4	7	4
Stress index	0.95	0.95	0.95	0.95	0.95

1) Irrigation with lime-treated acid mine drainage (Barnard et al., 1998); day degrees for flowering, maturity and leaf senescence are high to allow a long season with several harvests
2) Roodeplaat trial (Section 4.1)
3) Irrigation with lime-treated acid mine drainage (Barnard et al., 1998)
4) Measured data obtained from Bennie et al. (1996)

TABLE B1
SPECIFIC CROP GROWTH PARAMETERS INCLUDED IN THE SWB DATABASE (Continued)

Crop	Peas, green 1) (cv. Puget)	Potato, autumn 2) (cv. BP 1)	Potato, spring 3) (cv. Buffelspoort BP 13)	Pumpkin 4) (cv. Minette)	Pumpkin 4) (cv. Miniboer)
Canopy radiation extinction coefficient	0.63	0.55	0.55	0.52	0.7
Corrected dry matter-water ratio (Pa)	5.5	6.8	6.8	5.5	5.5
Radiation conversion efficiency (kg MJ^{-1})	0.0015	0.00175	0.00175	0.001	0
Base temperature (°C)	4	2	2	10	10
Temperature for optimum crop growth (°C)	10	10	10	21.1	21
Cutoff temperature (°C)	30	28	28	32.2	32
Emergence day degress (d °C)	180	350	400	0	0
Day degrees at end of vegetative growth (d °C)	980	750	980	400	200
Day degrees for maturity (d °C)	1800	2300	2650	1000	1000
Transition period day degrees (d °C)	10	250	50	600	800
Day degrees for leaf senescence (d °C)	900	900	2000	300	400
Maximum crop height (m)	0.4	0.75	0.75	0.7	0.6
Maximum root depth (m)	1.1	0.7	1.2	0.8	0.8
Fraction of total dry matter translocated to heads	0.05	0.45	0.45	0.05	0.1
Canopy storage (mm)	1	1	1	1	1
Leaf water potential at maximum transpiration (kPa)	-1500	-550	-550	-1500	-1500
Maximum transpiration (mm d^{-1})	9	7	7	9	9
Specific leaf area (m^2 kg^{-1})	19	20.5	20.5	16	18
Leaf-stem partition parameter (m^2 kg^{-1})	0.5	2	2	1.1	1.1
Total dry matter at emergence (kg m^{-2})	0.0019	0.005	0.005	0.0019	0
Fraction of total dry matter partitioned to roots	0.2	0.1	0.1	0.2	0.2
Root growth rate (m^2 kg$^{-0.5}$)	4	3	4	5	5
Stress index	0.95	0.98	0.98	0.95	1

1) Data obtained from Annandale et al. (1996)
2) Measured data obtained from Dr JM Steyn (Agricultural Research Council - Roodeplaat Vegetable and Ornamental Plant Institute - Potato Programme)
3) Measured data obtained from Bennie et al. (1996)
4) Roodeplaat trial (Section 4.1)

TABLE B1
SPECIFIC CROP GROWTH PARAMETERS INCLUDED IN THE SWB DATABASE (Continued)

Crop	Rhodes grass 1) (cv. Katambora)	Runner beans 2) (cv. Lazy Housewife)	Rye 1) (cv. SSR 1)	Ryegrass 1) (cv. Midmar)	Smuts finger grass 1) (cv. Irene)
Canopy radiation extinction coefficient	0.8	0.329	0.49	0.47	0.8
Corrected dry matter-water ratio (Pa)	3.5	6	4	4	4
Radiation conversion efficiency (kg MJ^{-1})	0.0015	0.00093	0.0015	0.0013	0.0015
Base temperature (°C)	10	10	4	4	10
Temperature for optimum crop growth (°C)	20	18.3	15	15	20
Cutoff temperature (°C)	30	26.6	25	25	30
Emergence day degress (d °C)	0	50	50	0	0
Day degrees at end of vegetative growth (d °C)	700	600	700	500	700
Day degrees for maturity (d °C)	1500	950	2000	2000	1500
Transition period day degrees (d °C)	10	50	900	300	10
Day degrees for leaf senescence (d °C)	700	450	900	600	700
Maximum crop height (m)	0.3	2.3	1.2	0.5	0.3
Maximum root depth (m)	0.4	0.6	0.4	0.4	1.4
Fraction of total dry matter translocated to heads	0.005	0.05	0.01	0.01	0.01
Canopy storage (mm)	1	1	1	1	1
Leaf water potential at maximum transpiration (kPa)	-1500	-1500	-1500	-1500	-1500
Maximum transpiration (mm d^{-1})	9	9	9	9	9
Specific leaf area (m^2 kg^{-1})	15	23.1	15	10	7
Leaf-stem partition parameter (m^2 kg^{-1})	0.9	0.8	2	0.8	0.2
Total dry matter at emergence (kg m^{-2})	0.05	0.0019	0.0019	0.05	0.05
Fraction of total dry matter partitioned to roots	0.005	0.2	0.02	0.005	0.05
Root growth rate (m^2 $kg^{-0.5}$)	4	4	4	4	4
Stress index	0.95	0.95	0.95	0.95	0.95

1) Irrigation with lime-treated acid mine drainage (Barnard et al., 1998)
2) Roodeplaat trial (Section 4.1)

TABLE B1
SPECIFIC CROP GROWTH PARAMETERS INCLUDED IN THE SWB DATABASE (Continued)

Crop	Sorghum 1) (cv. PAN 888)	Soybean 1) (cv. Ibis)	Soybean 2) (cv. Wayne, 0.25 m row spacing)	Soybean 2) (cv. Wayne, 1 m row spacing)	Squash 3) (cv. Table Queen)
Canopy radiation extinction coefficient	0.48	0.52	0.42	0.35	0.706
Corrected dry matter-water ratio (Pa)	4.5	5	5	5	3.5
Radiation conversion efficiency (kg MJ^{-1})	0.0012	0.0012	0.0012	0.0012	0.00068
Base temperature (°C)	10	10	10	10	10
Temperature for optimum crop growth (°C)	25	25	25	25	21.1
Cutoff temperature (°C)	30	30	30	30	32.2
Emergence day degress (d °C)	50	50	80	80	0
Day degrees at end of vegetative growth (d °C)	1000	1050	950	950	400
Day degrees for maturity (d °C)	1500	1450	1450	1450	1000
Transition period day degrees (d °C)	10	10	10	10	600
Day degrees for leaf senescence (d °C)	450	1150	950	950	400
Maximum crop height (m)	1	0.9	1.1	1	0.4
Maximum root depth (m)	0.4	0.5	1.8	1.8	0.8
Fraction of total dry matter translocated to heads	0.01	0.2	0.2	0.2	0.05
Canopy storage (mm)	1	1	1	1	1
Leaf water potential at maximum transpiration (kPa)	-1500	-1500	-1200	-1200	-1500
Maximum transpiration (mm d^{-1})	9	9	9	9	9
Specific leaf area (m^2 kg^{-1})	18	14	27.25	25.91	9.7
Leaf-stem partition parameter (m^2 kg^{-1})	0.5	105	4.1	3.67	1.2
Total dry matter at emergence (kg m^{-2})	0.0019	0.0019	0.0019	0.0019	0.005
Fraction of total dry matter partitioned to roots	0.01	0.01	0.177	0.138	0.2
Root growth rate (m^2 $kg^{-0.5}$)	4	4	6.31	7.54	4
Stress index	0.95	0.95	0.8	0.8	0.95

1) Irrigation with lime-treated acid mine drainage (Barnard et al., 1998)
2) Measured data obtained from Mason et al. (1980)
3) Roodeplaat trial (Section 4.1)

TABLE B1
SPECIFIC CROP GROWTH PARAMETERS INCLUDED IN THE SWB DATABASE (Continued)

Crop	Squash 1) (cv. Waltham)	Sugarcane 2) (var. N14)	Sunflower 3) (cv. CAR1199)	Sunflower 3) (cv. SO306)	Sweet corn 1) (cv. Cabaret)
Canopy radiation extinction coefficient	0.946	0.46	0.8	0.8	0.5
Corrected dry matter-water ratio (Pa)	3.5	6.74	5	5	9
Radiation conversion efficiency (kg MJ^{-1})	0.00036	0.0018	0.0013	0.0013	0.0026
Base temperature (°C)	10	10	4	4	11
Temperature for optimum crop growth (°C)	21.1	20	28	28	20
Cutoff temperature (°C)	32.2	30	40	40	30
Emergence day degress (d °C)	0	100	50	50	50
Day degrees at end of vegetative growth (d °C)	400	2200	1200	1250	500
Day degrees for maturity (d °C)	1100	5000	1700	1700	800
Transition period day degrees (d °C)	700	100	500	450	200
Day degrees for leaf senescence (d °C)	500	3300	1700	1700	300
Maximum crop height (m)	0.3	3.5	2	2	1.7
Maximum root depth (m)	0.8	1.3	1.3	1.3	1
Fraction of total dry matter translocated to heads	0.05	0.05	0.2	0.2	0.05
Canopy storage (mm)	1	1	1	1	1
Leaf water potential at maximum transpiration (kPa)	-1500	-1500	-1500	-1500	-1500
Maximum transpiration (mm d^{-1})	9	9	9	9	9
Specific leaf area (m^2 kg^{-1})	9.9	14	16.65	16.65	15.1
Leaf-stem partition parameter (m^2 kg^{-1})	1	1.5	1	1	2
Total dry matter at emergence (kg m^{-2})	0.005	0.0019	0.0019	0.0019	0.0019
Fraction of total dry matter partitioned to roots	0.2	0.107	0.137	0.137	0.2
Root growth rate (m^2 $kg^{-0.5}$)	5	4	7	7	4
Stress index	0.95	0.95	0.95	0.95	0.95

1) Roodeplaat trial (Section 4.1)
2) Measured data obtained from Thompson (1991)
3) Measured data obtained from Andre Nel (Grain Crops Research Institute - Agricultural Research Council - Potchefstroom)

TABLE B1
SPECIFIC CROP GROWTH PARAMETERS INCLUDED IN THE SWB DATABASE (Continued)

Crop	Sweet corn 1) (cv. Dorado)	Sweet corn 1) (cv. Jubilee)	Sweet corn 1) (cv. Paradise)	Swisschard 1) (cv. Ford Hook Giant)	Tobacco 2) (Air-dried)
Canopy radiation extinction coefficient	0.4	0.36	0.3	0.44	0.6
Corrected dry matter-water ratio (Pa)	8	9	9	8	8
Radiation conversion efficiency (kg MJ^{-1})	0.0027	0.0038	0.0022	0.002	0
Base temperature (°C)	11	11	11	4.4	12
Temperature for optimum crop growth (°C)	20	20	20	15	25
Cutoff temperature (°C)	30	30	30	23.9	32
Emergence day degress (d °C)	50	50	50	50	0
Day degrees at end of vegetative growth (d °C)	500	450	450	1509	860
Day degrees for maturity (d °C)	800	900	900	1509	860
Transition period day degrees (d °C)	200	200	200	10	10
Day degrees for leaf senescence (d °C)	250	450	350	1509	500
Maximum crop height (m)	1.7	2.1	2.1	0.3	1.5
Maximum root depth (m)	0.8	0.6	0.6	0.8	0.8
Fraction of total dry matter translocated to heads	0.05	0.05	0.05	0.5	0.2
Canopy storage (mm)	1	1	1	1	1
Leaf water potential at maximum transpiration (kPa)	-1500	-1500	-1500	-1500	-1500
Maximum transpiration (mm d^{-1})	9	9	9	9	9
Specific leaf area (m^2 kg^{-1})	17.8	14.1	16.6	12.64	14
Leaf-stem partition parameter (m^2 kg^{-1})	1.5	2	2	1.46	0.6
Total dry matter at emergence (kg m^{-2})	0.0019	0.0019	0.0019	0.003	0
Fraction of total dry matter partitioned to roots	0.2	0.2	0.2	0.2	0.1
Root growth rate (m^2 $kg^{-0.5}$)	4	4	4	3	4
Stress index	0.95	0.95	0.95	0.95	1

1) Roodeplaat trial (Section 4.1)
2) Measured data obtained from JJB Pretorius (University of Pretoria)

TABLE B1
SPECIFIC CROP GROWTH PARAMETERS INCLUDED IN THE SWB DATABASE (Continued)

Crop	Tomato 1) (cv. HTX14)	Tomato 1) (cv. P747)	Tomato 1) (cv. Zeal)	Triticale 2) (cv. Cloc 1)	Wheat 3) (cv. Gamtoos)
Canopy radiation extinction coefficient	0.32	0.32	0.26	0.49	0.6
Corrected dry matter-water ratio (Pa)	7	7	7	4	5.5
Radiation conversion efficiency (kg MJ^{-1})	0.0022	0.0018	0.0016	0.0013	0.0015
Base temperature (°C)	11	11	11	4	4
Temperature for optimum crop growth (°C)	22.5	22.5	22.5	15	15
Cutoff temperature (°C)	26.6	28.6	26.6	25	25
Emergence day degress (d °C)	0	0	0	0	50
Day degrees at end of vegetative growth (d °C)	300	300	300	250	1000
Day degrees for maturity (d °C)	930	930	930	2000	1700
Transition period day degrees (d °C)	630	630	630	1000	10
Day degrees for leaf senescence (d °C)	300	300	300	700	500
Maximum crop height (m)	0.45	0.65	0.6	1	1
Maximum root depth (m)	0.8	0.8	0.6	0.6	1.8
Fraction of total dry matter translocated to heads	0.05	0.05	0.05	0.01	0.01
Canopy storage (mm)	1	1	1	1	1
Leaf water potential at maximum transpiration (kPa)	-1500	-1500	-1500	-1500	-1500
Maximum transpiration (mm d^{-1})	9	9	9	9	9
Specific leaf area (m^2 kg^{-1})	14.3	12.1	15.5	10	12
Leaf-stem partition parameter (m^2 kg^{-1})	2	2	2	0.5	1.2
Total dry matter at emergence (kg m^{-2})	0.005	0.005	0.005	0.05	0.0019
Fraction of total dry matter partitioned to roots	0.2	0.2	0.2	0.005	0.2
Root growth rate (m^2 $kg^{-0.5}$)	4	4	4	4	7
Stress index	0.95	0.95	0.95	0.95	0.95

1) Roodeplaat trial (Section 4.1)
2) Irrigation with lime-treated acid mine drainage (Barnard et al., 1998)
3) Measured data obtained from Bennie et al. (1996)

TABLE BI
SPECIFIC CROP GROWTH PARAMETERS INCLUDED IN THE SWB DATABASE (Continued)

Crop	Wheat 1) (cv. Inia)	Wheat 2) (cv. SST 86)
Canopy radiation extinction coefficient	0.49	0.9
Corrected dry matter-water ratio (Pa)	4	5.5
Radiation conversion efficiency (kg MJ^{-1})	0.0017	0.0015
Base temperature (°C)	4	0
Temperature for optimum crop growth (°C)	15	10
Cutoff temperature (°C)	25	30
Emergence day degress (d °C)	50	50
Day degrees at end of vegetative growth (d °C)	750	1400
Day degrees for maturity (d °C)	1500	2300
Transition period day degrees (d °C)	400	10
Day degrees for leaf senescence (d °C)	900	1400
Maximum crop height (m)	1	1
Maximum root depth (m)	0.4	1.5
Fraction of total dry matter translocated to heads	0.01	0.05
Canopy storage (mm)	1	1
Leaf water potential at maximum transpiration (kPa)	-1500	-1500
Maximum transpiration (mm d^{-1})	9	9
Specific leaf area (m^2 kg^{-1})	12	17
Leaf-stem partition parameter (m^2 kg^{-1})	1.2	1.2
Total dry matter at emergence (kg m^{-2})	0.0019	0.0019
Fraction of total dry matter partitioned to roots	0.02	0.15
Root growth rate (m^2 $kg^{-0.5}$)	7	4
Stress index	0.95	0.95

1) Irrigation with lime-treated acid mine drainage (Barnard et al., 1998)
2) Measured data obtained from Walker et al. (1995)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE

Crop		Almonds 1)	Apples 2) (cv. Golden Delicious)	Apples, cherries I 3)	Apples, cherries II 4)	Apples, cherries III 5)
Period (days)	Initial stage	50	31	50	50	50
	Development stage	120	56	120	120	120
	Mid-season stage	50	36	50	50	50
	Late-season stage	30	119	30	30	30
Growing season (days)		250	242	250	250	250
Basal crop coefficient	Initial stage	0.2	0.2	0.35	0.45	0.5
	Mid-season stage	0.9	0.4	0.9	1.15	0.9
	Late-season stage	0.6	0.2	0.65	0.9	0.7
Stress factor	Initial stage	0.5	-	0.5	0.5	0.5
	Development stage	0.5	-	0.5	0.5	0.5
	Mid-season stage	0.5	-	0.5	0.5	0.5
	Late-season stage	0.5	-	0.5	0.5	0.5
Root depth (m)	Initial stage	1.5	0.5	1.5	1.5	1.5
	Mid-season stage	1.5	0.65	1.5	1.5	1.5
	Late-season stage	1.5	0.65	1.5	1.5	1.5
Crop height (m)	Initial stage	5	1.8	4	4	4
	Mid-season stage	5	3	4	4	4
	Late-season stage	5	3	4	4	4
Depletion allowed (%)	Initial stage	50	50	50	50	50
	Mid-season stage	50	50	50	50	50
	Late-season stage	50	50	50	50	50
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-1500	-1000	-1500	-1500	-1500
Potential yield (t ha^{-1})		-	-	-	-	-

1) FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
2) Measured data obtained from Ms T Volschenk (Agricultural Research Council - Infruitec, Stellenbosch)
3) Killing frost, no ground cover; FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
4) Killing frost, active ground cover; FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
5) No killing frost, no ground cover; FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

Crop		Apples, cherries IV 1)	Artichoke 2)	Asparagus 2)	Avocado 2)	Babala 2)
Period (days)	Initial stage	50	20	20	-	20
	Development stage	120	40	30	-	20
	Mid-season stage	50	220	30	-	55
	Late-season stage	30	30	20	-	35
Growing season (days)		250	310	100	-	130
Basal crop coefficient	Initial stage	0.75	0.8	0.15	0.5	0.15
	Mid-season stage	1.15	0.95	0.9	0.9	1.05
	Late-season stage	0.8	0.9	0.2	0.7	0.2
Stress factor	Initial stage	0.5	0.5	0.5	0.5	0.5
	Development stage	0.5	0.5	0.5	0.5	0.5
	Mid-season stage	0.5	0.5	0.5	0.5	0.5
	Late-season stage	0.5	0.5	0.5	0.5	0.5
Root depth (m)	Initial stage	1.5	0.25	0.25	1	0.25
	Mid-season stage	1.5	1	1	1	1.5
	Late-season stage	1.5	1	1	1	1.5
Crop height (m)	Initial stage	4	0.01	0.01	5	0.01
	Mid-season stage	4	1	0.4	5	3
	Late-season stage	4	1	0.4	5	3
Depletion allowed (%)	Initial stage	50	50	50	50	50
	Mid-season stage	50	50	50	50	50
	Late-season stage	50	50	50	50	50
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-1500	-1500	-1500	-1500	-1500
Potential yield (t ha^{-1})		-	-	-	-	-

1) No killing frost, active ground cover; FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
2) FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

Crop		Banana 1) (I year)	Banana 1) (II year)	Barley 1)	Beans 1) (dry)	Beans 1) (green)
Period (days)	Initial stage	90	90	25	20	20
	Development stage	90	90	35	30	30
	Mid-season stage	90	90	45	30	30
	Late-season stage	90	90	30	10	10
Growing season (days)		360	360	135	90	90
Basal crop coefficient	Initial stage	0.15	0.6	0.15	0.15	0.15
	Mid-season stage	1.05	1.1	1.1	1.1	0.95
	Late-season stage	1.05	1.05	0.15	0.25	0.8
Stress factor	Initial stage	1.3	1.3	0.2	0.2	0.2
	Development stage	1.3	1.3	0.6	0.6	0.6
	Mid-season stage	1.3	1.3	0.5	1	1
	Late-season stage	1.3	1.3	0.4	0.4	0.4
Root depth (m)	Initial stage	0.25	0.8	0.25	0.25	0.25
	Mid-season stage	0.8	0.8	1.1	1	1
	Late-season stage	0.8	0.8	1.1	1	1
Crop height (m)	Initial stage	0.01	2	0.01	0.01	0.01
	Mid-season stage	2	4	1	0.4	0.4
	Late-season stage	2	4	1	0.4	0.4
Depletion allowed (%)	Initial stage	35	35	60	45	45
	Mid-season stage	35	35	60	45	45
	Late-season stage	35	35	90	60	60
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-1500	-1500	-1500	-1500	-1500
Potential yield (t ha^{-1})		-	-	-	-	-

1) FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

Crop		*Beetroot 1) (cv. Crimson Globe)*	Beets 2) (table)	Berries 2) (bushes)	Bush beans 1) (cv. Bronco)	Bush beans 1) (cv. Provider)
Period (days)	Initial stage	26	25	50	6	19
	Development stage	79	35	120	30	26
	Mid-season stage	50	25	50	20	17
	Late-season stage	5	10	30	5	7
Growing season (days)		160	95	250	61	69
Basal crop coefficient	Initial stage	0.13	0.15	0.2	0.13	0.13
	Mid-season stage	1.18	0.95	1	0.9	0.94
	Late-season stage	1.04	0.85	0.4	0.7	0.55
Stress factor	Initial stage	0.5	0.5	0.5	0.5	0.5
	Development stage	0.5	0.5	0.5	0.5	0.5
	Mid-season stage	0.5	0.5	0.5	0.5	0.5
	Late-season stage	0.5	0.5	0.5	0.5	0.5
Root depth (m)	Initial stage	0.25	0.25	1.5	0.25	0.25
	Mid-season stage	0.8	0.8	1.5	0.6	0.4
	Late-season stage	0.8	0.8	1.5	0.6	0.4
Crop height (m)	Initial stage	0.01	0.01	1.5	0.01	0.01
	Mid-season stage	0.4	0.4	1.5	0.5	0.5
	Late-season stage	0.4	0.4	1.5	0.5	0.5
Depletion allowed (%)	Initial stage	50	50	50	45	45
	Mid-season stage	50	50	50	45	45
	Late-season stage	50	50	50	60	60
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-1500	-1500	-1500	-1500	-1500
Potential yield (t ha^{-1})		-	-	-	-	-

1) Roodeplaat trial (Section 4.1)
2) FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

Crop		Cabbage 1) (cv. Grand Slam)	Cacao 2)	Carrots 1) (cv. Kuroda)	Castorbeans 2)	Cattails 2) (killing frost)
Period (days)	Initial stage	5	90	46	25	90
	Development stage	62	90	64	40	90
	Mid-season stage	97	90	49	65	90
	Late-season stage	1	90	1	50	90
Growing season (days)		165	360	160	180	360
Basal crop coefficient	Initial stage	0.13	0.9	0.12	0.15	0.2
	Mid-season stage	1.22	1	1.22	1.1	1.15
	Late-season stage	1.22	1	1.22	0.45	0.2
Stress factor	Initial stage	0.4	0.5	0.5	0.5	0.5
	Development stage	0.4	0.5	0.5	0.5	0.5
	Mid-season stage	0.5	0.5	0.5	0.5	0.5
	Late-season stage	0.5	0.5	0.5	0.5	0.5
Root depth (m)	Initial stage	0.25	1	0.25	0.25	1
	Mid-season stage	0.8	1	0.8	1	1
	Late-season stage	0.8	1	0.8	1	1
Crop height (m)	Initial stage	0.05	-	0.01	0.01	2
	Mid-season stage	0.3	-	0.3	0.5	2
	Late-season stage	0.3	-	0.3	0.5	2
Depletion allowed (%)	Initial stage	40	20	35	50	50
	Mid-season stage	40	20	35	50	50
	Late-season stage	40	20	35	50	50
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-1500	-1500	-1500	-1500	-1500
Potential yield (t ha^{-1})		-	-	-	-	-

1) Roodeplaat trial (Section 4.1)
2) FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

Crop		Cattails 1) (no frost)	Celery 1)	Chickpea 1)	Chilli pepper 2) (cv. Super Cayenne)	Citrus I 3)
Period (days)	Initial stage	90	25	20	28	60
	Development stage	90	40	30	22	90
	Mid-season stage	90	45	35	20	90
	Late-season stage	90	15	15	5	120
Growing season (days)		360	125	100	75	360
Basal crop coefficient	Initial stage	0.5	0.15	0.15	0.13	0.6
	Mid-season stage	1.15	0.95	1.1	0.37	0.65
	Late-season stage	0.5	0.9	0.25	0.28	0.6
Stress factor	Initial stage	0.5	0.5	0.5	0.5	0.5
	Development stage	0.5	0.5	0.5	0.5	0.5
	Mid-season stage	0.5	0.5	0.5	0.5	0.5
	Late-season stage	0.5	0.5	0.5	0.5	0.5
Root depth (m)	Initial stage	1	0.25	0.25	0.25	1.4
	Mid-season stage	1	0.4	1	0.6	1.4
	Late-season stage	1	0.4	1	0.6	1.4
Crop height (m)	Initial stage	2	0.01	0.01	0.05	4
	Mid-season stage	2	0.6	0.8	0.6	4
	Late-season stage	2	0.6	0.8	0.6	4
Depletion allowed (%)	Initial stage	50	20	50	20	50
	Mid-season stage	50	20	50	30	50
	Late-season stage	50	20	50	50	50
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-1500	-1500	-1500	-1500	-1500
Potential yield (t ha^{-1})		-	-	-	-	-

1) FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
2) Roodeplaat trial (Section 4.1)
3) No ground cover, 70% canopy; FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

Crop		Citrus II 1)	Citrus III 2)	Citrus IV 3)	Citrus V 4)	Citrus VI 5)
Period (days)	Initial stage	60	60	60	60	60
	Development stage	90	90	90	90	90
	Mid-season stage	90	90	90	90	90
	Late-season stage	120	120	120	120	120
Growing season (days)		360	360	360	360	360
Basal crop coefficient	Initial stage	0.5	0.35	0.75	0.75	0.8
	Mid-season stage	0.6	0.45	0.8	0.8	0.85
	Late-season stage	0.55	0.45	0.75	0.8	0.85
Stress factor	Initial stage	0.5	0.5	0.5	0.5	0.5
	Development stage	0.5	0.5	0.5	0.5	0.5
	Mid-season stage	0.5	0.5	0.5	0.5	0.5
	Late-season stage	0.5	0.5	0.5	0.5	0.5
Root depth (m)	Initial stage	1.4	1.4	1.4	1.4	1.4
	Mid-season stage	1.4	1.4	1.4	1.4	1.4
	Late-season stage	1.4	1.4	1.4	1.4	1.4
Crop height (m)	Initial stage	3	2	4	3	2
	Mid-season stage	3	2	4	3	2
	Late-season stage	3	2	4	3	2
Depletion allowed (%)	Initial stage	50	50	50	50	50
	Mid-season stage	50	50	50	50	50
	Late-season stage	50	50	50	50	50
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-1500	-1500	-1500	-1500	-1500
Potential yield (t ha^{-1})		-	-	-	-	-

1) No ground cover, 50% canopy; FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
2) No ground cover, 20% canopy; FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
3) With active ground cover or weeds, 70% canopy; FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
4) With active ground cover or weeds, 50% canopy; FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
5) With active ground cover or weeds, 20% canopy; FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

Crop		Citrus 1)	Clover 2)	Cocksfoot 2)	Coffee 2) (bare soil)	Coffee 2) (with weeds)
Period (days)	Initial stage	153	10	10	90	90
	Development stage	31	30	30	90	90
	Mid-season stage	120	10	10	90	90
	Late-season stage	61	10	10	90	90
Growing season (days)		365	60	60	360	360
Basal crop coefficient	Initial stage	0.5	0.3	0.85	0.8	1
	Mid-season stage	0.9	1.15	0.9	0.9	1.05
	Late-season stage	0.55	1.05	0.9	0.9	1.05
Stress factor	Initial stage	0.5	0.5	0.5	0.5	0.5
	Development stage	0.5	0.5	0.5	0.5	0.5
	Mid-season stage	0.5	0.5	0.5	0.5	0.5
	Late-season stage	0.5	0.5	0.5	0.5	0.5
Root depth (m)	Initial stage	1.2	0.7	1	2	2
	Mid-season stage	1.2	0.7	1	2	2
	Late-season stage	1.2	0.7	1	2	2
Crop height (m)	Initial stage	3	0.01	0.05	3	3
	Mid-season stage	3	0.6	0.3	3	3
	Late-season stage	3	0.6	0.3	3	3
Depletion allowed (%)	Initial stage	50	35	50	50	50
	Mid-season stage	50	35	50	50	50
	Late-season stage	50	35	50	50	50
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-2000	-1500	-1500	-1500	-1500
Potential yield (t ha^{-1})		-	-	-	-	-

1) Measured data obtained from GC Green and MF du Plessis (Water Research Commission, Pretoria)
2) FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

Crop		Conifer trees 1)	Cotton 1)	Cowpeas 1)	Crownvetch 1)	Crucifers 1)
Period (days)	Initial stage	90	30	20	10	25
	Development stage	90	50	30	30	35
	Mid-season stage	90	55	60	10	25
	Late-season stage	90	45	25	10	10
Growing season (days)		360	180	135	60	95
Basal crop coefficient	Initial stage	0.95	0.15	0.15	0.3	0.15
	Mid-season stage	1	1.1	1.1	1.15	0.95
	Late-season stage	1	0.6	0.3	1.05	0.8
Stress factor	Initial stage	0.5	0.4	0.5	0.5	0.5
	Development stage	0.5	0.4	0.5	0.5	0.5
	Mid-season stage	0.5	0.5	0.5	0.5	0.5
	Late-season stage	0.5	0.4	0.5	0.5	0.5
Root depth (m)	Initial stage	2	0.25	0.25	1	0.25
	Mid-season stage	2	1.4	1	1	1
	Late-season stage	2	1.4	1	1	1
Crop height (m)	Initial stage	10	0.01	0.01	0.05	0.01
	Mid-season stage	10	1.1	0.5	0.3	0.3
	Late-season stage	10	1.1	0.5	0.3	0.3
Depletion allowed (%)	Initial stage	50	60	50	50	50
	Mid-season stage	50	60	50	50	50
	Late-season stage	50	90	50	50	50
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-1500	-1500	-1500	-1500	-1500
Potential yield (t ha^{-1})		-	-	-	-	-

1) FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

Crop		Cucumber 1) (fresh)	Cucumber 1) (machine)	Dates 1)	Eggplant 2) (cv. Black Beauty)	Eragrostis 1)
Period (days)	Initial stage	20	20	90	20	10
	Development stage	30	30	90	32	30
	Mid-season stage	40	40	90	22	10
	Late-season stage	15	15	90	1	10
Growing season (days)		105	105	360	75	60
Basal crop coefficient	Initial stage	0.15	0.15	0.85	0.12	0.75
	Mid-season stage	0.95	0.95	0.9	0.58	0.8
	Late-season stage	0.7	0.8	0.9	0.52	0.8
Stress factor	Initial stage	0.5	0.5	0.8	0.5	0.5
	Development stage	0.5	0.5	0.8	0.5	0.5
	Mid-season stage	0.5	0.5	0.8	0.5	0.5
	Late-season stage	0.5	0.5	0.8	0.5	0.5
Root depth (m)	Initial stage	0.25	0.25	2	0.25	1.4
	Mid-season stage	1	1	2	0.6	1.4
	Late-season stage	1	1	2	0.6	1.4
Crop height (m)	Initial stage	0.01	0.01	8	0.05	0.05
	Mid-season stage	0.3	0.3	8	0.6	0.3
	Late-season stage	0.3	0.3	8	0.6	0.3
Depletion allowed (%)	Initial stage	50	50	50	50	50
	Mid-season stage	50	50	50	50	50
	Late-season stage	50	50	50	50	50
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-1500	-1500	-1500	-1500	-1500
Potential yield ($t\ ha^{-1}$)		-	-	-	-	-

1) FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
2) Roodeplaat trial (Section 4.1)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

Crop		Fescue 1)	Flax 1)	Grapes 1) (table)	Grapes 1) (wine)	Grass I 2)
Period (days)	Initial stage	10	-	10	10	90
	Development stage	30	-	50	50	90
	Mid-season stage	10	-	100	100	90
	Late-season stage	10	-	60	40	90
Growing season (days)		60	-	200	200	360
Basal crop coefficient	Initial stage	0.85	0.15	0.15	0.15	0.85
	Mid-season stage	0.9	1.05	0.8	0.65	0.9
	Late-season stage	0.9	0.2	0.4	0.4	0.9
Stress factor	Initial stage	0.5	0.5	0.2	0.2	1
	Development stage	0.5	0.5	0.7	0.7	1
	Mid-season stage	0.5	0.5	0.85	0.85	1
	Late-season stage	0.5	0.5	0.4	0.4	1
Root depth (m)	Initial stage	1	0.25	1.5	1.5	0.5
	Mid-season stage	1	1.2	1.5	1.5	0.5
	Late-season stage	1	1.2	1.5	1.5	0.5
Crop height (m)	Initial stage	0.05	0.01	2	2	0.07
	Mid-season stage	0.3	0.8	2	2	0.07
	Late-season stage	0.3	0.8	2	2	0.07
Depletion allowed (%)	Initial stage	50	50	40	40	40
	Mid-season stage	50	50	40	40	40
	Late-season stage	50	50	40	40	40
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-1500	-1500	-1500	-1500	-1500
Potential yield (t ha^{-1})		-	-	-	-	-

1) FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
2) Mowed, cool season varieties, including dense stands of Blue grass, ryegrass and fescue; FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

Crop		Grass II 1)	Grass pasture I 2)	Grass pasture II 3)	Green pepper 4) (cv. King Arthur)	Hops 5)
Period (days)	Initial stage	90	90	90	35	-
	Development stage	90	90	90	27	-
	Mid-season stage	90	90	90	12	-
	Late-season stage	90	90	90	1	-
Growing season (days)		360	360	360	75	-
Basal crop coefficient	Initial stage	0.75	0.3	0.3	0.13	0.15
	Mid-season stage	0.8	0.8	0.7	0.4	1
	Late-season stage	0.8	0.8	0.7	0.4	0.8
Stress factor	Initial stage	1	1	1	0.5	0.5
	Development stage	1	1	1	0.5	0.5
	Mid-season stage	1	1	1	0.5	0.5
	Late-season stage	1	1	1	0.5	0.5
Root depth (m)	Initial stage	0.5	1	1	0.25	-
	Mid-season stage	0.5	1	1	0.6	-
	Late-season stage	0.5	1	1	0.6	-
Crop height (m)	Initial stage	0.07	0.15	0.1	0.05	7
	Mid-season stage	0.07	0.15	0.1	0.5	7
	Late-season stage	0.07	0.15	0.1	0.5	7
Depletion allowed (%)	Initial stage	40	50	50	20	50
	Mid-season stage	40	50	50	30	50
	Late-season stage	40	50	50	50	50
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-1500	-1500	-1500	-1500	-1500
Potential yield (t ha^{-1})		-	-	-	-	-

1) Mowed, warm season varieties, including Bermuda grass and St. Augustine grass; FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
2) Rotation; FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
3) Poor management; FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
4) Roodeplaat trial (Section 4.1)
5) FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

Crop		Kikuyu 1)	Kiwi 1)	Lentil 1)	Lettuce 2) (cv. Great Lakes)	Lucerne 1)
Period (days)	Initial stage	10	-	20	52	10
	Development stage	30	-	30	46	30
	Mid-season stage	10	-	60	26	10
	Late-season stage	10	-	40	1	10
Growing season (days)		60	-	150	125	60
Basal crop coefficient	Initial stage	0.75	0.2	0.15	0.14	0.3
	Mid-season stage	0.8	1	1.1	1.14	1.15
	Late-season stage	0.8	1	0.2	1.14	1.1
Stress factor	Initial stage	0.5	0.5	0.5	0.5	0.5
	Development stage	0.5	0.5	0.5	0.5	0.5
	Mid-season stage	0.5	0.5	0.5	0.5	0.5
	Late-season stage	0.5	0.5	0.5	0.5	0.5
Root depth (m)	Initial stage	1.4	1	0.25	0.25	1.5
	Mid-season stage	1.4	1	0.8	0.6	1.5
	Late-season stage	1.4	1	0.8	0.6	1.5
Crop height (m)	Initial stage	0.05	6.5	0.01	0.05	0.05
	Mid-season stage	0.3	6.5	0.5	0.4	0.7
	Late-season stage	0.3	6.5	0.5	0.4	0.7
Depletion allowed (%)	Initial stage	50	50	50	30	55
	Mid-season stage	50	50	50	30	55
	Late-season stage	50	50	50	30	55
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-1500	-1500	-1500	-1500	-1500
Potential yield (t ha^{-1})		-	-	-	-	-

1) FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
2) Roodeplaat trial (Section 4.1)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

Crop		Maize 1)	Maize 2) (cv. PNR 6552)	Maize 3) (cv. PNR 6479, Ermelo)	Maize 3) (cv. PNR 6479, Kroonstad)	Maize 3) (cv. PNR 473, Setlagole)
Period (days)	Initial stage	20	20	20	20	20
	Development stage	50	50	50	50	50
	Mid-season stage	40	40	40	40	40
	Late-season stage	40	40	40	40	40
Growing season (days)		150	150	150	150	150
Basal crop coefficient	Initial stage	0.15	0.15	0.15	0.15	0.15
	Mid-season stage	1.1	1.1	1.1	1.1	1.1
	Late-season stage	0.15	0.15	0.15	0.15	0.15
Stress factor	Initial stage	0.4	0.4	0.4	0.4	0.4
	Development stage	0.6	0.6	0.6	0.6	0.6
	Mid-season stage	1.25	1.25	1.25	1.25	1.25
	Late-season stage	0.8	0.8	0.8	0.8	0.8
Root depth (m)	Initial stage	0.25	0.25	0.25	0.25	0.25
	Mid-season stage	1.5	1.8	1.2	1.4	2.1
	Late-season stage	1.5	1.8	1.2	1.4	2.1
Crop height (m)	Initial stage	0.01	0.01	0.01	0.01	0.01
	Mid-season stage	2.2	2.2	2.2	2.2	2.2
	Late-season stage	2.2	2.2	2.2	2.2	2.2
Depletion allowed (%)	Initial stage	50	50	50	50	50
	Mid-season stage	60	60	60	60	60
	Late-season stage	70	70	70	70	70
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-2000	-2000	-2000	-2000	-2000
Potential yield (t ha^{-1})		-	-	-	-	-

1) FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
2) Measured data obtained from Bennie et al. (1996)
3) Measured data obtained from Hensley et al. (1994)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

Crop		Maize 1) (forage)	Mango 1)	Marrow 2) (cv. Long White Bush)	Marrow 2) (cv. President)	Melons 1)
Period (days)	Initial stage	25	90	30	28	25
	Development stage	35	90	30	27	35
	Mid-season stage	40	90	21	19	40
	Late-season stage	30	90	4	11	20
Growing season (days)		130	360	85	85	120
Basal crop coefficient	Initial stage	0.15	-	0.13	0.12	0.15
	Mid-season stage	1.1	-	0.93	0.77	1
	Late-season stage	0.5	-	0.73	0.3	0.7
Stress factor	Initial stage	0.4	0.8	0.5	0.5	0.5
	Development stage	0.4	0.8	0.5	0.5	0.5
	Mid-season stage	1.3	0.8	0.5	0.5	0.5
	Late-season stage	0.5	0.8	0.5	0.5	0.5
Root depth (m)	Initial stage	0.25	2	0.25	0.25	0.25
	Mid-season stage	1.3	2	0.8	1	1.2
	Late-season stage	1.3	2	0.8	1	1.2
Crop height (m)	Initial stage	0.01	-	0.05	0.05	0.01
	Mid-season stage	3	-	0.65	0.6	0.4
	Late-season stage	3	-	0.65	0.6	0.4
Depletion allowed (%)	Initial stage	50	60	50	50	35
	Mid-season stage	50	60	50	50	35
	Late-season stage	50	60	50	50	35
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-2000	-1500	-1500	-1500	-1500
Potential yield (t ha^{-1})		-	-	-	-	-

1) FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
2) Roodeplaat trial (Section 4.1)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

Crop		Milkvetch 1)	Mint 1)	Oats 1)	Olives 1)	Onions 2) (cv. Mercedes)
Period (days)	Initial stage	10	-	20	50	61
	Development stage	30	-	30	120	49
	Mid-season stage	10	-	60	50	35
	Late-season stage	10	-	40	30	20
Growing season (days)		60	-	150	250	165
Basal crop coefficient	Initial stage	0.3	0.4	0.15	0.55	0.13
	Mid-season stage	1.15	1.1	1.1	0.75	0.8
	Late-season stage	1.05	1.05	0.15	0.65	0.38
Stress factor	Initial stage	0.5	0.5	0.5	0.5	0.45
	Development stage	0.5	0.5	0.5	0.5	0.8
	Mid-season stage	0.5	0.5	0.5	0.5	0.8
	Late-season stage	0.5	0.5	0.5	0.5	0.3
Root depth (m)	Initial stage	1	0.25	0.25	1.5	0.25
	Mid-season stage	1	1	1	1.5	0.8
	Late-season stage	1	1	1	1.5	0.8
Crop height (m)	Initial stage	0.05	0.01	0.01	8	0.05
	Mid-season stage	0.3	0.8	1	8	0.5
	Late-season stage	0.3	0.8	1	8	0.5
Depletion allowed (%)	Initial stage	50	50	50	65	30
	Mid-season stage	50	50	50	65	30
	Late-season stage	50	50	50	65	60
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-1500	-1500	-1500	-1500	-1500
Potential yield (t ha^{-1})		-	-	-	-	-

1) FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
2) Roodeplaat trial (Section 4.1)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

Crop		Onions 1) (green)	Palm trees 1)	Panicum 1)	Peach 2) (cv. Transvaalia, first year)	Peach 2) (cv. Transvaalia, second year)
Period (days)	Initial stage	20	90	10	53	40
	Development stage	30	90	30	110	60
	Mid-season stage	10	90	10	20	53
	Late-season stage	5	90	10	66	30
Growing season (days)		65	360	60	249	183
Basal crop coefficient	Initial stage	0.15	0.9	0.75	0.06	0.16
	Mid-season stage	0.9	0.95	0.8	0.6	0.7
	Late-season stage	0.9	0.95	0.8	0.2	0.16
Stress factor	Initial stage	0.45	0.5	0.5	0.5	0.5
	Development stage	0.8	0.5	0.5	0.5	0.5
	Mid-season stage	0.8	0.5	0.5	0.5	0.5
	Late-season stage	0.3	0.5	0.5	0.5	0.5
Root depth (m)	Initial stage	0.25	1	1.4	0.1	0.5
	Mid-season stage	0.5	1	1.4	0.5	1.2
	Late-season stage	0.5	1	1.4	0.5	1.2
Crop height (m)	Initial stage	0.01	8	0.05	0.4	1.8
	Mid-season stage	0.5	8	0.3	1.8	2.5
	Late-season stage	0.5	8	0.3	1.8	2.5
Depletion allowed (%)	Initial stage	30	65	50	50	50
	Mid-season stage	30	65	50	50	50
	Late-season stage	60	65	50	50	50
Maximum transpiration (mm d^{-1})		9	9	9	7	7
Leaf water potential at maximum transpiration (kPa)		-1500	-1500	-1500	-1000	-1000
Potential yield (t ha^{-1})		-	-	-	-	-

1) FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
2) Early cultivar; Hatfield trial (Section 4.2)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

Crop		Peanuts 1) (cv. Harts)	Peas 2)	Peas 1) (cv. Orb)	Peppers 2) (fresh)	Pineapple 2)
Period (days)	*Initial stage*	25	20	70	30	90
	Development stage	35	30	30	35	90
	Mid-season stage	45	35	20	40	90
	Late-season stage	45	15	30	20	90
Growing season (days)		150	100	150	125	360
Basal crop coefficient	Initial stage	0.15	0.15	0.15	0.15	0.15
	Mid-season stage	1	1.1	1.1	1	0.25
	Late-season stage	0.5	1.05	0.2	0.8	0.25
Stress factor	Initial stage	0.4	0.2	0.2	1.4	0.5
	Development stage	0.6	0.9	0.9	0.6	0.5
	Mid-season stage	0.8	0.7	0.7	1	0.5
	Late-season stage	0.4	0.2	0.2	0.6	0.5
Root depth (m)	Initial stage	0.25	0.25	0.25	0.25	0.5
	Mid-season stage	1.8	1.1	1.2	0.8	0.5
	Late-season stage	1.8	1.1	1.2	0.8	0.5
Crop height (m)	Initial stage	0.01	0.01	0.01	0.01	1.2
	Mid-season stage	0.6	0.4	0.4	0.7	1.2
	Late-season stage	0.6	0.4	0.4	0.7	1.2
Depletion allowed (%)	*Initial stage*	45	35	35	20	50
	Mid-season stage	45	35	35	30	50
	Late-season stage	50	35	35	50	50
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-800	-1500	-1500	-1500	-1500
Potential yield (t ha^{-1})		-	-	-	-	-

1) Measured data obtained from Bennie et al. (1996)
2) FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

Crop		Pistachios 1)	Potato 1)	Pumpkin 1)	Pumpkin 2) (cv. Minette)	Pumpkin 2) (cv. Miniboer)
Period (days)	Initial stage	-	25	20	34	9
	Development stage	-	45	30	24	53
	Mid-season stage	-	45	30	18	22
	Late-season stage	-	30	20	9	1
Growing season (days)		-	145	100	85	85
Basal crop coefficient	Initial stage	0.2	0.15	0.15	0.14	0.14
	Mid-season stage	1.1	1.1	0.95	0.96	0.94
	Late-season stage	0.4	0.65	0.7	0.48	0.94
Stress factor	Initial stage	0.5	0.45	0.5	0.5	0.5
	Development stage	0.5	0.8	0.5	0.5	0.5
	Mid-season stage	0.5	0.8	0.5	0.5	0.5
	Late-season stage	0.5	0.3	0.5	0.5	0.5
Root depth (m)	Initial stage	1.5	0.25	0.25	0.25	0.25
	Mid-season stage	1.5	1.2	1	0.8	0.8
	Late-season stage	1.5	1.2	1	0.8	0.8
Crop height (m)	Initial stage	4.5	0.01	0.01	0.05	0.05
	Mid-season stage	4.5	0.8	0.4	0.7	0.6
	Late-season stage	4.5	0.8	0.4	0.7	0.6
Depletion allowed (%)	Initial stage	50	20	50	50	50
	Mid-season stage	50	30	50	50	50
	Late-season stage	50	50	50	50	50
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-1500	-550	-1500	-1500	-1500
Potential yield (t ha^{-1})		-	-	-	-	-

1) FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
2) Roodeplaat trial (Section 4.1)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

Crop		Radishes 1)	Rhodes grass 1)	Rice 1)	Runner beans 2) (cv. Lazy Housewife)	Rye 1)
Period (days)	Initial stage	10	10	20	6	20
	Development stage	10	30	30	37	30
	Mid-season stage	15	10	40	26	60
	Late-season stage	2	10	30	8	40
Growing season (days)		40	60	120	77	150
Basal crop coefficient	Initial stage	0.15	0.75	1	0.14	0.15
	Mid-season stage	0.85	0.8	1.15	1.02	1.1
	Late-season stage	0.75	0.8	0.7	0.78	0.15
Stress factor	Initial stage	0.5	0.5	0.5	0.5	0.5
	Development stage	0.5	0.5	0.5	0.5	0.5
	Mid-season stage	0.5	0.5	0.5	0.5	0.5
	Late-season stage	0.5	0.5	0.5	0.5	0.5
Root depth (m)	Initial stage	0.25	1	0.25	0.25	0.25
	Mid-season stage	0.5	1	1	0.6	1
	Late-season stage	0.5	1	1	0.6	1
Crop height (m)	Initial stage	0.01	0.05	0.01	0.01	0.01
	Mid-season stage	0.3	0.3	1	2.3	1.2
	Late-season stage	0.3	0.3	1	2.3	1.2
Depletion allowed (%)	Initial stage	50	50	50	50	50
	Mid-season stage	50	50	50	50	50
	Late-season stage	50	50	50	50	50
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-1500	-1500	-1500	-1500	-1500
Potential yield (t ha^{-1})		-	-	-	-	-

1) FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
2) Roodeplaat trial (Section 4.1)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

Crop		Ryegrass 1)	Safflower 1)	Short wetlands 1)	Sisal 1)	Smuts finger grass 1)
Period (days)	Initial stage	15	20	90	-	10
	Development stage	30	30	90	-	30
	Mid-season stage	65	45	90	-	10
	Late-season stage	40	25	90	-	10
Growing season (days)		150	125	360	-	60
Basal crop coefficient	Initial stage	0.15	0.15	1	0.15	0.75
	Mid-season stage	1.1	1.1	1.05	0.55	0.8
	Late-season stage	0.15	0.2	1.05	0.55	0.8
Stress factor	Initial stage	0.5	0.3	0.5	0.5	0.5
	Development stage	0.5	0.55	0.5	0.5	0.5
	Mid-season stage	0.5	0.6	0.5	0.5	0.5
	Late-season stage	0.5	0.6	0.5	0.5	0.5
Root depth (m)	Initial stage	0.25	0.25	0.5	0.25	1.4
	Mid-season stage	1	1.5	0.5	0.7	1.4
	Late-season stage	1	1.5	0.5	0.7	1.4
Crop height (m)	Initial stage	0.01	0.01	0.3	0.01	0.05
	Mid-season stage	0.4	1	0.3	2	0.3
	Late-season stage	0.4	1	0.3	2	0.3
Depletion allowed (%)	Initial stage	50	60	50	80	50
	Mid-season stage	50	60	50	80	50
	Late-season stage	50	60	50	80	50
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-1500	-1500	-1500	-1500	-1500
Potential yield (t ha^{-1})		-	-	-	-	-

1) FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

Crop		Sorghum 1)	Soybean 1)	Soybean 2) (cv. Wayne)	Squash 1)	Squash 3) (cv. Table Queen)
Period (days)	Initial stage	20	20	30	20	10
	Development stage	40	35	40	30	47
	Mid-season stage	30	60	30	30	27
	Late-season stage	30	25	27	20	1
Growing season (days)		120	140	127	100	85
Basal crop coefficient	Initial stage	0.15	0.15	0.15	0.15	0.12
	Mid-season stage	0.95	1.1	1.1	0.9	0.6
	Late-season stage	0.35	0.3	0.3	0.7	0.6
Stress factor	Initial stage	0.4	0.4	0.4	0.5	0.5
	Development stage	0.4	0.8	0.8	0.5	0.5
	Mid-season stage	0.55	1	1	0.5	0.5
	Late-season stage	0.4	0.4	0.4	0.5	0.5
Root depth (m)	Initial stage	0.25	0.25	0.2	0.25	0.25
	Mid-season stage	1.5	1	1.8	0.8	0.8
	Late-season stage	1.5	1	1.8	0.8	0.8
Crop height (m)	Initial stage	0.01	0.01	0.2	0.01	0.05
	Mid-season stage	1	0.9	1	0.3	0.4
	Late-season stage	1	0.9	1	0.3	0.4
Depletion allowed (%)	Initial stage	50	50	50	50	50
	Mid-season stage	55	60	55	50	50
	Late-season stage	90	90	60	50	50
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-1500	-1500	-1200	-1500	-1500
Potential yield (t ha^{-1})		-	-	-	-	-

1) FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
2) Measured data obtained from Mason et al. (1980)
3) Roodeplaat trial (Section 4.1)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

Crop		Squash 1) (cv. Waltham)	Stone fruit I 2)	Stone fruit II 3)	Stone fruit III 4)	Stone fruit IV 5)
Period (days)	Initial stage	18	50	50	50	50
	Development stage	46	120	120	120	120
	Mid-season stage	27	50	50	50	50
	Late-season stage	1	30	30	30	30
Growing season (days)		92	250	250	250	250
Basal crop coefficient	Initial stage	0.13	0.35	0.45	0.45	0.75
	Mid-season stage	0.7	0.85	1.1	0.85	1.1
	Late-season stage	0.7	0.6	0.85	0.6	0.8
Stress factor	Initial stage	0.5	0.5	0.5	0.5	0.5
	Development stage	0.5	0.5	0.5	0.5	0.5
	Mid-season stage	0.5	0.5	0.5	0.5	0.5
	Late-season stage	0.5	0.5	0.5	0.5	0.5
Root depth (m)	Initial stage	0.25	1.5	1.5	1.5	1.5
	Mid-season stage	0.8	1.5	1.5	1.5	1.5
	Late-season stage	0.8	1.5	1.5	1.5	1.5
Crop height (m)	Initial stage	0.05	3	3	3	3
	Mid-season stage	0.3	3	3	3	3
	Late-season stage	0.3	3	3	3	3
Depletion allowed (%)	Initial stage	50	50	50	50	50
	Mid-season stage	50	50	50	50	50
	Late-season stage	50	50	50	50	50
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-1500	-1500	-1500	-1500	-1500
Potential yield (t ha^{-1})		-	-	-	-	-

1) Roodeplaat trial (Section 4.1)
2) Peaches, apricots, pears, plums and pecans; killing frost, no ground cover; FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
3) Peaches, apricots, pears, plums and pecans; killing frost, active ground cover; FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
4) Peaches, apricots, pears, plums and pecans; no killing frost, no ground cover; FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
5) Peaches, apricots, pears, plums and pecans; no killing frost, active ground cover; FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

Crop		Strawberries 1)	Sudan grass 1)	Sugarbeet 1)	Sugarcane 2)	Sunflower 1)
Period (days)	Initial stage	-	-	25	45	25
	Development stage	-	-	35	60	35
	Mid-season stage	-	-	50	170	45
	Late-season stage	-	-	50	60	25
Growing season (days)		-	-	160	335	130
Basal crop coefficient	Initial stage	0.3	0.6	0.15	0.15	0.15
	Mid-season stage	0.8	1.1	1.15	1.2	1.1
	Late-season stage	0.7	1.05	0.5	0.7	0.2
Stress factor	Initial stage	0.5	0.5	0.5	0.8	0.4
	Development stage	0.5	0.5	0.8	0.8	0.6
	Mid-season stage	0.5	0.5	1.2	0.8	0.8
	Late-season stage	0.5	0.5	1	0.8	0.8
Root depth (m)	Initial stage	0.25	1	0.25	0.25	0.25
	Mid-season stage	0.3	1	1	1.3	1.3
	Late-season stage	0.3	1	1	1.3	1.3
Crop height (m)	Initial stage	0.01	0.01	0.01	0.01	0.01
	Mid-season stage	0.2	0.8	0.6	3.5	2
	Late-season stage	0.2	0.8	0.6	3.5	2
Depletion allowed (%)	Initial stage	15	50	50	60	45
	Mid-season stage	15	50	60	60	50
	Late-season stage	15	50	60	60	80
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-1500	-1500	-1500	-1500	-1500
Potential yield (t ha^{-1})		-	-	-	-	-

1) FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
2) Measured data obtained from Thompson (1991)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

Crop		Sunflower 1) (cv. CAR1199)	Sunflower 1) (cv. SO306)	Sweet corn 2)	Sweet corn 3) (cv. Cabaret)	Sweet corn 3) (cv. Dorado)
Period (days)	Initial stage	20	20	20	18	16
	Development stage	20	20	30	27	26
	Mid-season stage	40	40	30	17	17
	Late-season stage	20	20	10	1	6
Growing season (days)		100	100	90	63	65
Basal crop coefficient	Initial stage	0.15	0.15	0.15	0.14	0.14
	Mid-season stage	1.1	1.1	1.1	1.04	0.76
	Late-season stage	0.2	0.2	1	0.99	0.53
Stress factor	Initial stage	0.4	0.4	0.5	0.5	0.5
	Development stage	0.6	0.6	0.5	0.5	0.5
	Mid-season stage	0.8	0.8	0.5	0.5	0.5
	Late-season stage	0.8	0.8	0.5	0.5	0.5
Root depth (m)	Initial stage	0.25	0.25	0.25	0.25	0.25
	Mid-season stage	1.3	1.3	1.2	1	0.8
	Late-season stage	1.3	1.3	1.2	1	0.8
Crop height (m)	Initial stage	0.2	0.2	0.01	0.01	0.01
	Mid-season stage	2	2	1.5	1.7	1.7
	Late-season stage	2	2	1.5	1.7	1.7
Depletion allowed (%)	Initial stage	45	45	50	50	50
	Mid-season stage	50	50	50	50	50
	Late-season stage	80	80	50	50	50
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-1500	-1500	-1500	-1500	-1500
Potential yield (t ha^{-1})		-	-	-	-	-

1) Measured data obtained from Andre Nel (Grain Crops Research Institute - Agricultural Research Council - Potchefstroom)
2) FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
3) Roodeplaat trial (Section 4.1)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

Crop		Sweet corn 1) (cv. Jubilee)	Sweet corn 1) (cv. Paradise)	Sweet potato 2)	Sweet sorghum 2)	Swisschard 1) (cv. Ford Hook Giant)
Period (days)	Initial stage	22	33	-	20	36
	Development stage	37	26	-	40	73
	Mid-season stage	23	19	-	30	50
	Late-season stage	3	7	-	30	1
Growing season (days)		85	85	-	120	160
Basal crop coefficient	Initial stage	0.14	0.14	0.15	0.15	0.13
	Mid-season stage	1.03	1	1.1	1.15	1.21
	Late-season stage	0.86	0.61	0.55	1	1.21
Stress factor	Initial stage	0.5	0.5	0.5	0.5	0.5
	Development stage	0.5	0.5	0.5	0.5	0.5
	Mid-season stage	0.5	0.5	0.5	0.5	0.5
	Late-season stage	0.5	0.5	0.5	0.5	0.5
Root depth (m)	Initial stage	0.25	0.25	0.25	0.25	0.25
	Mid-season stage	0.6	0.6	1.2	2	0.8
	Late-season stage	0.6	0.6	1.2	2	0.8
Crop height (m)	Initial stage	0.01	0.01	0.01	0.01	0.01
	Mid-season stage	2.1	2.1	0.8	3	0.3
	Late-season stage	2.1	2.1	0.8	3	0.3
Depletion allowed (%)	Initial stage	50	50	65	50	20
	Mid-season stage	50	50	65	50	20
	Late-season stage	50	50	65	50	20
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-1500	-1500	-1500	-1500	-1500
Potential yield (t ha^{-1})		-	-	-	-	-

1) Roodeplaat trial (Section 4.1)
2) FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

Crop		Tea 1) (non-shaded)	Tea 1) (shaded)	Tobacco 1)	Tobacco 2) (flue-cured)	Tomato 1)
Period (days)	Initial stage	-	-	20	15	30
	Development stage	-	-	30	32	40
	Mid-season stage	-	-	30	25	45
	Late-season stage	-	-	30	25	30
Growing season (days)		-	-	110	97	145
Basal crop coefficient	Initial stage	0.9	1	-	0.25	0.15
	Mid-season stage	0.95	1.1	-	0.8	1.15
	Late-season stage	0.9	1.05	-	0.2	0.55
Stress factor	Initial stage	0.5	0.5	0.4	0.4	0.5
	Development stage	0.5	0.5	1	1	0.6
	Mid-season stage	0.5	0.5	1	1	1.1
	Late-season stage	0.5	0.5	0.5	0.5	0.8
Root depth (m)	Initial stage	-	-	0.25	0.1	0.25
	Mid-season stage	-	-	0.8	0.7	1
	Late-season stage	-	-	0.8	0.7	1
Crop height (m)	Initial stage	1	2	0.1	0.1	0.01
	Mid-season stage	1	2	0.7	1.5	1
	Late-season stage	1	2	0.7	1.5	1
Depletion allowed (%)	Initial stage	50	50	40	50	30
	Mid-season stage	50	50	50	40	40
	Late-season stage	50	50	65	60	50
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-1500	-1500	-1500	-1500	-1500
Potential yield (t ha^{-1})		-	-	-	-	-

1) FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
2) Measured data obtained from JJB Pretorius (University of Pretoria)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

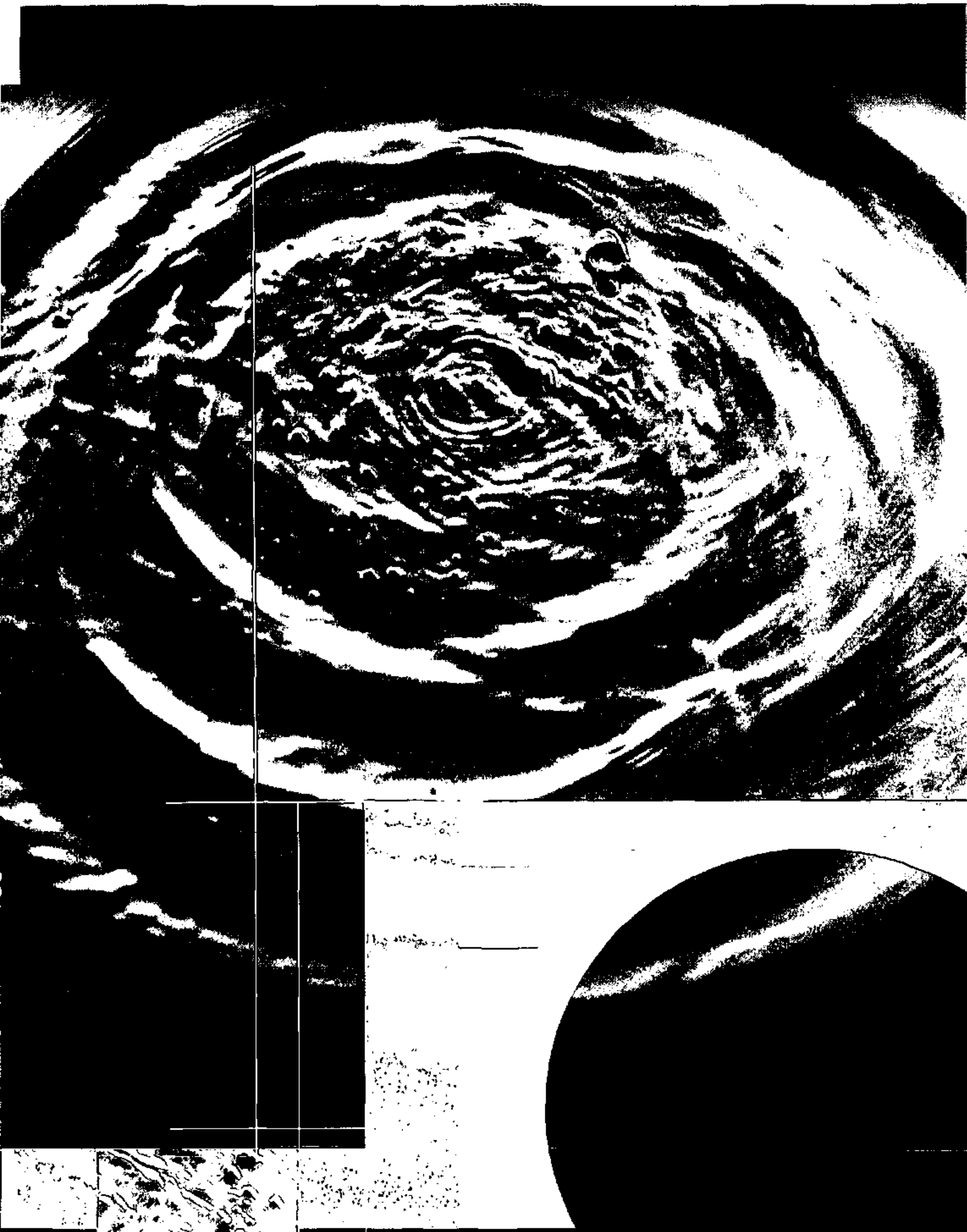
Crop		Tomato 1) (cv. HTX14)	Tomato 1) (cv. P747)	Tomato 1) (cv. Zeal)	Triticale 2)	Turnip 2)
Period (days)	Initial stage	34	27	32	15	-
	Development stage	22	38	27	30	-
	Mid-season stage	17	17	20	65	-
	Late-season stage	10	1	4	40	-
Growing season (days)		83	83	83	150	-
Basal crop coefficient	Initial stage	0.14	0.13	0.12	0.15	0.15
	Mid-season stage	0.68	0.9	0.62	1.1	1
	Late-season stage	0.27	0.9	0.48	0.15	0.85
Stress factor	Initial stage	0.5	0.5	0.5	0.5	0.5
	Development stage	0.6	0.6	0.6	0.5	0.5
	Mid-season stage	1.1	1.1	1.1	0.5	0.5
	Late-season stage	0.8	0.8	0.8	0.5	0.5
Root depth (m)	Initial stage	0.25	0.25	0.25	0.25	0.25
	Mid-season stage	0.8	0.8	0.6	1	1
	Late-season stage	0.8	0.8	0.6	1	1
Crop height (m)	Initial stage	0.05	0.15	0.05	0.01	0.01
	Mid-season stage	0.45	0.65	0.6	1	0.4
	Late-season stage	0.45	0.65	0.6	1	0.4
Depletion allowed (%)	Initial stage	30	30	30	50	50
	Mid-season stage	40	40	40	50	50
	Late-season stage	50	50	50	50	50
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-1500	-1500	-1500	-1500	-1500
Potential yield (t ha^{-1})		-	-	-	-	-

1) Roodeplaat trial (Section 4.1)
2) FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)

TABLE B2
FAO CROP FACTORS INCLUDED IN THE SWB DATABASE (Continued)

Crop		Walnut 1)	Watermelon 1)	Wheat 1)	Wheat 2) (cv. Gamtoos)	Wheat 3) (cv. SST 86)
Period (days)	Initial stage	50	30	15	30	15
	Development stage	120	40	30	60	30
	Mid-season stage	50	50	65	30	65
	Late-season stage	30	30	40	30	40
Growing season (days)		250	150	150	150	150
Basal crop coefficient	Initial stage	0.4	0.15	0.15	0.15	0.15
	Mid-season stage	1.05	1	1.1	0.8	1.1
	Late-season stage	0.6	0.7	0.15	0.15	0.15
Stress factor	Initial stage	0.5	0.5	0.4	0.4	0.4
	Development stage	0.5	0.6	0.6	0.6	0.6
	Mid-season stage	0.5	1.1	0.8	0.8	0.8
	Late-season stage	0.5	0.8	0.4	0.4	0.4
Root depth (m)	Initial stage	2	0.25	0.25	0.25	0.25
	Mid-season stage	2	1	1	1.8	1.5
	Late-season stage	2	1	1	1.8	1.5
Crop height (m)	Initial stage	4.5	0.01	0.01	0.01	0.01
	Mid-season stage	4.5	0.4	1	1	1
	Late-season stage	4.5	0.4	1	1	1
Depletion allowed (%)	Initial stage	50	40	60	60	60
	Mid-season stage	50	40	60	60	60
	Late-season stage	50	50	90	90	90
Maximum transpiration (mm d^{-1})		9	9	9	9	9
Leaf water potential at maximum transpiration (kPa)		-1500	-1500	-1500	-1500	-1500
Potential yield (t ha^{-1})		-	-	-	-	-

1) FAO literature (Doorenbos and Pruitt, 1992; Smith, 1992a; Allen et al., 1996)
2) Measured data obtained from Bennie et al. (1996)
3) Measured data obtained from Walker et al. (1995)



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