DEVELOPMENT AND APPLICATION OF A SIMULATION MODEL TO DETERMINE THE PRODUCTION POTENTIAL OF THEMEDA-VELD IN A SEMI-ARID CLIMATE

BY

MICHEAL DAVID HOWARD

Submitted in fulfilment of the requirements for the degree of

PHILOSOPHIAE DOCTOR

In the Faculty of Agriculture,

Department of Agrometeorology,

University of the Orange Free State

November 1997

Supervisor: Professor J.M. de Jager

ABSTRACT

A methodology was developed, tested and applied to objectively determine the production potential of *Themeda*-veld in the semi-arid regions of South-Africa. In its development, efforts from various scientists from agricultural disciplines such as soil science, pasture science, and meteorology are combined. An innovation is the use of an expolinear growth function, which permits simulation of green leaf dry matter and leaf area *per se* as a means computation of leaf area is avoided. The number of input parameters needed by the expolinear crop growth function to compute daily dry-matter production is kept to a minimum (2), which can be easily derived from experimental data.

The water balance equations used by the model were accounted for on two ecotopes. Results indicate an over estimation of the soil water content. The model achieved an overall root mean square error ($RMSE$) of 11.4 mm and 14.5 mm and a correlation coefficient (r^2) of 54% and 43% on the Shorrocks and Swartland ecotopes, respectively. The inclusion of rainfall intensity data for computing infiltration and run-off could improve the outcome of the model.

Validation of model performance within seasons indicated a moderate fit with an overall $RMSE$ of 315 kg ha^{-1} and higher (across seasons and environments). The r^2 was 45 % and higher for benchmark ecotopes dominated by *Themeda -triandra* species.

Intensive validation of model performance was carried out on eight locations. Validations on final seasonal maximum yields across seasons and environments suggested that an improved and versatile model had been developed. For *Themeda*-veld an overall r^2 of 84 % with a $RMSE$ of 230 kg ha^{-1} at 8 locations was obtained.

The model was further refined to compute growth of a moderate veld condition. Results from measured versus simulated yields on 20 years of data indicated a r^2 of 77%. The $RMSE$ was 270 kg ha^{-1}. The mean absolute error (MAE) was 214 kg ha^{-1}.

A Geographical Information System (GIS) was used to determine the production potential and climatic risk spatially. This allowed the quantification of production risk faced by an individual farmer or manager at any location. In the event of disastrous drought conditions, nearly 80 % of the *Themeda*-veld produce less than 500 kg ha^{-1}. On average 75 % of *Themeda*-veld is capable of producing between 900 and 1300 kg ha^{-1}. Under the most favourable conditions, 80 % of the *Themeda*-veld could produce more than 1100 kg ha^{-1} annum^{-1}. These results provide a basis for examining the effects of climatic risk on production management and land use.

In considering land use, the massive geographical shifts found in the yield isolines with risk level suggested that this general tendency may limit animal production to such an extent that greater adaptability in management is required. This means, a range of agro-ecosystems (i.e. crop production like maize and or wheat and cultivated pastures) needs to be considered when farming in these areas. In some years, higher value crops would be appropriate, and in other years, a fodder or cultivated pasture may be suitable.

To Prof. J.M. de Jager who has become in recent time a colleague and friend, my appreciation for your most valuable contributions, thoughts, guidance and encouragement. In our fruitful and sometimes heated debates you always managed to focus the attention on what and how to achieve the objectives.

This thesis was truly a multi-disciplinary effort.

Prof. H.A. Snyman (Department of Pasture Science in the Faculty of Agricultural at the University of the Orange Free State) supplied the calibration data for the model. Thanks for your valuable comments.

Dr. Malcolm Hensley and Mr. Petrus van Staden (Soil Scientists) from the Agricultural Research Council (ARC) supplied data to test the water balance routines. They contributed to the overall testing and improvements made to the water balance model.

A colleague Mr. Mias van der Westhuizen (Pasture Scientist) with whom I worked with during my years as a researcher (at the Department of Agricultural and Environmental Affairs) provided the unpublished data to test the biomass growth functions of the model.

Mr. Andries Potgieter, Johan van den Berg and the Section of Information and Technology, Department of Agricultural and Environmental Affairs supplied the soil depth and clay maps for the Geographic Information System used.

The editorial skills and always kind remarks of Mr. Mike Fair are greatly appreciated.

Finally, a special thanks has to go to my family for all the understanding and moral supports they provided. Families are the ones who usually suffer most from the extended hours of work. Their patience with a stressed husband and lately a father of two has significantly contributed to the

overall success of this work. Riana, you have done a wonderful job in teaching and looking after our daughter. Many, many, many Thanks.

Psalm 147:8 Who covereth the heaven with clouds, who prepareth rain for the earth, who maketh grass to grow upon the mountains.

TABLE OF CONTENTS

CHAPTER 1 : RATIONALE: SETTING THE SCENE

CHAPTER 2 : THEORY AND ALGORITHMS

INDEX OF TABLES

Page

Page

INDEX OF FIGURES

Page

CURRICULUM VITAE

Micheal David Howard was born on 14 July 1965 in Messina, Republic of South Africa. After graduating from Estcourt High School in 1983, he spent two years in the defence force as part of the compulsory military service. In 1986, he started his under graduate degree in Agriculture at the University of the Orange Free State. In 1989 he graduated in the B.Agric degree Course with distinction in Pasture and Animal Science, at the University of the Orange Free State, where he had the honour of receiving a medal as the best B.Agric student in the 3 years. In 1991 he received his Hons.B.Sc.Agric degree at the University of the Orange Free State. In 1990 the Department of Agriculture appointed him as an Assistant Researcher. He followed through the ranks where he became a principle researcher early in 1995. Working as a researcher for the Department of Agriculture, he received with distinction his Masters degree in Agriculture at the University of the Orange Free State in 1993. He has also received a medal as the best Masters degree student. In 1994 he had the honour of receiving the best Young Scientist award from the Grassland Society of South Africa. In 1995 he was appointed lecturer in the Department of Agrometeorology, Faculty of Agricultural at the University of the Orange Free State.

CHAPTER 1

RATIONALE: SETTING THE SCENE

"Though this be madness, yet there is method in 't." W. Shakespeare

1.1 INTRODUCTION

Climate plays probably the most important role in successful dryland farming. These Farming systems depend on the amount of rainfall received and its distribution throughout the year. To succeed, rainfall should be at the right time, in the right amount and distributed evenly to avoid water stress during critical growth stages of the crops. This is not always possible due to seasonal variability, which may result in untimely water deficits.

Natural resources like soil and water are limited in South Africa. Less than 13 % of South Africa's total land area is fertile soil of which 3 % can be regarded as high potential land. On the other hand, approximately 85 % of the total land area are under natural vegetation (Directorate Agricultural Statistics, 1996). The extensive grazing areas of the Republic of South Africa, with an average rainfall of 500 mm and less, comprise 65 % of these natural vegetations (Snyman, 1985)

Natural physical resources such as precipitation, and soil characteristics (depth and texture) largely determine the production capacity of our natural systems (veld) in association with stocking rate. Natural veld (rangeland) is inexpensive and is naturally maintained. Unfortunately the population does not directly benefit from natural ecosystems. Energy captured from the sun in these ecosystems can only be converted by grazing animals to produce food for the nation (Fogel and Manuel, 1980). In the arid and semi-arid areas droughts occur regularly and under these conditions the amount of available grazing is a major factor influencing animal production. In sweet veld areas, mismanagement even under normal rainfall conditions can limit the available grazing and affects animal production more than the quality of the diet (Fourie, Opperman & Roberts, 1985). According to the authors ((see Fourie, Opperman & Roberts, 1985), carrying capacity in the semi-arid regions of Vryburg is over-estimated by as much as 100 %.

The Free State covers about 12.94x10^6 ha (comprising less than 12 % of the total land area in the RSA). The most intensive botanical survey carried out in South-Africa was that of Acocks (1988) and recently Low and Rebello (1996), classifying the Free State in 9 broad vegetation types of which the

- Eastern Mixed Nama Karoo,
- Dry Sandy Highveld grassland (Dry *Themeda-Cymbopogon* veld), and
- Moist Cool Highveld Grassland

constitute approximately 75 % of the land area (see Fig 1.1)

Acocks (1988) concluded that veld deterioration is likely to take place unless effective grassland management is applied to halt this process. Such marked changes will bring about certain socio-economic problems. One of the major causes for veld deterioration is over-estimation of its grazing potential (Fouché 1992, De Klerk, 1986 and Tidmarsh, 1968).

1.2 MOTIVATION

In the White paper on Agriculture issued in 1995 by the Department of Agriculture, farmers will be held responsible for the sustainable utilisation of our natural agricultural resources (soil and vegetation). Over-utilisation of the natural resources could lead to mismanagement practices and deterioration of these valuable assets.

Knowledge of the potential production or carrying capacity of veld is a prerequisite for the development of sound management systems, planning of farms or reserves, financial aid schemes and the evaluation of production systems. The need to quantify the long-term agricultural potential of veld has become urgent. Also, farming practices should be based upon the variability of resources i.e. soils and rainfall (see Fouché, 1992). Ultimately, a careful and realistic assessment of the underlying risks posed and opportunities presented by the environment must be made.

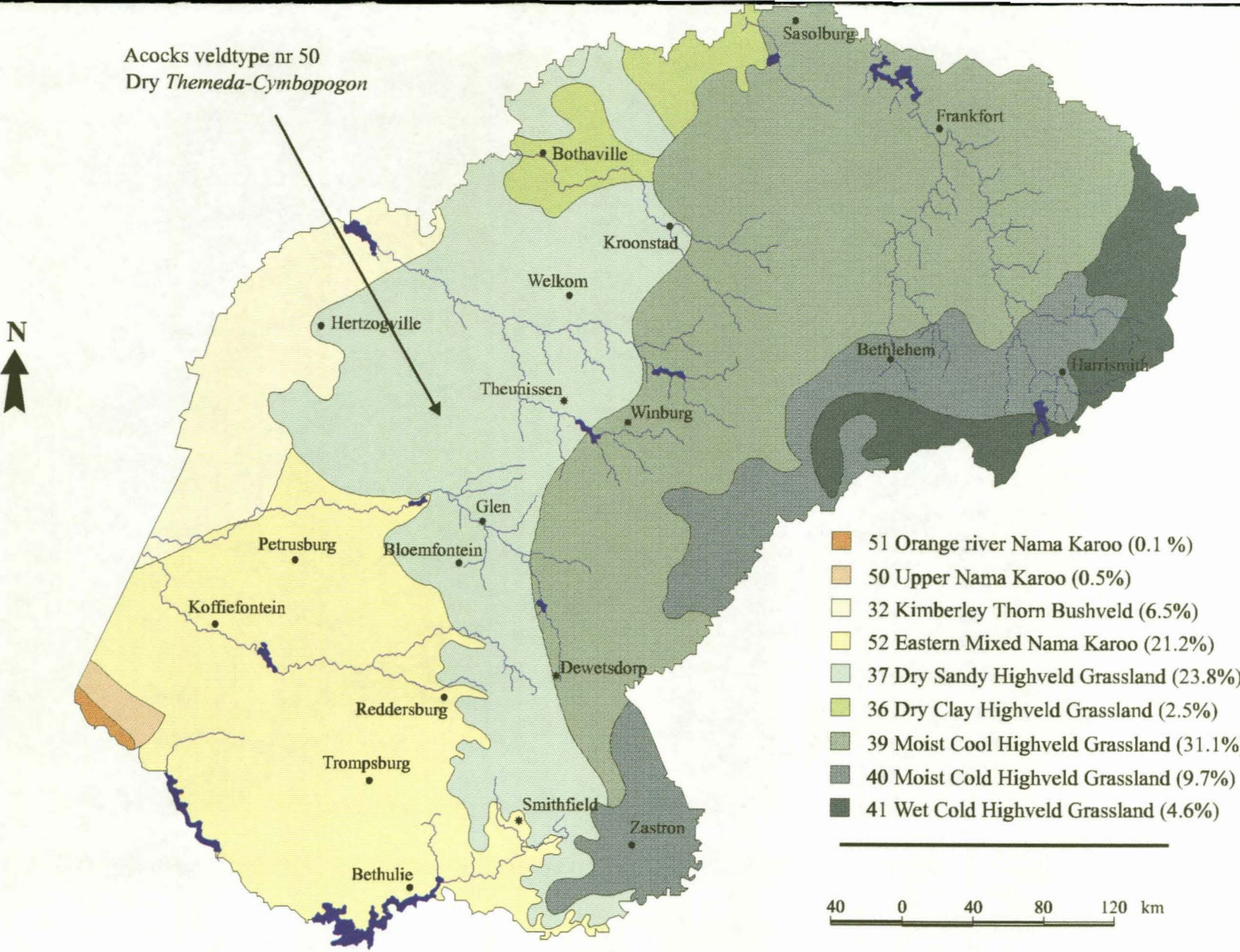

Figure 1.1 Classification map of vegetation in the Free state (reproduced from Low and Rebello, 1996).

For determining the long-term agricultural potential of veld in the Free State, experimental sites need to be established where biomass production can be measured. Covering a large area like the Free State, with sufficient trials would be expensive. Collecting long-term data is tedious, time consuming and expensive and furthermore results only become available after 6 years or more.

Constructing a mathematical model, taking into account climatology, soil texture and variability in veld condition is a viable solution to the problem of determining the long-term production potential for veld in the Free State (see Fouché, 1992).

PRODUCING ANOTHER MODEL?

As part of this thesis a new model has emerged. However, the driving force behind this development was not the need for a new model *per se*. Rather, there is a need for utilising the latest developments found in the Putu suite of crop models (see de Jager, 1997) and produce a model capable of computing growth of *Themeda*-veld. This model was eventually implemented and used in a Geographical Information System (GIS) by the Agricultural Research Council (ARC) for computing drought severity.

In the past, three models have been reported to simulate growth of not only natural veld but also cultivated pastures. It has been shown that these models could be adapted to simulate growth of various plant species i.e. *Cenchrus cilliaris* (Putu13) see Du Pisani (1992) and *Digitaria Eriantha* (Putu14) see Howard (1994). Initially, these models evolved from the work of de Jager (1968), Booysen (1983) and Fouché (1992). The latter produced the Putu11 version of the model.

Putu11, was used extensively in the semi-arid regions and simulates dry matter yields with a good degree of accuracy (Fouché, 1992). Currently, Putu11 is used by the Department of Agriculture and Environmental affairs in the Free State to determine drought severity (de Jager, Howard and Fouché, 1997).

Putu11, is largely a deterministic process based model. Briefly, the model distinguishes between five growth stages where each growth stage is characterised by a set of parameters that regulate growth. Adaptation to accommodate simulation of various species requires knowledge of (1) the growth patterns of species concerned and (2) the critical amount of thermal time units needed to switch from one growth stage to the next.

For scientists and more so for extension officers trying to implement such a model to determine for example the production potential of veld, which in fact is characterised by many species the problem of adapting the model becomes complex.

By simplifying the model, but without loss of accuracy, its applicability and versatility could be enhanced. Such a model is required to be:

- able to accommodate simulation of various plant species,
- robust in its predictive ability across a wide range of environmental conditions in the Free State, and
- simple to use i.e. does not require parameters that are difficult to derive.

The model proposed in this work is characterised by a set of three growth parameters, and distinguishes between an active growth season and a dormant period.

Hensley, van den Berg, Anderson, Oberholzer, du Toit, Berry and de Jager (1994) outlined the value of simulating the water balance correctly. What was required was simulation of the water balance in a multi-layered soil by adapting the initial two-layered soil water balance routines in Putu11 and evaluating it. It was decided to incorporate the soil water balance routines from the Putu Anycrop version into Putu11.

1.3 OBJECTIVES

Overall objectives of the study were to:

- Describe the theory of the model;
- Do relevant calibration and validation tests on the model;
- Determine the distribution of production potential of *Themeda*-veld and underlying climate risk throughout the Free State using a Geographical Information System (GIS); and
- Examine the versatility of the model by computing growth in a veld of moderate condition characterised mainly by *Eragrostis* species.

1.4 PROCEDURE

The specific modelling operations undertaken were the following:

1. Introduce the expolinear crop growth function to grassland;
2. Apply the concept of evaporation coefficient theory;
3. Include a multi-layer soil water balance procedure;
4. Use the concept of "lost time" in the expolinear function to estimate the resilience of a climax veld by making it a function of maximum yield attained during the previous season; and
5. Apply a function that shortens the active growth period due to plant water stress.

The model was calibrated on 20 years of measured biomass yields from a single site. Validation of the model was carried out at 10 sites to establish full credibility.

Main innovations included:

- A computational procedure taking into account veld condition; and
- The implementation of resilience expressed as a function of the dry material carried over from the previous season.

The usefulness and application of the model developed, is constrained to the Dry Sandy Highveld Grassland (see Low and Rebello, 1996) known as the Dry *Cymbopogon-Themeda* veld (Veldtype No 50, see Acocks, 1988). The work endeavours to compute the production potential of *Themeda*-veld i.e. where *Themeda-triandra* is the dominant key specie in the sward.

Relevant literature surveys will be included in each Chapter.

1.5 CRITERION FOR MODELLING ACCURACY

In the semi-arid regions of South Africa, grassland yields differ from season to season. A range from 300 to 3000 kg ha^{-1} is possible (see Snyman, 1997a). The mean (final) yield computed from harvesting data (10 experimental plots, see Appendix D) is around 1100 kg ha^{-1}, of which one standard deviation is 603 kg ha^{-1}. An error equivalent to 50% of one standard deviation was deemed acceptable when estimating the annual production potential of veld in the Dry Sandy Highveld Grassland. Hence, it was decided the model would be deemed accurate when a root mean square error (*RMSE*) of less than 300 kg ha^{-1} $season^{-1}$ was attained.

Seasonal measured accumulative above ground biomass also varies from season to season, depending on the outcome of the season. The overall mean seasonal biomass production as computed from four experimental plots (Shorrocks, Swartland, Mynrust and Franshoek, see Appendix D) is 790 kg ha^{-1}. The standard deviation computed is 480 kg ha^{-1}. Obtaining a *RMSE* of less than 240 kg ha^{-1} would prove the model accurate for computing biomass growth within seasons.

The following criteria

- A systematic root mean square error of less than 60% of the root mean square error produced, and
- A simulation index of agreement (D) and a correlation coefficient (r^2) of 80 % or more.

were considered acceptable when estimating the soil water content.

References

Acocks, J.P.H., 1988. Veld Types of South Africa. Memoirs of botanical survey of South-Africa No. 57

Booysen, J., 1983. Twee metodes vir die kwantitatiewe simulering van groeitoestande van klimaksgras. M.Sc. Agric verhandeling. U.O.V.S. Bloemfontein.

De Jager, J.M., 1968. Carbon dioxide exchange and photosynthesis activity in forage grasses. Unpl. Ph.D. Thesis. Univ. of Wales. 1968.

De Jager, J.M., 1997. Research on a computerised management system. Report to the Water Research Commission. NO K5/581/0/97.

De Jager, J.M., Howard, M.D. and Fouché, H.J. 1997. Computing drought severity and forecasting its future impact on grazing in a GIS. In: Hazards and disaster: A series of definitive works. Volume on drought. Edited by Donald Wilhite of the International Drought Mitigation Centre, Univ. Nebraska, Lincoln (1997) Routledge Publishers.

De Klerk, C.H., 1986. 'n Ondersoek na faktore wat in die weg staan van die aanvaarding van aanbevole veldbeheerpraktyke. Suid-Afrikaanse Instituut vir Landbouvoorligting. Universiteit van Pretoria.

Directorate Agricultural Statistics, 1996. Abstracts of Agricultural Statistics 1996. Directorate Agricultural Statistics, Pretoria.

Du Pisani, L.G., 1992. Simulasie studies met *Cenchrus ciliarus* L. cv. Molopo. Ph.D. proefskrif. U.O.V.S. Bloemfontein.

Fogel, M.M. & Manuel, A.G., 1980. Climatic data needs for efficient management of arid lands. In: Resource Inventories: Developing cost-efficient methods. La Pa Mexico. USDA.

Fouché, J.H., 1992. Simulering van die produksie potensiaal van veld en die kwantifisering van droogte in die Sentrale Oranje-Vrystaat. Ph.D. proefskrif, UOVS, Bloemfontein.

Fourie, J.H., Opperman, D.P.J. & Roberts, B.R., 1985. Influence of stocking rate and grazing systems on available grazing in the Northern Cape. *J. Grassld. Soc. Sth. Afr.* 2,3: 24-26.

Hensley, M., van den Berg, W.J., Anderson, J.J., Oberholzer, L.J., du Toit, M.S., Berry, W. and de Jager, J.M., 1994. Modelling the water balance on benchmark ecotopes. Water research commission progress report.

Howard, M.D., 1994. Simulation studies on *Digitaria eriantha* steud. Subsp. *Eriantha* at differing soil nitrogen levels. MSc. Agric. U.O.V.S. Bloemfontein.

Low, A.B. and Rebelo, A.G., 1996. Vegetation of South-Africa, Lesotho and Swaziland. Department of Environmental Affairs and Tourism. Pretoria.

National Research Council (NRC). 1987. Predicting Feed Intake of Food-Producing Animals. Washington, D.C. : National Academy Press.

Plegge, S.D., Goodrich, R.D., Hanson, S.A. and Kirick, M.A., 1984. Predicting dry matter intake of feedlot cattle. In Proceedings of the Minnesota Nutrition Conference, P 56

Preston, R.L. 1972. Nutritional implications in economy of gain of feedlot cattle. *J.Anim.Sci.* 35:153

Snyman, H.A.,1985. Vogbalansstudies op natuurlike veld van die sentrale Oranje-Vrystaat. Ph.D. proefskrif, UOVS, Bloemfontein.

Snyman, H.A. 1997a. The influence of range condition on the hydrological characteristic in a semi-arid rangeland. Proceedings XVIII International Grassland Congress, Canada. Vol 2 (23),1-2.

Tidmarsh, C.E.M., 1968. Bioclimatology with special reference to agriculture. *S.Afr.J.Sci.* 64:456-459.

White paper on Agriculture, 1995. Department of Agriculture. Pretoria. P Bag X01.

CHAPTER 2

THEORY AND ALGORITHMS

"The scientific method of analysing, explaining and classifying has become conscious of its limitations, which arise out of the fact that by its intervention science alters and refashions the object of investigation. In other words, method and object can no longer be separated. The scientific world-view has ceased to be a scientific view in the true sense of the word.... "

From The Physicist's Conception of Nature [1955] by Werner Heisenberg

Essentially, the atmosphere and soil provides the ingredients necessary for plant growth and development. The weather elements temperature, wind, radiation and air pressure interact vigorously each instant with animal and plant mechanisms. This Chapter explains the mathematics used to describe the processes involved.

2.1 Model structure

Algorithms of state of the art scientific knowledge are combined to build crop growth models. An empirical model, consisting of a regression equation (e.g. a logistic function) can describe crop growth. Weather variables such as radiation and rainfall could be incorporated in such regressions. Empirical models produce accurate results when the regression parameters are determined from extensive sets of experimental data. Applications and predictions based on regression equations are restricted to the range of conditions in which they were developed. Such empirical, descriptive models, however, provide little insight into the nature of the mechanisms, or processes, being simulated.

Putu15, the model developed here, is largely a mechanistic model which explains vegetative growth processes in a natural environment. Leaf area development and growth of different plant organs are examples. The model numerically simulates how these processes are driven by environmental conditions using differential equations in which each parameter has been determined theoretically, or experimentally, or sometimes even guessed. The model is thus a mathematical description of a real system devised to aid resource managers to understand climate-soil-plant interactions.

Dry matter accumulation is described as a function of the meteorological variables solar radiation, temperature, precipitation, and evaporation. The effect of radiation is quantified in terms of the energy balance.

For the purpose of simulating annual production potential, daily computational iterations are convenient. Furthermore, meteorological data are conveniently available on a daily basis. Figure 2.1 illustrates how the main processes are computed in the Putu15 model.

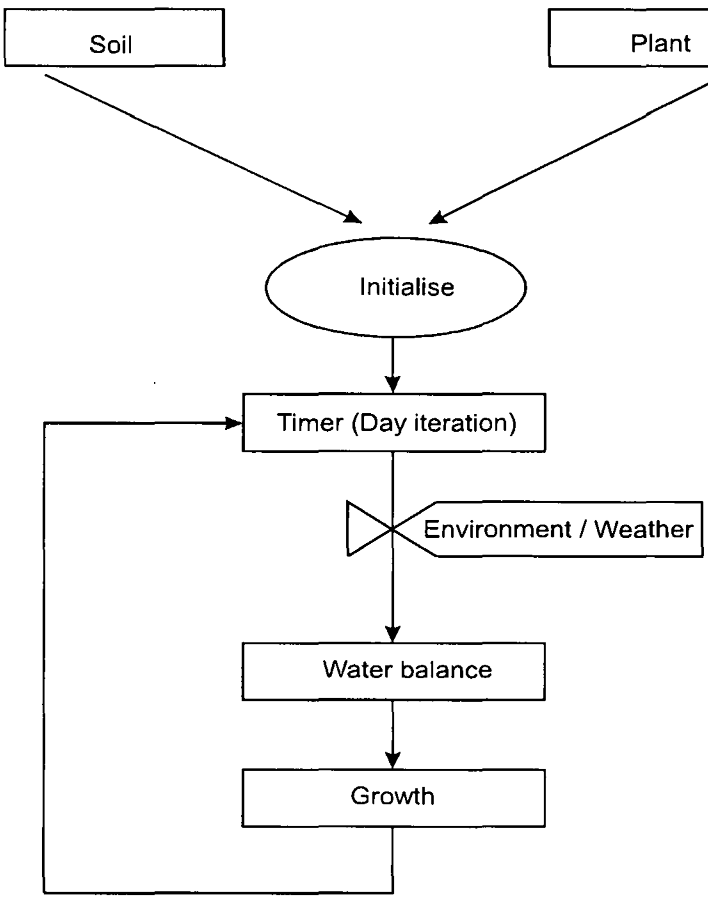

Figure 2.1 Flow chart of the main subroutines in Putu15 simulating growth of natural vegetation.

Putu15 iterates in day time steps throughout a full growing season (365/366 days), simulating processes within the modules illustrated in Figure 2.1. The source code in language C for Putu15 is given in Appendices A1-4. Where specific code statements are referred to in the ensuing text code line numbers will be quoted in parenthesis.

Prior to simulating the effect of soil water content on growth accumulation through the season, information about the soil and plant character is needed by the model. A description of this information will now follow.

Soil:

a. Soil water characteristic:

The matric potential is defined as the energy per unit volume water required to transfer an infinitesimal quantity of water from a reference pool of soil water at the elevation of the soil to the point of interest in the soil at reference air pressure (Jury, Gardner & Gardner, 1991).

The functional relationship between the matric potential Ψ_m (J (kg H_2O)$^{-1}$) and the volumetric soil (subscript s denote soil) water content θ_S (m^3 water (m^3 soil)$^{-1}$) is called the soil water characteristic (SWC) or the matric potential-water content function. It is also known as the soil moisture release curve (Campbell, 1985).

The empirical equations for the SWC of the type developed by Williams, Prebble, Williams and Hignett (1983) on 78 horizons in 17 profiles representing 12 Australian soil groups and Bennie, Coetzee, Van Antwerpen, Van Rensburg and Burger (1988) on relatively coarse textured irrigation soils in the central RSA is implemented in Putu15. Briefly, the SWC is given by:

$$\Psi_s = \Psi_{so}\left(\frac{\theta}{\theta_o}\right)^b,$$

where; Ψ_s soil water potential i.e. suction pressure on water held in a soil matrix (kPa)

Ψ_{so} Suction pressure on water in a soil in which soil water content is at *SWUL* (see page 15).

subscript $_o$ denote upper limit or reference level.

In which the exponent b is computed from

[A1, 275] $$b = \frac{\log\left(\frac{-10}{-1500}\right)}{\log\left(\frac{\theta_{10}}{\theta_{1500}}\right)}$$ [-]

Where: θ_{10}: Volumetric water content at -10 kPa

θ_{1500}: Volumetric water content at -1500 kPa

This constant (b) is needed in Putu15 to describe the SWC from which the onset of plant water stress is simulated.

Modelling procedures require values of both the volumetric water content at -10 kPa (θ_{10}) and -1500 kPa (θ_{1500}). Calculation of θ_{10} and θ_{1500} require laboratory experiments measuring the water content at -10 and -1500 kPa, respectively.

For convenience (as will be describe in Chapter 4, Model Applications, and GIS) it was decided to compute θ_{10} and θ_{1500} from equations derived by Hutson (1984) and or Bennie, *et al* (1988). The methodologies for determining θ_{10} and θ_{1500} are explained by de Jager (1997). This procedure is outlined in Appendix A1, line statements 261 to 274.

In previous versions of the Putu grassland models (Putu11 and Putu 14,see Fouché, 1992; Howard, 1993) the soil water characteristic where calculated following Campbell (1977) and Hutson (1984). The main differences between these three version of Putu are illustrated in Figure 2.2

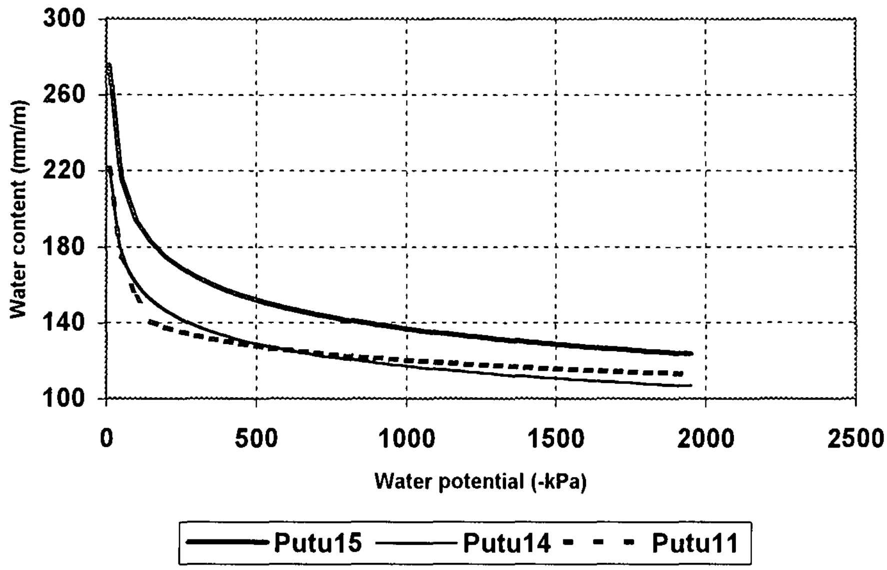

Figure 2.2 Comparison of the soil moisture characteristics for a soil consisting of 20% clay, 10% silt and having a bulk density of 1.5Mg m^{-3} using Putu15, 14 and 11.

b. Soil properties

Soil physical properties required to calculate the SWC and the amount of readily available water are, clay (%), silt (%) and soil bulk density (Mg m^{-3}). Furthermore, soil layer depth (m) and the maximum soil rooting depth (m) are needed to compute the daily soil water balance.

Definitions:

Soil bulkdensity ρ_b: Jury, Gardner & Gardner (1991) defined soil bulk density as the mass of dry soil per volume of soil (Mg cm^{-3}).

Porosity θ_p: The proportion (mm m^{-1}) of soil volume, which is pore space (Jury, Gardner & Gardner, 1991).

Drained Upper Limit (DUL). The soil water content (mm m^{-1}) after 60 days say when exponential decay in deep drainage has caused all free water to have drained through the soil and the water remaining is held by capillary forces great enough to resist gravity (see de Jager, 1997).

The Upper Limit of Soil Water ($SWUL$). The soil water potential (Ψ_{so}) and soil water content (ϑ) associated with the condition reached immediately after a soil wetting event, without evaporation and the initial excess water has rapidly drained away (percolated) and the water remaining almost (80% of θ_p) fills the soil pore space (de Jager, 1997). At this phase deep drainage commences with an exponential decay rate. The subscript o denote upper limit or reference level.

Numerical implementation:

Porosity is computed from the given soil bulk density.

[A1, 275] $$\theta_p = \left[1 - \frac{\rho_b}{2.65}\right].10^3$$ [mm m^{-1}]

The soil bulk density is soil specific. De Jager (1997) gave typical values of soil bulk density for seven categories of soil. Hillel (1982) determined particle density for soils to be around 2.65 (g cm^{-3}).

In practice, DUL should be measured. Instead it was here decided to define DUL as the amount of water retained at a matric potential of -30 kPa (see de Jager, 1997), therefore;

[A1, 274] $$DUL = \theta_{1500}\left[\frac{-30}{-1500}\right]^{\frac{1}{b}}$$ [mm m^{-1}]

$SWUL$ is estimated from a range of relevant matric potentials determined by the soil classification. In essence the assumption is made that for clay soils $SWUL$ could be computed from the SWC at a potential $\Psi \approx$ -10 kPa and for sand at $\Psi \approx$ -5 kPa. The numerical implementation for a clay soil takes place in appendix A1 line statement 280 that reads,

$$SWUL = \theta_{1500}\left[\frac{-10}{-1500}\right]^{\frac{1}{b}}$$

c. Soil water content:

Initial soil water content (θ) in each layer ($V[i]$) on day one of the growing season is needed (see Figure 2.1). These values are equal to the values simulated for the last day of the previous season (i.e. 30 June). This amounts to simulating the soil water content continuously. For grasslands, this approach is essential, particularly in the drier parts of South Africa.

Plant: (physiological characteristics)

Plant physiological characteristics effecting evaporation rate are required for the computation of plant water use and represents the potential evaporation rate of water for a full canopy cover. In Putu15, parameters Kvo and Kso are evaporation coefficients defined as the fractions of reference evaporation supplied by complete plant or complete soil surface cover (see, De Jager & Van Zyl, 1989).

The growth of natural vegetation is specified by a set of parameters in the expolinear equation of Goudriaan and Monteith (1990). These values could be derived from either experimental data, or could be obtained from literature. Parameters describing the growth pattern of the vegetative plants are,

- sward maximum growth rate (Cm, kg $ha^{-1}d°$),
- extinction coefficient (k),
- leaf area ratio (LAR, ha kg^{-1}) and
- the initial plant cover at onset of growth (Lo).

The magnitude of each parameter is quantified in Chapter 3 (Model calibration and validation)

Weather:

Meteorological parameters used by the model are maximum and minimum air temperature (°C), rainfall, and reference crop evaporation (mm d^{-1}). The calculation of reference evaporation using the Priestley-Taylor and the Penman-Monteith equations will be describe in sub-section 2.2.3.

Subroutine ReadWeatherfile reads the weather data from a file. An example of the format of the weather file is given in Appendix A.5. In the model this function is called at line statement 187 (Appendix A.1) and statements 394 to 423.

2.2 Driving forces affecting growth

Prior to computing growth, calculation of the driving forces (rate variables) affecting growth, is needed. The computational procedure are presented in Appendix A.2 (subroutine TempRoutine and EnvironmentalVar, see Figure 2.1). These calculations will now be explained.

2.2.1 Temperature :

The average daily air temperature is calculated as the arithmetic mean of the daily minimum and maximum temperature, thus

[A2, 11] $$\bar{T} = \left[\frac{Tmax + Tmin}{2}\right] \qquad [2.1]$$

$\bar{T}$	: average air temperature	[°C]
$Tmax$	: Maximum temperature (if $Tmax > 30$, then $Tmax = 30$)	[°C]
$Tmin$	: Minimum temperature	[°C]

In the model, the rate of development of the vegetation is measured in terms of thermal time (HU) which is calculated above a base temperature of $BO = 10$ °C. The daily summation of temperatures effective in plant growth and development, is expressed as:

[A2, 11-22, 37] $$HU = \sum_{j=1}^{j=n}\left(\bar{T} - BO\right); \qquad \bar{T} < BO, \bar{T} = BO \qquad [2.2]$$

With BO the base temperature (lower threshold) and n the number of days elapsed.

Daily rate of leaf area development is also determined by HU as will be explained in subsection 2.4.1 as is the rate of senescence (explained in subsection 2.2.5)

In Putu15, the value of $BO = 10$ is derived from the work of Booysen (1983) and Fouché (1992). Howard (1993) implemented the same value when simulating leaf growth of *Digitaria eriantha*.

2.2.2 Growth limiting factors

Based on the work of De Jager (1968) growth limiting factors each corresponding to the individual environmental element are mathematically combined in an overall growth limiting factor, F, using a multiplicative law of independent mutual limitation. Thus, F is computed as:

$$F = \pi_i F_i ,$$

where i denotes a given environmental limiting factor i.e. radiation, temperature or plant water status. In the model described here, F is computed from limiting factors for temperature (Ft, see Eq 2.3, Figure 2.3) and water, Fv, which is actual transpiration relative to potential transpiration ($Ptrans$). Potential evapotranspiration is determined from the atmospheric evaporative demand (AED, defined in subsection 2.3.3: plant and soil evaporation) and the vegetative cover. AED is computed from reference evaporation (E_O) multiplied by the max. crop evaporation coefficient (de Jager, 1997).

[A2, 35] $$Ft = e^{\left[-0.00277\left(\bar{T}-T_0\right)^2\right]}$$ (For $T_0 = 20$) [2.3]

[A3, 238] $$Fv = \left[\frac{Trans}{Ptrans}\right]$$ [2.4]

[A2, 36] $$F = 100.Fv.Ft$$ [%] [2.5]

The computational procedure of reference evaporation will be described in subsection 2.2.3. The methodology for computing transpiration ($Trans$) from the canopy surface will be described in the section dealing with water extraction from the root zone (sub-section 2.3.4).

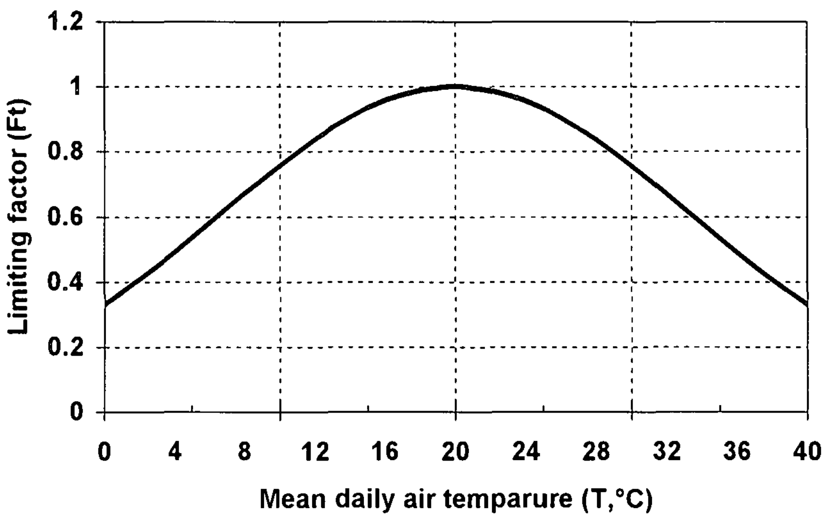

Figure 2.3 Relationship between temperature and environmental limiting factor (Ft).

The overall limiting factor (F) is combined with $\left(\bar{T}-BO\right)$ to compute effective growing thermal time dT viz.

[A2, 44] $$dT = \left(\bar{T} - BO\right) \bullet F$$ [2.6]

and therefore

[A2, 45] $$TIMEthml = \sum_{j=1}^{365\,or\,366} dT$$ [2.7]

To compute daily biomass and leaf growth the model (Putu15) uses $TIMEthml$. Briefly this means that biomass accumulation in the plant is computed in terms of heat summation above a reference temperature (BO) and is adjusted for the effect of low, or high temperatures and soil moisture content.

2.2.3 Reference crop evaporation:

Doorenbos and Pruitt (1977) defined reference crop evaporation as the rate of evaporation from an extensive surface of 80 to 150 mm tall green grass cover, uniform in height, actively growing, completely shading the ground, and not short of water or nutrients.

Strictly speaking, transpiration is the evaporation of water through leaves. Evaporation of water also takes place from the soil or from a free-water surface. Evapotranspiration is the sum of evaporation from leaves (transpiration) and evaporation from the soil in a vegetative surface.

Climatological methods to estimate crop evaporation (E_o) have been reviewed by:

Bowen, 1926; Thornwaite and Holzman, 1939; Penman, 1948; Blaney & Criddle, 1950; Swinbank, 1951; Makkink, 1957; Slatyer & Mcillroy, 1961; Jensen & Haise, 1963; Monteith, 1963 and 1964; Van Bavel, 1966; Tanner, 1967; Priestley & Taylor, 1972; Caprio, 1974; Linacre, 1977; Allen, 1986 and Van Zyl & de Jager, 1987.

In principle, evaporation from a surface is proportional to the gradient of vapour pressure between the evaporating surface and the surrounding air. The vapour pressure at the evaporating surface is equal to the saturated vapour pressure at the prevailing temperature of that surface. The vapour pressure of the air is a function of the ambient temperature and its relative humidity.

The rate of evaporation depends on the diffusion resistance between the evaporating surface and the air. The magnitude of the resistance is strongly related to wind speed.

The major problem in the climatological approach is that the temperature of the evaporative surface is usually not derivable from standard meteorological observations.

Evaporation of 1 mm layer of water requires 2.4 MJ m^{-2} of energy and can be estimated by means of the quantification of an energy balance. The energy dissipation, during evaporation leads to cooling of the evaporating surface, which reduces the vapour gradient. Hence a driving force is required to maintain the surface temperature, and thus, maintain the vapour pressure gradient. Part of this driving force is supplied by the net radiation received by surface.

Net radiation is the balance between incoming (short-wave) radiation from the sun and radiation losses due to reflection and outgoing (long-wave) radiation. Heat supplied by advected air is another source of energy, which can be appreciable in situations where vegetation is surrounded by extensive bare areas. Evaporation from vegetation is thus governed by two factors: radiation and the aerodynamics above the vegetation.

Penman (1948) was the first to describe evapotranspiration in physical mathematical terms. He calculated evaporation from a free-water surface for 10-day periods. There is ongoing discussion in the literature whether the Penman formulae are also applicable if daily weather data values are used. For large day/night duration differences, Doorenbos & Pruitt, (1977); Feddes, Kowalik & Zaradny, (1978) and Doorenbos & Kassam (1979) suggested the use of correction factors. This is explained in subsection 2.2.4.

Penman used evaporation coefficients to estimate bare soil and grass sward evaporation from the computed free-water surface. The value calculated according to the Penman equations is the potential evapotranspiration (E_p). The computation of potential evapotranspiration and its derivation will now be discussed.

Theory: Following the derivation of Lang (1973) the energy budget for a grass surface is described by

$$H + C + A + \lambda E_0 = 0 \quad [2.8]$$

Where: $H = R_n + G$

Notation:

R_n	: net radiation	[W m^{-2}]
G	: Soil heat flux density	[W m^{-2}]
C	: Sensible heat flux density	[W m^{-2}]
A	: Advected heat flux density	[W m^{-2}]
λ	: Latent heat of evaporation	[2.45 MJ kg^{-1}]
E_o	: Reference crop evaporation	[kg m^{-2} s^{-1}]

Advection, A, is defined as the downwind transport of energy, or mass, in a horizontal plane (Rosenberg, Blad & Verma, 1983). The sign convention of Houghton (1985) is used in Eq 2.8 viz.

all incoming energy (including advection) is denoted positive and all outgoing energy negative. Rearranging Eq 2.8 gives:

$$R_n + G + A = -C - \lambda E_0$$

By introducing the Bowen ratio, $\beta = \left[\frac{C}{\lambda E_0}\right]$ (Bowen, 1926) into Eq 2.8, λE_0 may be determined from;

$$\lambda E_0 = \frac{-(R_n + G + A)}{(\beta + 1)} \qquad [2.9]$$

Also following Campbell (1977), $\beta = \gamma \frac{\Delta T}{\Delta e}$, where

γ = Psychometric constant $\left(= \frac{\rho C_p}{\lambda} = 66\right)$		[Pa]
$\Delta T = T_{a1} - T_{a2}$	: Temperature	[°C]
$\Delta e = e_1 - e_2$	: Water vapour pressure	[Pa]

Therefore in Eq 2.9, λE_0 may be determined by substituting measurements of R_n, G, A, together with T_a and e measurements at two different heights.

Later, Monteith (1964) introduced crop canopy resistance into the Penman formula and an aerodynamic resistance term (Thom, 1975) by assuming $A = 0$. The formulation resulted in the Penman-Monteith equation, expressing λE_0 as,

$$\lambda Eo = \frac{\delta}{\delta + \gamma^*}(Rn - G) + \frac{\rho Cp}{\delta + \gamma^*}\frac{(e_a(T) - e_d)}{r_a} \qquad [2.10]$$

Where $\gamma^* = \gamma\left(1 + \frac{r_c}{r_a}\right)$

Notation: $(Rn - G)$: available energy to evaporate water, also H [W m^{-2}]

δ	: Slope of the saturated water vapour pressure / temperature curve	[Pa °C^{-1}]
Cp	: Specific heat at constant pressure	[1010 J kg^{-1} °C^{-1}]
$e_a(T)$	: Saturation vapour pressure at temperature T	[kPa]

e_d : Atmospheric vapour pressure [kPa]

r_c : Crop canopy resistance [s m^{-1}]

30 s m^{-1} for hourly mean weather data (de Jager, 1984).

70 s m^{-1} for 24 hour, or longer, mean values of weather data (Allen, Jensen, Wright and Burman, 1989)

R_n : Net radiation [W m^{-2}]

r_a : Aerodynamic resistance [s m^{-1}]

λ : Latent heat of evaporation [MJ kg^{-1}]

γ : Psychometric constant [kPa °C^{-1}]

Both Allen (1986) and Van Zyl & de Jager (1987), found reliable correlation between measured and computed reference evaporation using bi-hourly meteorological values in the Penman-Monteith formulae. The latter obtained the results illustrated in Figure 2.4.

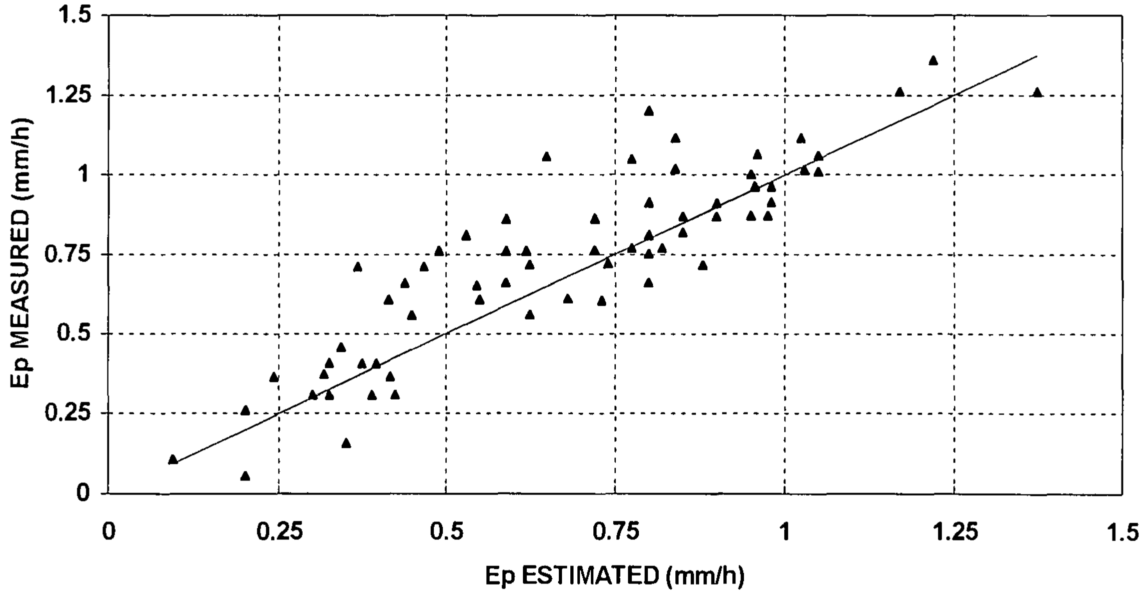

Figure 2.4 A comparison between potential evaporation in wheat (E_p) measured and estimated using the Penman-Monteith equation corrected for atmospheric stability as measured over short grass (see van Zyl & de Jager, 1987).

In Putu (11,13 and 14), the Priestley-Taylor equation may be derived from equation 2.10. The potential short grass evaporation rate in mm d^{-1}, E_O, may be estimated using the Priestly-Taylor equation modified for high temperature (see de Jager, 1997), thus

$$E_o = \frac{1}{\lambda}\left[\frac{\Delta}{(\Delta + \gamma)}\right]1.28(R_n - G)$$

Reads $$E_o = \frac{1}{\lambda}\left[\frac{\Delta}{(\Delta + \gamma)}\right]1.28(0.65 \bullet RFD)$$

for temperatures less than 20 °C. For temperatures greater than 20 °C, E_O, is computed from,

$$E_O = \frac{1}{\lambda}\left[\frac{\Delta}{(\Delta + \gamma)}\right][1.28 + 0.08(\mathrm{Tmax} - 20)](0.65\, RFD)$$

Where the following notation applies:

λ : The coefficient of latent heat of evaporation at constant temperature [2.45 MJ kg^{-1} or 2450 J g^{-1}].

Δ : The slope of the saturation vapour pressure temperature curve [kPa °C^{-1}]

γ : The psychrometric constant [kPa °C^{-1}]

RFD : Radiant flux density [W m^{-2}]

In Putu15, daily reference evaporation (E_o) is calculated [using equation 2.10; A2, 58] prior to the iteration phase (see Figure 2.1). Daily values of E_O, is stored in a variable called Data[i].Eo, where i denotes the day of growth.

2.2.4 Physiological ageing (senescence):

Senescence refers to the loss of capacity to carry out physiological processes and to the loss of living biomass. The fundamental processes involving physiological ageing and breakdown are difficult to quantify. Plant material is assumed to die once its life cycle has been completed. The dying rate may be accelerated as a result of drought stress or mutual shading. Gallagher (1979) defined the concept of life-span, which is crop specific, in terms of temperature, thus;

$$f_{rai} = \frac{\bar{T} - T_{b,age}}{35 - T_{b,age}} \qquad [2.11a]$$

Where f_{rai} : Physiologic ageing factor [-]

$\bar{T}$: Daily average temperature [°C]

$T_{b,age}$: Lower threshold temperature for physiologic ageing. [°C]

Similarly, this theory has been extended in the Putu15 model. The rate constant β, as used by Johnson & Thornley (1983) is applied and heat units (HU) replace average temperature in Eq 2.11a. Thus,

$$\beta = \gamma 20 \left[\frac{HU - T_b}{1220 - T_b} \right] \qquad \text{(for } \beta \geq 0\text{)} \qquad [d^{-1}] \qquad [2.11b]$$

Where $\gamma 20$: rate constant (0.015 d^{-1}, Johnson and Thornley (1983); 0.01d^{-1}, Putu15)

T_b : Base heat units below which growth does not occur (70 °C d)

As will be seen in Chapter 3 (Model calibration), the use of Eq 2.11a in the model yielded moderate results. β Is applied and used in subsection 2.5.1.

2.3 Soil-Plant water relations

Plant production involves intake of atmospheric CO_2 through stomatal openings in the epidermis. Most of the water that plants take up from the soil is lost to the atmosphere by transpiration through the same stomata. If soil water taken up by the roots is not replenished, the soil will dry out to such an extent that the plants wilt and ultimately die.

The tenacity with which the soil matrix retains its water must be overcome by the suction exerted by the roots in order for the plant to take up soil water. This suction known as the soil water potential is measurable. In hydrology, the matric potential is used and is commonly expressed as energy unit per weight of soil water. Optimum ranges of matric potentials exist within which the plant takes up water freely. Above or below this level the plants experiences stress. It reacts by actively curbing daily water consumption through partial or complete closure of the stomata. The consequence of this stomatal closure reduces CO_2 intake, reduces assimilation and, reduces dry matter production. For modelling plant growth, the mathematical description of the effects of water status on physiological processes such as photosynthesis, leaf area expansion, partitioning and growth are required.

A growth model must therefore trace soil water potential to determine when and to what degree the plant is exposed to water stress. This of utmost importance under rainfed conditions as in grasslands. This is commonly done with the aid of a soil water balance equation.

2.3.1 Elements of the water balance

For natural vegetation, water transpired in the plant growth process (E_V) is described by (see, Fig 2.5):

$$E_v = (P \pm \Delta S) - (E_s + R + D) \qquad [2.12]$$

Where:

E_V	: Evaporation from the plant (transpiration)	[mm d^{-1}]
P	: Precipitation	[mm d^{-1}]
ΔS	: change in soil water content	[mm d^{-1}]
E_S	: Evaporation from the soil	[mm d^{-1}]
R	: Runoff	[mm d^{-1}]
D	: Deep drainage	[mm d^{-1}]

Hensley (1993) outlined the value of quantifying each process in Eq 2.12. Long-term quantification of the terms in the water balance, especially in the dry parts of the R.S.A. will greatly improve agricultural management practices.

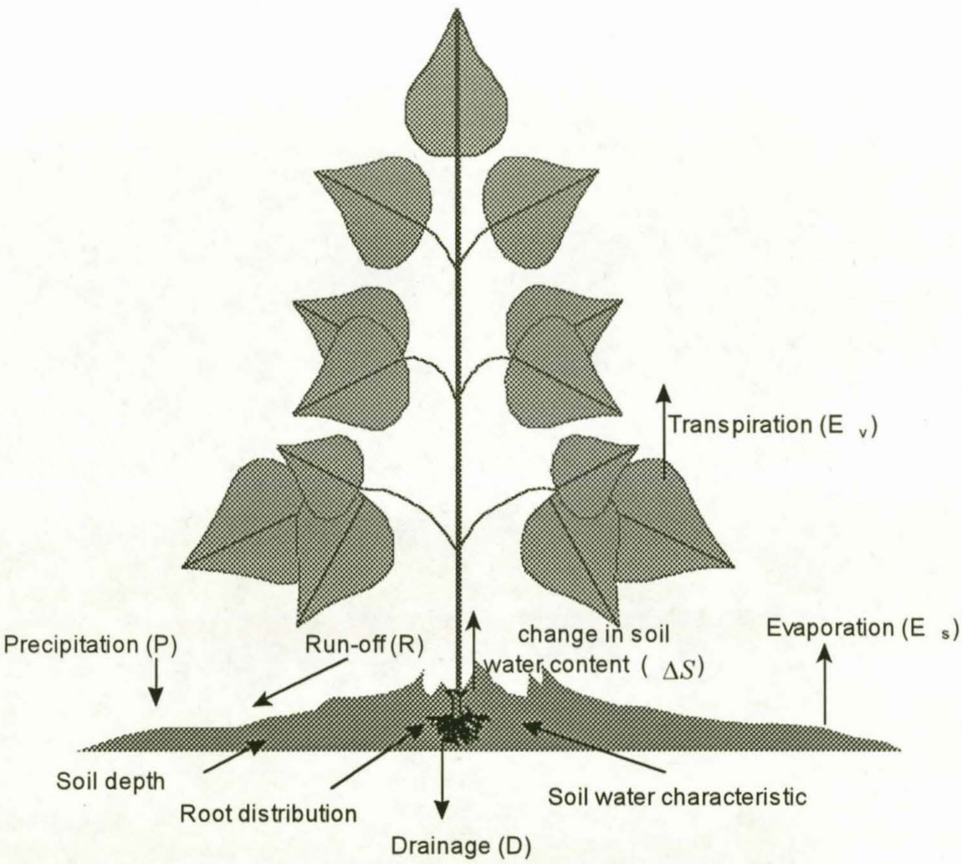

Figure 2.5 Elements of a water balance model at a vegetative surface.

Since weather determines the ultimate control on plant water use and growth, most operational models are driven by weather data. The most important component of the water balance is evapotranspiration, about which much has been written pertaining to grassland (De Jager, Opperman & Booysen, 1980; Hayes, O'Rourke, Terjung and Todhunter, 1982; Snyman, 1982; Van Keulen, 1982; Wight, Hanson and Whitmer, 1984; Wight, Hanson and Cooley, 1986; Wight and Hanson, 1988; Snyman, 1988; Snyman; 1989).

The aim of this section is to describe the water balance model used in Putu15. With precipitation (measured), depth (measured), and the soil water characteristic known, the water balance of a vegetative surface may be described in terms of :

- root distribution,
- plant and soil evaporation
- soil and leaf water potential,
- water extraction from the root zone (ΔS)
- infiltration and percolation (run-off, and deep drainage)

2.3.2 Root distribution:

There are few models of root growth and extension. The problem is complex and knowledge of plant and soil characteristics are needed. Lungley (1973) considered branching models for root growth.

Of particular interest, is the work of Gerwitz and Page (1974). They considered data on many plant root systems, including the effects of soil water, fertility, plant age and mass. An explicit expression for root density (R_d , per unit volume of soil) is given by:

$$R_d = \lambda W_r e^{[-\lambda z]} \qquad [2.13]$$

Where:

W_r	: Root mass density	[kg root dry matter (m^2 ground)$^{-1}$]
z	: Distance below the soil surface	[m]
λ	: Constant	[m^{-1}]

Integrating Eq 2.13 with respect to z between $z = 0$ and z gives $W_r(1 - e^{-\lambda z})$. The fraction of root mass that lies between the soil surface and depth z is then given by $1 - e^{-\lambda z}$.

These calculations are described for Putu15 in Appendix A3. The mathematical functions for layered root mass proceeds at line statements 27-47. Here, A is λ, $DZRT_i$ is Z (subscript i denote layer number) and $ZEFFO$ is maximum rooting depth.

2.3.3 Plant and Soil evaporation:

Definitions:

Atmospheric evaporative demand (AED): The water vapour transfer to the atmosphere, required to sustain the energy balance of a given vegetative surface [see Eq 2.8] in its present growth stage, when the water status of its root zone permits unhindered evaporation from the vegetation and the water status of the top 150 mm of soil equals its current value (see De Jager and Van Zyl, 1989).

Reference evaporation (E_O): the rate of total evaporation from an extended surface of 80 mm to 150 mm tall vegetative grass cover of uniform height, actively growing, completely shading the ground and not deficient in water or nutrients (Doorenbos and Pruitt, 1977). Reference evaporation is also expressed as the rate of evaporation from a 300 to 500 mm tall crop of lucerne (*Medicago sativa L.*) (Jensen and Allen, 1990).

Evaporation coefficient: the ratio of AED to reference evaporation (de Jager, 1997)

Accurate estimation of water utilisation by a vegetative cover is of utmost importance. Atmospheric evaporative demand, AED, represents the upper limit of evaporation as determined by atmospheric conditions and the degree of vegetation cover and constitutes the water necessary to ensure maximum (water non-stressed) yield. An explicit expression for AED is;

$$AED = k_c . E_o , \qquad \text{or } k_c = \frac{AED}{E_o}$$

Where:

$k_c = k_{vg} + k_s$: Evaporation coefficients for the plant (k_{vg}) and soil (k_s).

Theory:

Potential plant evaporation (the upper limit):

Evaporation coefficient theory prescribes that plant- and soil evaporation strives to meet AED. The potential plant evaporation (*Ptrans* ;E_{VO}, mm d^{-1}) is computed from (see, De Jager, 1997) :

[A2, 60] $E_{vo} = k_{vg}.E_o$ [mm d^{-1}]

Where

[A2, 59] $k_{vg} = k_{vo}.FI_g$ [-]

[A2, 56] $FI_g = 1 - e^{\left[0.7-0.3FG.LAI_g\right]}$

FI_g : relative plant evaporation rate when the soil surface is dry. [-]

FG : surface dry-down factor. Fraction of potential soil evaporation permitted from top 150mm of soil

k_{vo} : Evaporation coefficient for complete vegetative cover.

LAI_g : Green leaf area index

Several expressions for FG appear in the literature (Ritchie, 1972; Hanks and Hill, 1980, Monteith, 1981; Wright 1981; de Jager, van Zyl, Bristow and van Rooyen, 1982;). In the model [A2,54], FG is computed (after de Jager, 1997) as a function of the volumetric water content in the first soil layer ($i = 1$) and the water content at -10 kPa (θ_o) ;

[A2,54] $FG = e^{-0.03(\theta_o - \theta)_1}$ where $(\vartheta_o - \theta)_1$ denotes soil water depletion for the top soil layer (De Jager *et al*, 1987).

Soil evaporation:

Identically, soil evaporation (E_S), is estimated from the evaporation coefficient theory of De Jager and Van Zyl (1989). They quantified E_S in terms of;

[A2, 62] $E_s = k_s.E_o$ [mm d^{-1}]

With

[A2, 61] $k_s = k_{so}.FG.\left(1 - FI_{st}\right)$ [-]

Where:

$$FI_{st} = 1 - e^{(-0.7.LAI_{st})}$$

LAI_{st} : Leaf area index of all standing material

k_{so} : Evaporation coefficient $k_{so} = 1$

In practice, parameters k_{vo} and k_{so} [A2, 59; 61] represent the upper limit of vegetation and soil evaporation rate respectively. These values are defined in appendix A1 line statement 105 and 106. It may be possible to modify the values to simulate growth processes representing moderate and poor veld conditions. Perhaps in the near future, the magnitude and extent of k_{vo} and k_{so} will be quantified experimentally for these veld types.

2.3.4 Water potential in the soil and plant:

Soil water potential:

Soil water status as sensed by roots is complex because deep roots could be in contact with wet soil while shallow roots could be experiencing low soil water potential. Furthermore, quite large differences in soil water potential also appear within a soil layer after a sequence of dry days between zones of dense vs. sparse root colonisation (see, Tardieu, 1996). Also, soil water potential in zones within a millimetre of a root can be half a megapascal below that in zones further distant from any root (Bruckler, Lafolie and Tardieu, 1991). As a consequence, an effective soil water potential as sensed by the plant needs to be computed. Soil water potential is estimated from soil water content using the soil water characteristic (see Soil Water Characteristic, page 12).

The soil water potential which the plant in effect senses, Ψ_{soil}, is defined viz. (see de Jager, 1997) as the root density weighted mean soil water potential for the entire root zone (see Appendix A.3;113-118). Thus:

[A3, 121] $$\Psi_{soil} = \sum_{i=1}^{n} g_n \frac{\Psi_{sn}}{g}$$ subscript $_n$ denotes soil layer number.

where the soil-root conductance for the entire root zone, is given by

[A3, 116] $$g = \sum_{i=1}^{n} g_n$$

Where g represents the maximum conductance (capacity to supply water) of the soil-root system. The equation of Bennie *et al* (1988) for soil-root conductance was normalised as follows: For the nth layer soil root conductance is given by:

[A3, 115] $$g_n = g_{on} (\rho_{rn})^{0.5} \frac{\ln\left[\frac{\theta_n}{\theta_{10\,n}}\right]}{\ln\left[\frac{\theta_{10\,n}}{\theta_{1600}}\right]}$$

Where,

[A1, 307-311] $g_{on} = G_o \Delta z_n$

Go : Is the maximum conductance of the root/soil, where it is assumed for most crops to be $Go = -0.05$ mm(H_2O)(d kPa m (soil))$^{-1}$

Δz_n : layer thickness for layer n [m]

ρ_{rn} : soil root density for layer n [kg m^{-1}]

subscript $_n$ denotes soil layer number.

Values obtained by calibration in practice are $Go = -0.05$ mm (d P_a m)$^{-1}$ for wheat and $Go = -0.03$ mm (d P_a m)$^{-1}$ for maize. These values compare well with the -0.036 mm (d P_a m)$^{-1}$ quoted by Campbell (1985). Symbols $\theta, \theta_{10}, \theta_{1600}$ denote current soil water content and values at 10 kPa and 1600 kPa respectively.

Leaf water potential:

The most useful single measurement of the degree of water stress in plants is the leaf water potential. Leaf water potential can be measured by liquid or vapour equilibration, by change in concentration or density of the solution in which the tissue is immersed, by thermocouple psychrometers, and by the Scholander pressure chamber method. Most useful is the thermocouple psychrometer where water potential (Ψ_w) is related to relative humidity by the following equation (Kramer, 1983):

$$\Psi_w = \frac{RT}{\bar{V}} \ln e / e^o$$

Where	R	: Is the gas constant	[8.31 J mole^{-1} °K]
	T	: Absolute temperature	[°K]
	$\bar{V}$	: Partial molal volume of water	[cm^3 mole^{-1}]
	e / e^o	: Relative humidity	

In Putu15, canopy leaf water potential, Ψ_v, is calculated as a function of atmospheric evaporative demand (AED), soil water potential (ψ_{soil}), a critical crop water potential (Ψ_{crit}), the hydraulic conductance of the soil-root system (g) and the soil water characteristic.

By analogy with Ohm's law,

[A3, 149] $$\Psi_v = \Psi_{soil} - \frac{E_v}{g}$$

When water is limiting growth, which is normally the case under rainfed conditions, transpiration E_v is estimated using a plant water stress factor F_v defined as follows:

[A3, 133] $$E_v = F_v . E_{vo} \qquad [2.14]$$

The plant water stress factor, Fv, is the fraction of E_{vo} permitted by the crop water status. It is a function of soil water status Ψ_{soil} and Ψ_{crit} defined as the crop specific xylem critical water potential at which plant water stress symptoms, such as stomatal closure appear (first material stress), with a concomitant reduction in E_v, CO_2 assimilation and yield. The water stress factor is expressed as $Fv = 1 - e^{-0.008(\Psi_{crit} - \Psi_v)}$. This is a non-linear equation for which Ψ_v can only be solved by numerical iteration.

Solving for leaf water potential

While the Newton-Raphson method may be employed to solve equations by iteration, a simple numerical method is used in Putu15 (see Appendix A3, 137-154). Briefly, a test value for Ψ_v is substituted in $F_v = 1 - e^{-0.008(\Psi_{crit} - \Psi_v)}$ to estimate E_v in equation 2.14.

The value obtained for E_v is then substituted in $\Psi_v = \Psi_{soil} - \frac{Ev}{g}$. Should the resulting Ψ_v value agree to within 5 kPa of the test value; the value of Ψ_v so obtained is used to calculate transpiration E_{vn} for each individual soil layer as explained in section 2.3.5.

In earlier versions of Putu (11,12 and 14) leaf water potential was simply calculated as a relationship of potential evaporation and the hydraulic conductance of the soil. This methodology (De Jager, 1997) represents a marked change in estimated leaf water potential for grasslands. Now it has become possible to estimate transpiration rate at low soil water levels.

2.3.5 Water extraction from the root zone (ΔS)

Water movement through the soil-plant-atmosphere system is best treated as a series of interrelated, interdependent processes. For example, the rate of water absorption is affected both by the rate of water loss and by the rate at which water can move from the soil to the root surface (Kramer, 1983). Water transport can be described by simple equations. In general terms:

$$flux = \frac{driving\ force}{resistance}$$

and more specifically

$$Waterflux = \frac{\Delta\Psi}{resistance(r)}.$$

This is similar to the equation for Ohm's law, describing the flow of electricity:

$$Current = \frac{voltage}{resistance}$$

Hence, by the Ohm's law analogy, the equation for steady-state water flow may be expressed;

$$waterflow = \frac{\Psi_{soil} - \Psi_{root}}{r_{soil}}$$

Now, the flow of water through the plant can be described in terms of driving forces and resistance's. An example of such a model or flow diagram is shown in Figure 2.6.

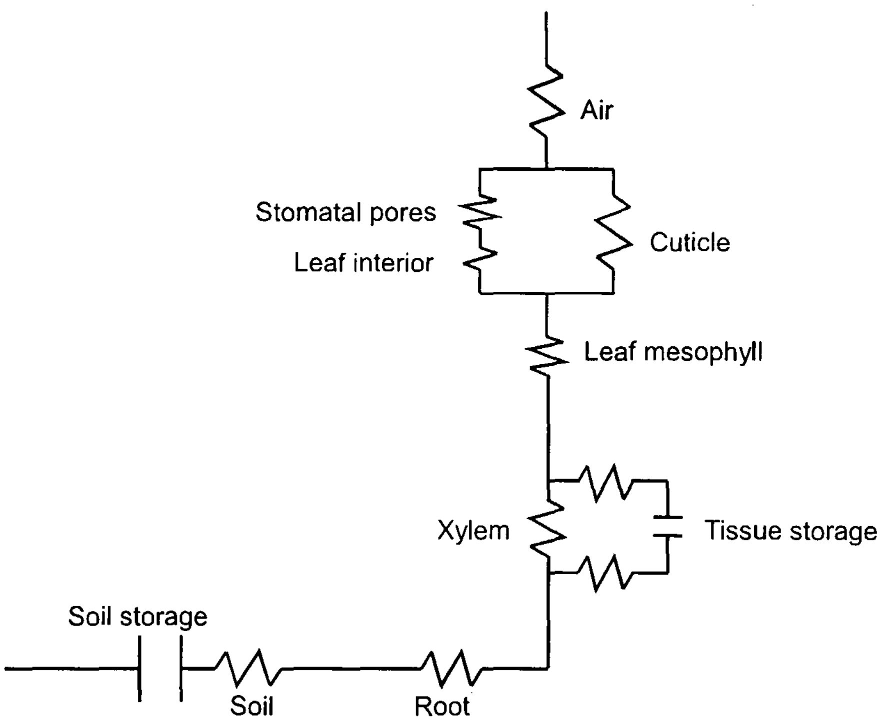

Figure 2.6 Diagram treating water movement through the soil-plant-atmosphere continuum analogous to movement of an electrical current through a conducting system containing resistance and capacitance (see Kramer and Kozlowski, 1979).

Similar to the model presented by Kramer (1983), the amount of water that will eventually flow to the atmosphere from each layer (due to transpiration) is computed from the difference in matric potential between the soil (Ψ_{sn}) and plant (Ψ_v) and the soil-root conductance (g_n) where n denotes the soil layer, viz:

[A3, 161-163] $E_{vn} = -g_n(\Psi_v - \Psi_n)$, from which

[A3, 178 and 211] $E_v = \sum_n E_{vn}$

Where, each layer's water use , E_{vn}, is then extracted from the water held in the nth layer.

Because soil evaporation occurs, the water content in the top layer (n=1) is given by,

[A3, 167-174] $W_{i1} = W_{(i-1)1} - E_{v1} - E_s$ [2.15]

subscript $_i$ denotes day of growth (1 to 365).

For water in layers 2 to 9,

[A3, 199-207] $W_n = W_{in} - E_{vn}$

Where: n : soil layer number

The water content is limited to the following boundary conditions. i.e. $SWUL_n$ and LL_n. The assumption was made that the lower limit (LL_n) of plant extractable water is equal to the volumetric water content at -1500 kPa. Given volumetric soil water content, θ:

- soil water amount W, can be calculated as $W_n = \theta_n \Delta z_n$ (see A3,177 and 208);
- plant available water content is calculated from $AW_n = W_n - W_{1500n}$ (see A3, 179 and 225); and
- total plant available water content is calculated as $TAW = \sum_n AW_n$ (see A3, 180 and 227).

2.3.6 Infiltration, percolation, run-off and deep drainage

Infiltration is the process by which water enters the soil. Through percolation, water is distributed to the root zone. Infiltration and percolation determines to a large extent the amount of available water for growth and production of vegetation. The process of infiltration is treated empirically. A predefined fraction of rain infiltrates the surface on the day of rainfall. In practice, under natural conditions (natural veld), the fraction of rainfall infiltrating the soil surface, F_{ro}, is affected by vegetation cover. Currently, this fraction is estimated (see Appendix A3, 291-308) as follows (see Fouché, 1992):

$F_{ro} = 0.2$	for $Rain > 50$	[mm d^{-1}]
$F_{ro} = 0.1$	for $50 > Rain > 25$	[mm d^{-1}]
$F_{ro} = 0.05$	for $25 > Rain > 15$	[mm d^{-1}]
$F_{ro} = 0$	for $15 > Rain > 0$	[mm d^{-1}]

The amount of water infiltrating the surface is given by:

[see A3,310] $$Inf = (1 - F_{ro})(Rain)$$ [2.16]

Volumetric water content in a soil layer increases as water enters the soil through infiltration, thus

[see A3, 315/6] $$\theta_n = \theta_n + \frac{Inf}{\Delta z}$$ [mm m^{-1}]

The fraction of excess water drained to the next layer $VCON$ is estimated from porosity and the drained upper limit (DUL)

[see A1, 278] $$VCON = \frac{\theta_p - DUL}{\theta_p}$$ [d^{-1}]

Percolation of water from the layer above $PERC_n$ (mm $layer^{-1}$) is added to the water content in a layer, thus:

[see A3, 315] $$W_n = W_{in} + PERC_n$$ [mm]

This percolation of excess water occurs subject to certain constraints:

- If the water content θ_n in soil layer n exceeds $SWUL_n$, then the water content in layer n is made equal to $SWUL_n$ i.e. $\theta_n = SWUL_n$. The excess amount $W_n - (SWUL_n)\Delta z_n$, is immediately cascaded to the next layer (Appendix A3,317-322).
- Furthermore, percolation takes place when θ is greater than DUL (Appendix A3, 325-330). Percolation of water to the next layer is then computed as a function of $VCON$ and the excess amount above DUL, viz.

  [A3, 327] $$PERC_{n+1} = VCON_n(\theta_n - DUL_n)\Delta Z_n \qquad [2.17]$$
- No percolation out of the layer is permitted when layer soil water content is less than DUL i.e. $PERC_n = 0$ if $\theta_n < DUL$.

The soil water balance now calculates layered soil water content. Putu(11,12 and 14) used a simplified water balance routine, dividing the soil depth into two components i.e. (upper 100 mm and the rest of the rooting depth). The implementation of rainfall intensity data to compute infiltration needs further investigation, which the time and scope of this study does not allow.

2.4 Leaf growth.

2.4.1 Temperature dependence.

During the early stages of vegetative growth, temperature and existing leaf area are the overriding factors. The rate of leaf appearance and final leaf size are constrained by temperature through its effect on cell division and extension and competition for light (Van Dobben, 1962; Acock, Charles-Edwards, Fitter, Ludwig, Warren Wilson & Withers, 1978; Sheehy, Cobby & Ryle, 1980; Causten & Venus, 1981). Some crops cease leaf growth at anthesis.

Single leaf photosynthesis, as reported by Woledge & Dennis (1982), may be described in terms of temperature. Squire (1990) expressed potential (no water or other stress) changes in leaf (length) per unit time (δl/δt) as the product of the coefficient of thermal rate of expansion, P_l, (units mm (°C d)$^{-1}$) and the difference between the average temperature (T) and the base temperature (BO), thus:

$$\frac{\delta l}{\delta t} = P_l (T - BO)$$

This theory, has been applied in the Putu15 model where [A2, 22] $DELHU = \left(\bar{T} - BO\right)$ is considered in the computation of leaf area index.

2.4.2 Computation of leaf area.

In crop growth models, the leaf area expansion submodel is one of the more crucial submodels, and the assumptions made greatly affect predictions of growth and yield. Generally, an increase in leaf area will increase transpiration through the stomatal openings (see Figure 2.5 and 2.6). This will lead to loss in soil water content and water stress if it does not rain.

Theory :

The fraction of incident radiation intercepted by the canopy is described by Beer's function;

$$f = 1 - \exp(-KL) \qquad [2.18]$$

where L is the leaf area index and K the light extinction coefficient which depends on the properties of the leaves and their orientation in relation to the spatial distribution of solar radiation.

Goudriaan and Monteith (1990) assumed that crop growth rate $\frac{\delta W}{\delta t}$ is proportional to light interception, therefore :

$$\frac{\delta W}{\delta t} = fC_m = [1 - \exp(-KL)]C_m \qquad [2.19]$$

Here, C_m is the maximum crop growth rate (kg ha^{-1} d^{-1}) that would be achieved if all incident light were intercepted ($f = 1$).

By definition (Goudriaan & Monteith, 1990),

$$\frac{\delta L}{\delta t} = p_l s \frac{\delta W}{\delta t} \quad [2.20]$$

Where;

the fraction of growth of total dry matter allocated to new leaves is p_l and the specific leaf area of these leaves is s .Then from Eq 2.19 and 2.20 ,

$$\frac{\delta L}{\delta t} = fC_m p_l s \quad [2.21]$$

and from Eq 2.18 it follows that

$$\frac{\delta L}{\delta t} = [1 - \exp(-KL)]C_m p_l s \quad [2.22]$$

By integration, Goudriaan and Monteith (1990) derived an explicit expression for computing leaf area index (L) ;

$$L = \frac{1}{K} \ln \left\{ 1 + [\exp(L_i) - 1] \exp\left(\int_0^t KR_m t \right) \right\} \quad [2.23]$$

where L_i is the initial leaf area index, and maximum relative growth rate,

$$R_m = C_m p_l s \quad [2.24]$$

Leaf area ratio LAR is given by

$$LAR = \frac{R_m}{C_m} \quad [2.25]$$

In Putu15, equation 2.22 computes the change in leaf area index per unit degree-day rather than per unit time. An over-all environmental limiting factor which accounts for the influence of plant water status and low and high temperatures is also included (see Appendix A4, 20).

2.5 Biomass growth:

Goudriaan and Monteith (1990) substituted the expolinear expression for L (equation 2.23) into the expression for $\frac{\delta W}{\delta t}$ (see equation 2.19) to produce the differential equation from which growth rate may be computed, viz.

$$\frac{\delta W}{\delta t} = C_m \frac{\left[\exp(KL_i) - 1\right]\exp\left(\int_0^t KR_m t\right)}{1 + \left[\exp(KL_i) - 1\right]\exp\left(\int_0^t KR_m t\right)} \qquad [2.26]$$

which by integration, Eq [2.26] gives;

$$W = \left(\frac{C_m}{R_m}\right)\ln\left[1 + \exp\left(KR_m\left(t - t_b\right)\right)\right] \qquad [2.27]$$

where the concept 'lost time' (t_b) is introduced. Lost time is defined as the time taken by the vegetation to effectively pass through the exponential growth rate when it becomes linear. By introducing equation 2.25 into equation 2.27 the form of expolinear growth function as used in Putu15 (see appendix A1,319) is found :

[A1, 321]

$$W = \frac{1}{k.LAR}\ln\left[1 + \exp\left(K.LAR.C_m\left(t - t_b\right)\right)\right] \qquad [2.28]$$

Once again where $t = TIMEthml$ (see equation 2.7) or heat units are used to measure age.

De Jager (1997) outlined the procedure to determine t_b and C_m. In Chapter 3 (Model calibration and validation) the methodologies used are outlined. Theoretically, t_b is computed from:

$$t_b = \frac{-\ln\left\{\frac{f_0}{1 - f_0}\right\}}{R_m} \qquad [2.29]$$

Here, f_0 is the fractional light interception at time zero. Where;

$$f_0 = 1 - \exp(-KL_o) \quad [2.30]$$

The expolinear function describes crop total dry mass vs. time growth curve (see Fig 2.7) with an initial exponential growth rate, which gradually decays into a constant maximum growth rate (C_m).

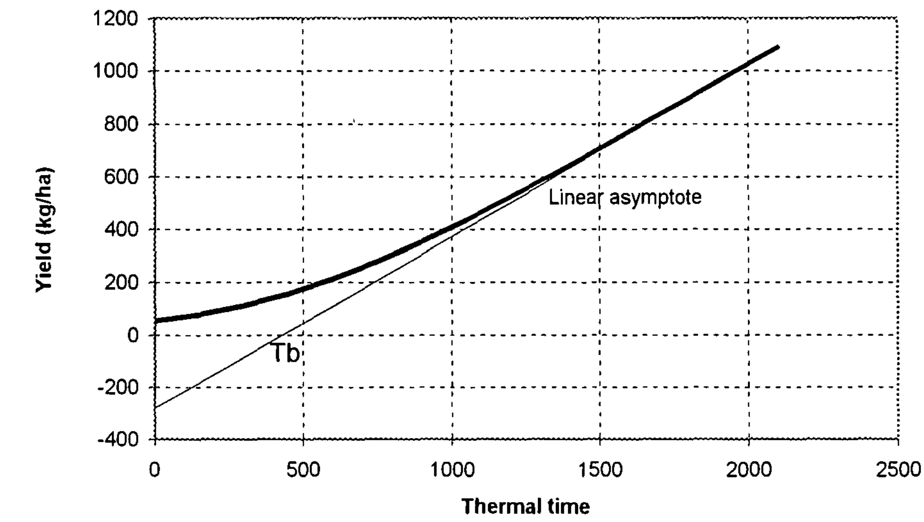

Figure 2.7 The expolinear growth function illustrating the linear asymptote. The value of t_b is 480 d°C, $C_m = 1.5$ kg ha^{-1} °C^{-1}, $K = 1$ and $Lo = 0.05$.

Temperature and growth

Experiments from controlled environments may be used to analyse the effect of temperature on daily dry-matter gain. This is illustrated in Figure 2.8. Should a constant 20°C be applied for a full growing season, then maximum growth rate of 25 kg ha^{-1} d^{-1} are reached around day 200 (DOG) which is mid January (i.e season start on 1 July).

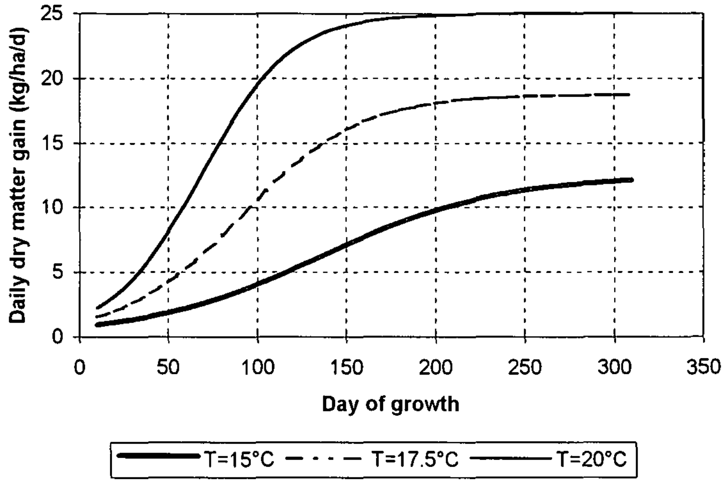

Figure 2.8 Daily dry-matter gain at constant temperatures of 20°C,17.5°C and 15°C.

2.5.1 Conceptual model (partitioning)

In South-Africa, particular in the semi-arid regions with warm summers and dry cold winters natural vegetation is characterised by a rapidly maturing plant material. The model of Johnson and Thornley (1983) categorises biomass growth into 4 classes i.e. growing leaves and stems ($LAI1, W1$), fully expanded leaves and stems ($LAI2, W2$), matured leaves and stems ($LAI3, W3$) and finally senesced leaves and stems ($LAI4, W4$).

The flux of material between compartments 1 to 4 depends largely upon a rate constant β, as defined in subsection 2.2.4 (physiological ageing). The model presented in Fig 2.9 gives a broad perspective of the growing components as the driving forces influence them. This model was adopted in Putu15. Mathematical calculation of the transfer of material from one compartment to the next is given in Appendix A4.

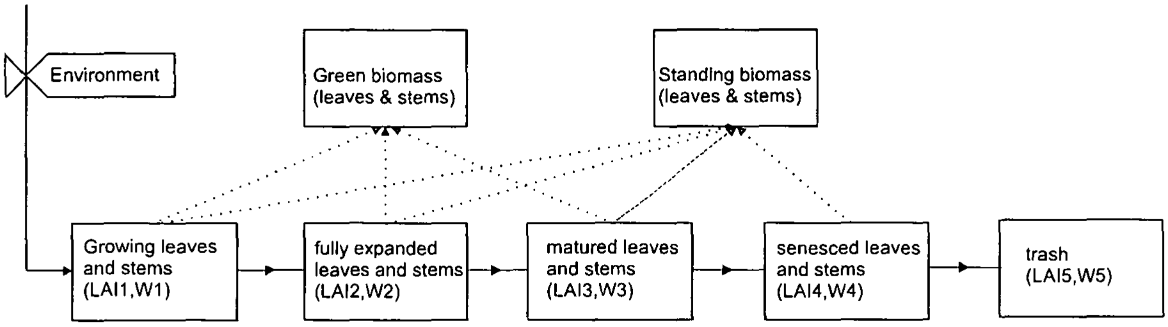

Figure 2.9 Schematic representation of the growth model (after Johnson and Thornley , 1983). LAI denotes leaf area index. W denotes stems.

Growth functions are well reported in the literature (see Thornley and Johnson, 1990). In many cases growth functions use time (t) as the independent variable. In Putu15, thermal time is used as the independent variable governing biomass growth. This represents a marked change from Putu11,13 and 14. Also, earlier versions had 5 distinctive growth stages, each characterised with there own set of growth functions (Fouché, 1992; Howard, 1993). Change from one stage to the next were governed primarily by leaf : stem ratios and critical heat units. This has been simplified.

The senescence rate is plant specific and is defined as the daily amount of living biomass, which no longer participates in plant growth processes. The rate of senescence is given as $\beta W4$ (Johnson & Thornley, 1983). Temperature has a direct effect on this process through (β).

2.5.2 Growth termination (dormancy):

An innovation implemented in the model is the way in which growth is terminated. It is assumed that the active growth period is related to:

- fraction of E_{vo} permitted by the crop physiological status (i.e. Fv); and
- the amount of heat units needed to be accumulated in a season for the crop to mature

The index, ($SeasTFv$), is computed as the summation of the ratio of actual transpiration to potential transpiration (Fv) and follows therefore;

[A4, 77] $SeasTFv = \sum_{j=1}^{j=n} Fv$

Here j is day of simulation and n is number of days in a normal growing season not experiencing drought.

From Table 2.1, the heat units expected in a season are approximately 2250°Cd. This is similar to the average amount of heat units before the first frosting event occurs. For Bloemfontein, and the surrounding area this event requires 297 days of growth or about 2200 day degrees (see Table 2.1)

Table 2.1 Statistical analyses of the number of growing days and heat units accumulated before first frost occurs calculated from 1 July for Bloemfontein (1923 to 1995).

Statistics	Days of growth	heat units
Mean	296.51	2218.97
Median	297.00	2228.15
Standard Deviation	12.08	152.44
Kurtosis	-0.68	-0.28
Range	53.00	692.20
Minimum	268.00	1817.80
Maximum	321.00	2510.00
Confidence Level(95.0%)	2.84	35.82

The total thermal time to dormancy was empirically determined to be :

[A4, 79] $Tpgrowth = 2200 * \left(1 - 0.3\left[1 - \frac{SeasTFv}{daydev}\right]\right)$

where: $daydev$ is the number of growing days.

2.5.3 Hypothetical growth

Growth in compartments 1 to 5 for a hypothetical season is presented in figure 2.10. It is clear that at the onset of dormancy plant material dies and consequently falls from the plant (sometimes referred to as abscission). The model also distinguishes between total standing dry matter (TSDM) and total standing green material (TSGM). It may be seen that senesced material ($W4$) equals total standing dry matter at the end of the growing season, as green biomass has died at the start of dormancy.

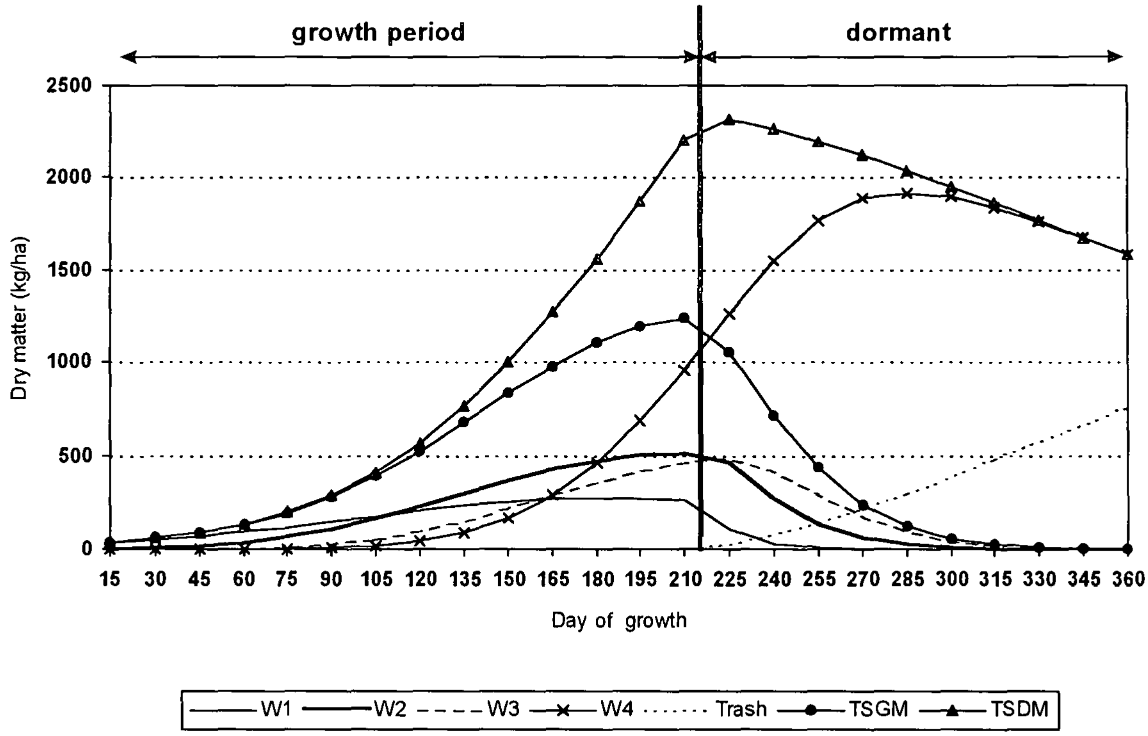

Figure 2.10 Hypothetical plant growth in compartments W1, W2, W3, W4, trash, total standing green material (TSGM) and total standing dry material (TSDM).

2.5.4 Introducing the concept of resilience into Putu

A explicit definition from the concise Oxford dictionary for resilience is "***recovering from a state of depression***". Veld in a good state of health does not change much over time. The overall resilience (to recover after periods of unfavourable conditions, such as a poor rainy season) of such a veld is good.

The resilience (R) of veld in good condition was expressed as a function of lost time (T_b) in the expolinear crop growth function to the Putu15 model. T_b is made a function of the maximum yield obtained from the previous season. By trial and error the expression developed reads:

[A1, 175-178] $$T_b = \left[\frac{-\log\left(\frac{fo}{1-fo}\right)}{R_m} \right] \left(1 + \frac{R}{100}\right)$$ [2.31]

Where $$R = \left[\frac{1250 - Wprev}{1250} \right] Const$$ [2.32]

($Wprev$: Maximum yield obtained from previous season kg ha^{-1})

R is expressed in terms of proportionality a constant ($Const = 40$) and the deviation from the long-term mean yield. An example of the influence of resilience on biomass growth is presented in Figure 2.11. The importance of this function is further illustrated in Chapter 3 under model calibration. Theoretically, the magnitude of R, depends on the constant in R.

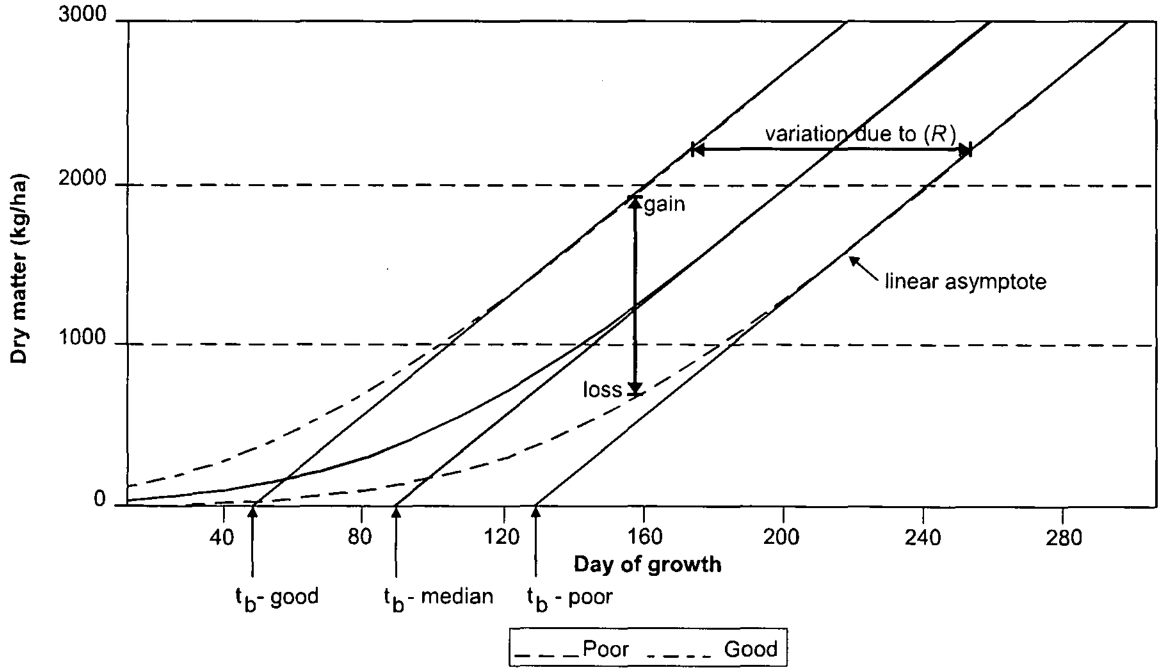

Figure 2.11 The influence of resilience on effective gain or loss of dry matter as determined by a good and poor pre-season.

2.5.5 The concept of veld condition:

Trollope, Potgieter and Zambatis (1989) defined veld condition as "the condition of the vegetation in relation to some functional characteristic, normally maximum forage production and resistance to soil erosion". On the other hand, Snyman (1993a) related the condition of the plant community to the ecological status (succession stage, botanical composition and cover) and also its productivity, nutritive value and palatability. Van der Westhuizen (1994) quantified veld condition in terms of the specie composition, and the grazing value of the species. Also, veld condition could be determined using various techniques (Van der Westhuizen, 1994).

A specific formulation for veld condition score is $VCS = f(a,b,...)$ where a could be the botanical composition, b the basal cover, plant productivity, composition, resistance to soil erosion, palatability, cover etc. at a given point in time. Through time and space (from site to site) a change in veld condition does occur.

To overcome the problems in defining veld condition and its effect on the output of the model, it is necessary to define clearly the output produced by Putu. **Putu computes the yield of a particular specie composition of natural grassland in a given ecological state** e.g. *Themeda triandra* climax grassland growing in the dry Sandy Highveld Grassland (from Low and Rebello, 1996. Also defined by Acock, 1988 as the Dry *Cymbopogon-Themeda* veld).

De Jager *pers com* (1997) suggests that should pasture scientists wish to extrapolate the yields and account for composition and animal utilisation then a conversion factor should be applied. This has been done with a veld condition weighting coefficient (VWC). The VWC is defined as the conversion factor by which total grassland yield must be multiplied to calculate the equivalent animal mass yield (AMY) the grassland would produce, viz.

$$AMY = VWC.Y \text{ where } Y = \sum W_{1..4}$$

With $VWC = \sum F_s.F_{sm}.F_p.F_u$

Where:

AMY	: Equivalent animal mass yield	(kg ha^{-1})
Y	: Grassland yield	(kg ha^{-1})
F_s	: Fraction of ground surface covered by a given specie.	
F_{sm}	: Vegetation mass of species per unit basal cover of species.	
F_p	: Relative palatability of given species.	
F_u	: Mass of animal biomass produced per unit of given specie consumed.	

The summation is over the principle species in the sward.

Snyman and Fouché (1993) described a typical veld in 3 ecological states (condition classes) for the Dry *Cymbopogon-Themeda* veld.

For a climax veld (good condition) the main bulk of production is derived from -

Digitaria eriantha, Themeda triandra, Sporobolus fimbriatus and to a lesser extent *Eragrostis chloromelas*.

In a sub-climax veld (moderate conditions), species such as -

Eragrostis lehmanniana, Eragrostis chloromelas and *Setaria sphacelata* predominate.

A Pioneer veld (mainly characterised by annual species) is considered to be a veld in a poor condition and which consists mainly of -

Aristida congesta and *Tragus koelerioides*.

Experimental data for a climax veld as described above, were used to calibrate Putu15. The calibrated model was then validated at 8 locations in the *Themeda*-veld (see Chapter 3). The versatility of Putu15 was demonstrated by further refinements on a sub-climax veld (see Chapter 4).

References

Acocks, J.P.H., 1988. Veldtypes of South Africa. Mem. Bot. Surv. S. Afr. NO. 58. Government Printer, Pretoria.

Acock, B., Charles-Edwards, D.A., Fitter, D.J., Ludwig, L.J., Warren Wilson, J. & Withers, A.C., 1978.

The contribution of leaves from different levels within a tomato crop to canopy net photosynthesis; an experimental examination of two canopy models. *Journal of Experimental Botany* 29:815-827.

Allen, R.G., 1986. A Penman for all seasons. *J. Irrig. and Drainage*, 112, 4: 348-368.

Allen R.G., Jensen M.E., Wright J.L. and Burman R.D., 1989. Operational estimates of Evapo-transpiration. *Agron. J.* 81: 650-662.

Bennie, A.T.P., 1984. Doeltreffende water opgaring in grond in hoë droogte risiko gebiede. In: Verslag en aanbeveling van werksessies oor : Die benutting van grond in hoë droogte risiko gebiede. GVSA Kongress, Bloemfontein.

Bennie, A.T.P., Coetzee, M.J., Van Antwerpen, R., Van Rensburg, L.D. and Burger, R.DU T., 1988. *'n Waterbalansmodel vir besproeiing gebaseer op profielwatervoorsieningstempo en gewaswaterbehoeftes.* Report 144/1/88 by Department of Soil Science, University of the Orange Free State, to the WRC.

Blaney, H.F. and Criddle, W.D., 1950. Determining water requirements in irrigated areas from climatological and irrigation data. USDA. *Soil Conservation Service Tech.Paper* No.96.48 pp

Bowen, I.S., 1926. The ratio of heat losses by conduction and by evaporation from any water surface. Phys. Rev 27: 779-787.

Booysen, J., 1983. Twee metodes vir die kwantitatiewe simulering van groeitoestande van klimaksgras. M.Sc. Agric verhandeling. U.O.V.S. Bloemfontein.

Bruckler, L. Lafolie, F. and Tardieu, F. 1991. Modelling the root water potential and water extraction in the two-dimensional case. II Field comparisons. *Soil Sci Am J* 55: 1213-1220.

Campbell , G.S., 1977. An introduction to Environmental Biophysics. Springer-Verlag. New York Inc. pp 159.

Campbell, G. S., 1985. Soil physics in Basic. Elsevier, Amsterdam.

Caprio, J.M., 1974. The solar thermal unit concept in problems related to plant development and potential evapotranspiration. In: Leith, H. (ed.). Phenology and Seasonality Modelling. Springer-Verlag. New York, pp 353-364.

Causten, D.R. & Venus, J.C., 1981. The biometry of plant growth. Edward Amold, London. Pp 307.

De Jager, J.M., 1968. Carbon dioxide exchange and photosynthetic activity in forage grasses. Unpl. PhD. Thesis. Univ of Wales. 1968.

De Jager, J.M., 1984. Future research requirements into micrometeorological aspects of irrigation.

Water. SA 10(4) 211-214.

De Jager, J.M., 1992. The Putu Decision support system. Monograph of the Department of Agrometeorology, University of the Orange Free State. Bloemfontein, pp 55.

De Jager, J.M., 1997. Research on a computerised management system. Report to the Water Research Commission. NO K5/581/0/97.

De Jager, J.M., Opperman, D.P.J. & Booysen, J., 1980. Produksie van natuurlike grasveld in die Sentrale Oranje-Vrystaat in verhouding tot klimaat. *Hand Weidingsveren. S. Afr.* 15. 65-68.

De Jager, J.M., van Zyl, W.H., Bristow, K.L. and van Rooyen, A., 1982. Besproeiingskedulering van koring in die besproeingsgebied van die Vrystaatstreek. Waternavorsingskommissie, pp 125.

De Jager, J.M. and Van Zyl, W.H., 1989. Atmospheric evaporative demand and evaporation coefficient. *Water S.A.*, 15: 103-110.

De Jager, J.M. and Van Zyl, W.H., 1991. Unpublished data.

Doorenbos, J. and Kassam, A.H., 1979. Yield response to water. Food and agriculture organisation of the United Nations. Rome.

Doorenbos, J. and Pruitt, W.O., 1977. Guidelines for predicting crop water requirements. FAO Irrigation and Drainage Paper 24 (rev.), pp 156.

Feddes, R.A., Kowalik, P.J. & Zaradny, H., 1978. Simulation of field water use and crop yield. Simulation Monographs. Pudoc, Wageningen. The Netherlands. 195 pp.

Fouché, J.H., 1992. Simulering van die produksie potensiaal van veld en die kwantifisering van droogte in die Sentrale Oranje-Vrystaat. Ph.D. proefskrif, UOVS, Bloemfontein.

Gallagher, J.N.,1979. Field studies for cereal leaf growth. 1. Initiation and expansion in relation to temperature and ontogeny. *Journal of experimental Botany* 30:625-636.

Gerwitz, A. and Page, E.R., 1974. An empirical mathematical model to describe plant root systems. *Journal of Applied Ecology* 11: 773-781.

Goudriaan, J. & Monteith, J.L., 1990. A mathematical Function for Crop Growth Based on Light Interception and Leaf Area Expansion. *Annals of Botany* 66: 695-701.

Hanks, R.J. & Hill, R.W., 1980. Modelling crop responses to irrigation in relation to soils, climate and salinity. Publication No 6, International Irrigation Information Centre (IIIC). Pergamon, pp. 66.

Hayes, J.T., O'Rourke, P.A., Terjung, W.H. & Todhunter, P.E., 1982. A feasible crop yield model for worldwide international food production, *Int J. Biometeorol*. 26, 239.

Hensley, M., 1993. Modelling the water balance on benchmark ecotopes. Research proposal to the water Research Commission.

Hillel, D., 1982. Introduction to soil physics. Academic Press, New York.

Houghton, D.D., 1985. Handbook of applied meteorology. John Wiley and sons. Pp. 1461.

Howard, M.D. 1993. Simulation studies on *Digitaria Eriantha* stud. Subsp. *eriantha* at differing soil nitrogen levels. Department Agrometeorology. U.F.S Unpublished MSc. Agric.

Hutson, J.L. 1984: Estimation of hydrological properties of South African soils. University of Natal, Pietermaritzburg, Department of soil Science and Agrometeorology. Unpublished Ph.D. Dissertation.

Jensen, M.E. (ed.) 1974 and Allen R.G. (1990). Evaporation and irrigation requirements. ASCE, Manuals and Report on Engineering practice No. 70, New York.

Jensen, M.E. and Haise, H.R., 1963. Estimating evapotranspiration from solar radiation. *J. Irrig. Drain. Div.* ASCE 89: 15-41.

Johnson, I.R. & Thornley, J.H.M., 1983. Vegetative crop growth model incorporating leaf area expansion and senescence, and applied to grass. *Plant, Cell and Environment*. 6: 721-729.

Jury, W.A., Gardner, W.R. & Gardner W.H., 1991. Soil Physics. John Wiley New York.

Kramer, P., and Kozlowski, T.T. 1979. Physiology of Woody plants. Academic Press, New York.

Kramer, P.J., 1983. Water relations of plants. Academic Press. New York.

Lang, A.R.G., 1973. Measurement of evapotranspiration in the presence of advection, by means of a modified energy balance procedure. *Agric. Meteorol.*, 12: 75-81.

Linacre, E.T., 1977. A simple formula for estimating evapotranspiration rates in various climates, using temperature data alone. *Agric. Meteorol.* 18: 409-424.

Low, A.B. & Rebelo, A.G. 1996. Vegetation of South-Africa, Lesotho and Swaziland. Department of Environmental Affairs and Tourism. Pretoria.

Lungley, D.R., 1973. The growth of root system - a numerical computer simulation model. Plant and Soil 38: 145-159.

Lynch, S.D., Reynders, A.G. & Schulze, R.E., 1994. Preparing input data for a national-scale

Ground water vulnerability map of Southern-Africa. *Water SA*. 20:3, 239-246.

Makkink, G.F. & van Heemst, H.D.J., 1975. Simulation of the water balance of arable land and pastures, PUDOC, Wageningen.

Makkink, G.F., 1957. Ekzameno de la formula de Penman. *Neth. J. Agric. Sci.* 5: 290-305.

Monteith, J.L., 1963. Gas exchange in plant communities. In: Evans, L.T. (ed.). Environmental control of Plant Growth. Academic Press, New York, pp. 95-112.

Monteith, J.L., 1964; Evaporation and environment. The State and Movement of Water in Living Organisms. Proc. 19th Symp. Soc. Exp. Biol., Academic Press, New York, pp. 205-234.

Monteith, J.L., 1981. Evaporation and surface temperature, Q.J.R. *Meteorol. Soc.*, 107: 1-28.

Ng, E. & Loomis, R.S., 1984. Simulation of growth and yield in the potato crop. Simulation Monographs, Pudoc, Wageningen, The Netherlands. pp 147.

Penman, H.L., 1948. Natural evapotranspiration from open water, bare soil and grass. Proc. R. Soc. London Ser. A. 193: 120-145.

Penning de Vries, F.W.T. & Van Laar H.H., 1982. Simulation of growth processes and the model BACROS. In Simulation of Plant growth and Crop Production, Edit Penning de Vries, F.W.T. & Van Laar, H.H. Eds., PUDOC, Wageningen, The Netherlands.

Priestly, C.H.B. and Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Mon Weather Rev. 100: 81-92.

Renard, K.G., Shirley, E.D., Williams, J.R. & Nicks, A.D., 1987. Hydrology compo-nent: Upland phases: In SPUR-Simulation of production and utilisation of rangeland. Edit Wight, J.R. & Skiles, J.W. National Technical Information Service. Springfield.

Richardson, C.W., Hanson, C.L. & Huber, A.L., 1987. Climate Generator. In SPUR-Simulation of production and utilisation of rangeland. Edit Wight, J.R. & Skiles, J.W. National Technical Information Service. Springfield.

Rimmington, G.M. & Charles-Edwards, D.A., 1987. Mathematical descriptions of plant growth and development. In Plant Growth modelling for Resource Management. Edit Wisiol, K. & Hesketh, J.D., CRC Press, Inc.

Ritchie, J.T., 1972. Model for predicting evapotranspiration from a row crop with incomplete cover. *Water Resour. Res.*, 8: 1204-1213.

Rosenberg, N.J., Blad, B.L. and Verma, S.B., 1983. Microclimate. The biological environment. 2nd ed. John Wiley and sons pp. 495.

Russel, G. , 1980. Crop evaporation surface resistance and soil water status. *Agric. Meteorol.* 21: 213-226.

Schulze, R.E.,Hutson, J.L. and Cass. A., 1985. Hydrological characteristics and properties of soils in Southern Africa 2: Soil water retention models. *Water SA.*,11: 129-136.

Sheehy, J.M., Cobby, J.M. Ryle, G.J.A., 1980. The use of a model to investigate the influence of some environmental on growth of perennial ryegrass. *Annals of Botany* 46:343-365.

Slatyer, R.O. and Mcillroy, I.C., 1961. Practical Microclimatology. CSIRO, Australia and UNESCO.

Snyman, H.A., & Fouché, H.J., 1993. Estimating seasonal herbage production of a semi-arid grassland based on veld condition, rainfall and evapotranspiration. *Afr. J. Range. For. Sci.* 1993 10(1) 21-24.

Snyman, H.A. & Van Rensburg, W.L.J., 1986. Hidrologiese siklus van natuurlike veld in die Sentrale-Oranje-Vrystaat. *SA Tydskrif vir Natuurwetenskap en tegnologie* 5, nr. 4.

Snyman, H.A. 1993a. Streef na optimale veldtoestand en weiding kapasiteit. SA Koöp 9(5): 25-28.

Snyman, H.A., 1982. Die hidrologiese siklus en waterverbruiksdoeltreffendheid van veld in verskillende suksessiestadia, in die Sentrale Oranje-Vrystaat. M.Sc.Agricverhandeling, U.O.V.S.

Snyman, H.A., 1988. Die bepaling van waterverbruiksdoeltreffendheid van veld in die Sentrale Oranje-Vrystaat vanaf evapotranspirasiemetings. Water S.A 14,3.

Snyman, H.A., 1989. Evapotranspirasie en waterverbruiksdoeltreffendheid van verskillende grasspesies in die Sentrale Oranje-Vrystaat. *Tydskrif Weidingsveren. S. Afr.* 6.3.

Squire, G.R., 1990. The leaf canopy and root system. In The Physiology of Tropical Crop Production. Edit Squire, G.R. C.A.B. International.

Swinbank, W.C., 1951. The measurement of vertical transfers of heat and water vapor by eddies in the lower atmosphere. *J. Meteorol.* 8: 135-145.

Tanner, C.B., 1967. Measurement of evapotranspiration. In Hagen, R.M., Haise M.R. and Edminster T.W.,(eds.). Irrigation of Agricultural Lands. *Am.Soc.Agron.*, Madison, Wisc.,pp.534.

Tardieu, F, 1996. Drought perception by plants. Do cells of droughted plants experience water stress ? In Drought tolerance in higher plants. Ed Belhassen E. Kluwer Academic Pub.

Thom, A.S., 1975. Momentum, mass and heat exchange of plant communities. In Monteith J.L.

(ed.), Academic Press, London. Vegetation and the atmosphere. Vol. 1, pp 278.

Thornley, J.H.M. & Johnson, I.R. 1990. Plant and crop modelling. Clarendon Press, Oxford.

Thornwaite, C.W. and Holzman, B., 1939. Measurement of evaporation from land and water surface. USDA *Tech. Bull.* 817: 1-75.

Trollope, W.S.W., Potgieter, A.L.F. & Zambatis, N., 1989. Assessing veld condition in the Kruger National Park using key grass species. *Koedoe* 32(1) : 67-93.

Van Bavel, C.H.M., 1966. Potential evaporation: The combination concept and its experimental verification. Water Resour., Res. 2: 455-467.

Van der Westhuizen, H.C., 1994. Die kwantifisering van veldtoestand in die Sentrale-Vrystaat.

Van Dobben,W.H.,1962. Influence of temperature and light conditions on dry matter distribution, development rate and yield in arable crops. Netherlands Journal of Agriculture Science 10:377-389.

Van Keulen, H., 1982. Crop production under semi-arid conditions, as determined by moisture availability. In Simulation of Plant Growth and Crop Production, Edit Penning de Vries, F.W.T. & Van Laar, H.H. Eds., PUDOC, Wageningen, The Netherlands.

Van Zyl, W.H. and de Jager, J.M., 1987. Accuracy of the Penman-Monteith equation adjusted for atmospheric stability. *Agric. For. Meteorol.*, 41: 57-64.

Wight, J.R. Hanson, C.L. & Cooley, K.R., 1986. Modelling Evapotranspiration from Sagebrush-Grass Rangeland. *J. of Range Manage.* 39:1, 81-85.

Wight, J.R. & Hanson, C.L. 1988. Modelling evapotranspiration and run-off from small Rangeland Catchments. In Third International Rangeland Congress. Edit Siungh, P., Shankar, C. & Srivasta, A.K. Range Management Society of India.

Wight, J.R., Hanson, C.L. & Whitmer, D., 1984. Using Weather Records with a forage production model to forecast Range forage production. *J. of Range Manage.*, 37:1, 3-6.

Williams, J., Prebble, R.E., William, W.T. and Hignet, C.T., 1983. The influence of texture, structure and clay minerology on the soil moisture characteristic. *Australian Journal of Soil Research* 21, 15-32.

Woledge, J. & Dennis, W.D., 1982. The effect of temperature on photosynthesis of ryegrass and white clover leaves. *Annals of Botany*, 50, 25-35.

Wright, J.L., 1981. Crop coefficients for estimates of daily crop evapotranspiration. In: Proc. Irrig. Scheduling Conf. ASEA, Chicago. Irrigation scheduling for water and energy conservation in the 80's. pp 18-26.

CHAPTER 3

MODEL CALIBRATION AND VALIDATION

"All truth passes through three stages. First, it is ridiculed. Second, it is violently opposed. Third, it is accepted as being self-evident." Arthur Schopenhauer (1788 - 1860)

3.1 Introduction

It is easy for scientists -- and even easier for layman -- to confuse models with reality. Models are numerical simulations of natural phenomena. Models have to be verified against observable facts. Models are only as good as the "reality checks" they are based on. Fortunately, the reality checks available to modellers are getting better all the time. In recent years, more data has become available to test the models and hypotheses made.

3.2 Methods and materials

Methods:

Testing of simulation models consists of two activities: (1) establishing that the source code representing the model performs as intended (verification), and (2) confirming that the simulation models accurately reproduce observed data (validation).

Structuring the code (Putu15) into self-contained, logical modules and subroutines (see Fig 2.1) tested model source code.

As for the latter, standard statistical tests as describe by Willmott (1982) were employed. Two methods to quantify goodness of fit of model performance were used. Firstly, the root mean square error and mean absolute error between simulations and measurements were calculated. Secondly, linear regressions were fitted to observe versus predicted data.

The root mean square error allows comparative assessment of how well model components performed. Linear regression measures agreement between model output and measurement (the closer the regression is to the 1:1 line and the closer the intercepts is to zero, the better the model's accuracy).

Materials:

The model was first calibrated on a Bloemdal soil (i.e. input parameters were evaluated) using 20 years of data (See Snyman and Fouché 1991; 1993, Snyman 1997a, 1997b) from Bloemfontein. The water balance model was evaluated on two benchmark ecotopes (Shorrocks and Swartland) at Glen (Department of Agriculture and Environmental affairs). Dr Hensley (from the Agricultural Research Council) and his team of experts collected the data.

Above ground biomass production reflects the amount of fodder available for grazing. The biomass produced per area (ha) determines the grazing pressure (stocking rate). Putu15 was validated at 10 sites (Data used were obtained from van der Westhuizen, 1994, unpublished Department of Agriculture and Environmental affairs Free state). The spatial distribution of these sites is presented in Figure 3.1 and listed in Table 3.1.

Table 3.1 Location of veld monitoring sites in the Free state giving the number, name, latitude, longitude, weather station name and distance from the site to the nearest rainfall station.

Site No	Name	Latitude S	Longitude E	Weather Station	Distance (km)	Mean Rainfall
1	Bloemfontein	29° 06'	26° 57'	Univ. Free State	0	560
34	Mynrust	29° 42'	26° 38'	Dewetsdorp	14	589
43	Middelplaas	29° 14'	26° 31'	Maselspoort	25	543
50	Vacant	28° 35'	26° 56'	Winburg	11.3	560
51	Swaarkry	28° 41'	26° 43'	Brandfort	27	537
54	Riviera	28° 21'	26° 57'	Winburg	19	565
55	Voëlvlei	28° 49'	27° 00'	Winburg	34	565
63	Franshoek	29° 59'	26° 16'	Smithfield	36	493
70	Rama	28° 21'	26° 45'	Theunissen	7	512
3,4	Glen	28° 57'	26° 20'	Glen	0	547

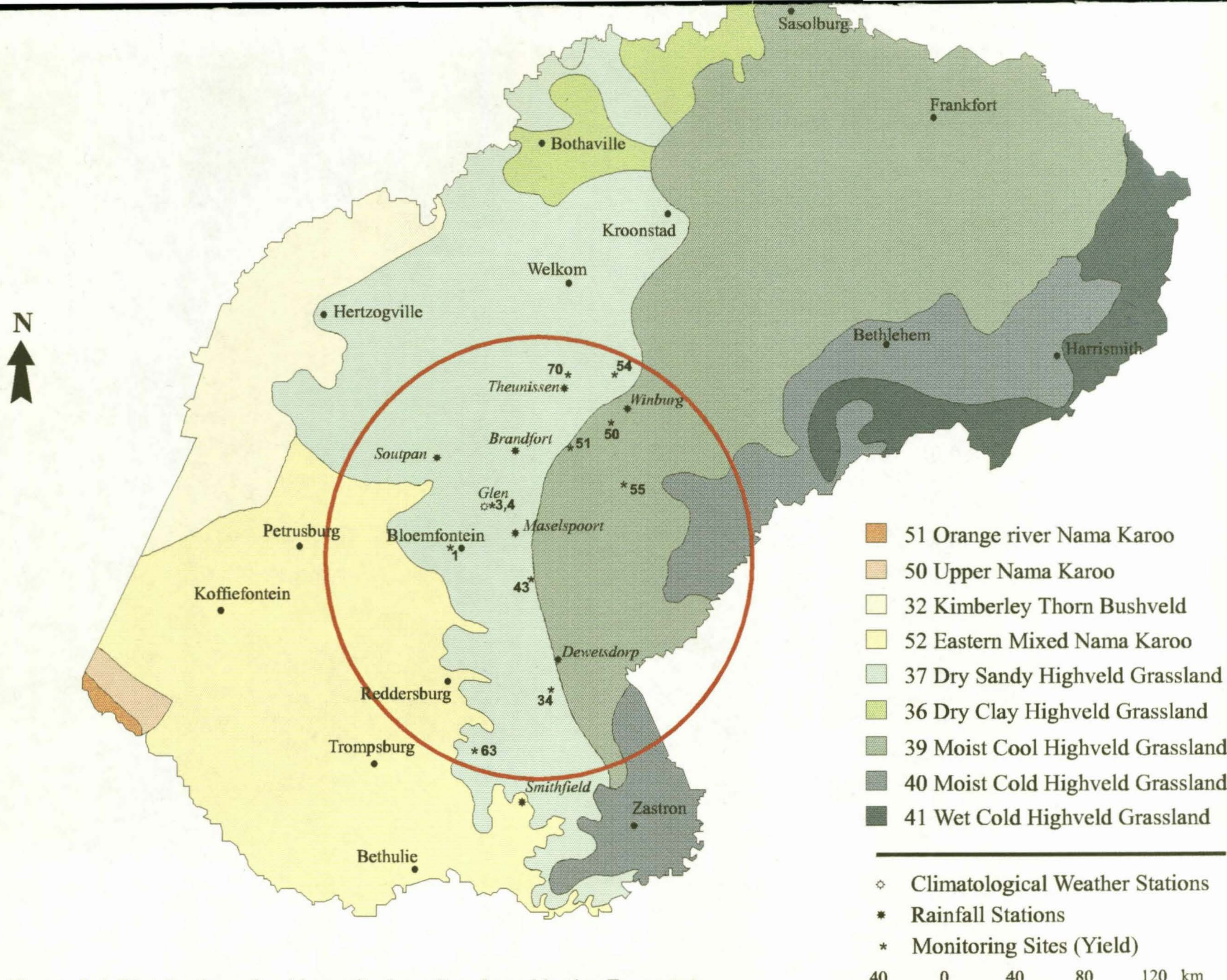

Figure 3.1 Distribution of veld monitoring sites found in the Free state.

Description of the study area

The study area (monitoring sites, see Figure 3.1) is representative of the Dry Sandy Highveld Grassland and the Moist Cool Highveld Grassland. This area is characterised by Acocks (1988) as veldtype 50 (Dry *Themeda-Cymbopogon* veldtype), earlier describe by Mostert, Roberts, Heslinga and Coetzee (1971). Main component of specie composition is *Themeda triandra, Cymbopogon plurinodis* and *Digitaria eriantha*. Other species like *Eragrostis chloromelas* are the dominant sub-climax specie. *Aristida bipartita* and *Cynodon hirsitus* are found on the heavy soils.

Climate

The area is characterised as a summer rainfall area with an average annual rainfall between 493 mm and 589 mm (see Table 3.1). Variation in annual precipitation is high (standard deviation of 160 mm). Rainfall and climatological data were collected from the Institute for Soil, Climate and Water (ISCW-databank, 1997).

This area is characterised by Le Houérou, Popov & See (1993) as a semi-arid bio-climatic zone. On average, 70% of the annual rainfall is distributed within months November to March (see Figure 3.2).

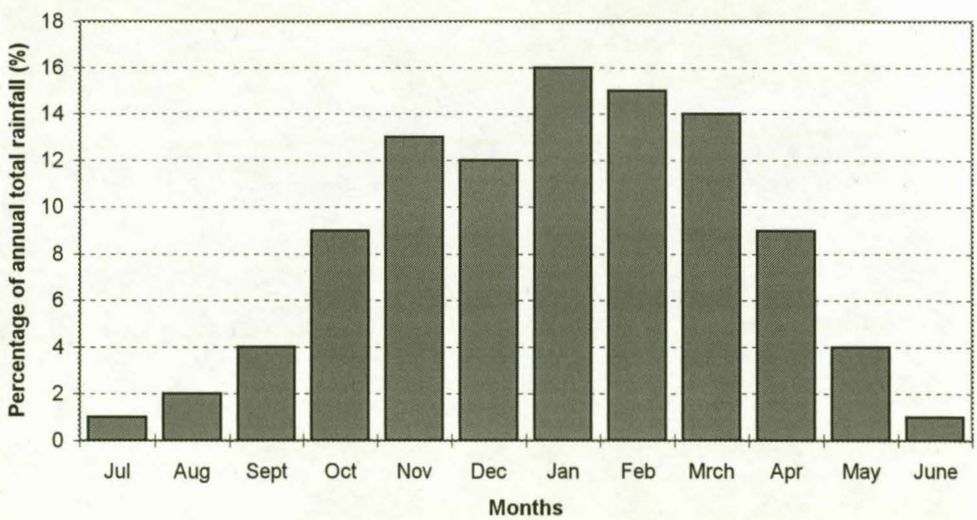

Figure 3.2 Average monthly distribution of rainfall at Glen.

Soil

The monitoring sites cover nine different landtypes (see classification by the Department of Agriculture, 1979). Textural properties of the soil are needed as input to the model. Given the description of the landtypes and taking into consideration the large variations that exist in each landtype, the soil depth, and clay content of the monitoring sites were estimated. These estimations are based on the findings of Dr Le Roux and Dr Hensley (*per comm.* 1997). Where possible, determination of the drained upper limit (DUL), the lower limit (LL) and soil rooting depth have been made (Shorrocks and Swartland ecotope). On most sites DUL and LL were estimate from the clay content.

Table 3.2 Main soil forms and landtypes for each veld monitoring site in the study area and the method used to determine the depth and clay content for each veld site.

Site No	Soil forms (Landtype)	Depth (m)	Clay (%)	Method
34	Valsriver (DB88A)	1.2	45	Estimate
43	Valsriver, Westleigh (CA22)	0.6	35	Estimate
50	Valsriver, Milkwood (DC16)	0.8	30	Estimate
51	Valsriver, Milkwood (DC16)	1	35	Estimate
54	Swartland, Bonheim, Mispah (DC12)	1	35	Estimate
55	Valsriver (DB37)	1	40	Estimate
63	Valsriver (DB88A)	0.8	50	Estimate
70	Bonheim (EA41)	1	40	Estimate
1	Bloemdal	1.2	25	Determined

3.3 Model calibration

3.3.1 Biomass production

(a) The parameters describing biomass growth

To evaluate equation 2.28 (see Chapter 2, expolinear crop growth function), parameters Cm, k, LAR and t_b must be known. Cm, was determined from experimental data obtained during the 1995/96 growing season (see Appendix C,1. Experimental plots at the University Free State). The increment in biomass per day (kg ha^{-1} d^{-1}) is given by:

$$Cm = \frac{\text{biomass change}}{\text{growth interval (d)}} = \frac{2428-1036}{243-185} = \frac{1392}{58} = 24 \text{ kg ha}^{-1}\text{ d}^{-1}$$

In Putu15, crop growth is measured in terms of thermal time. Thermal time is computed above a base temperature of 10°C. Cm then becomes 2.4 kg ha^{-1}d^{-1}°C^{-1}.

The initial value for leaf area ratio (LAR) for a climax veld was taken from Putu11 viz. $LAR = 0.002$ ha kg^{-1}.

Having determined Cm and LAR, t_b could be calculated from equation 2.29. This requires knowledge of the initial plant cover at the onset of the growing season. Snyman and Fouché (1993), showed this to be around 8 % and the value of $Lo = 0.08$ was adopted.

Equations 2.28, 2.29 and 2.30, can now be evaluated in terms of one unknown, k (the extinction coefficient). k is usually difficult to determine from measurements, particularly when working with a mixed stand of plant species. The software package, Model Maker, (see, Walker, 1997) was implemented to determine k. Briefly, this entailed that equations 2.28, 2.29 and 2.30 were entered into Model Maker. Thermal time were calculated from observed daily climatological data for the 1995/96 growing season and a base temperature of 10 °C. Then k was obtained by using the standard statistical optimisation routine supplied in Model Maker (specifically the Marquardt algorithm method was employed). The value of k found was 0.83±0.215. The value finally used in Putu15 is 0.8. Statistics for the optimisation are given in Table 3.3.

Table 3.3 Output produced by Model Maker for the determination of k.

	Degrees of Freedom	Weighted sum of squares	Mean Square	F-value = 0
Model	0	340.01	N/A	P-value =1
Residual (X^2)	5	34.136	6.82	Q-value=2.23e-06
Total	5			
r^2 = 0.90				

The 1995/96 and 1996/97 growing season provided biomass data to calibrate the model. Initially, Putu15 under estimated final yields by as much as 450 and 300 kg ha^{-1} for the 1995/96 and 1996/97 growing seasons, respectively. By increasing maximum growth rate Cm to 2.5 kgha^{-1}°C^{-1}, final yield was improved. Ultimately, by introducing the concepts of resilience (see Chapter 2, Eq 2.31 and 2.32) and using a value of $Const = 40$ improved the overall output of the model. (see Table 3.4 and Figure 3.3).

Table 3.4 Statistical results of model test for the 1995/96 and 1996/97 seasons. Number of observations (OBS), Mean absolute error (MAE, kg ha^{-1}), Root mean square error (RMSE, kgha^{-1}), Systematic root mean square error (S.RMSE, kg ha^{-1}), Unsystematic root mean square error (U.RMSE, kg ha^{-1}), correlation (r^2), Willmot index of agreement (D), slope and intercept.

Season	OBS	MAE	RMSE	S.RMSE	U.RMSE	r^2	D	Slope	Intercept
95/96	8	175.1	215.1	205.4	63.7	.99	.98	0.81	164.7
96/97	8	416.9	432.3	427.4	64.7	.99	.95	0.91	-258.6
96/97 $Const = 40$	8	72.9	96.3	54.8	79.2	.99	.99	1.05	-88.1
Total with $Const = 40$	16	123.9	166.7	72.2	150.2	.97	.99	.94	47.3

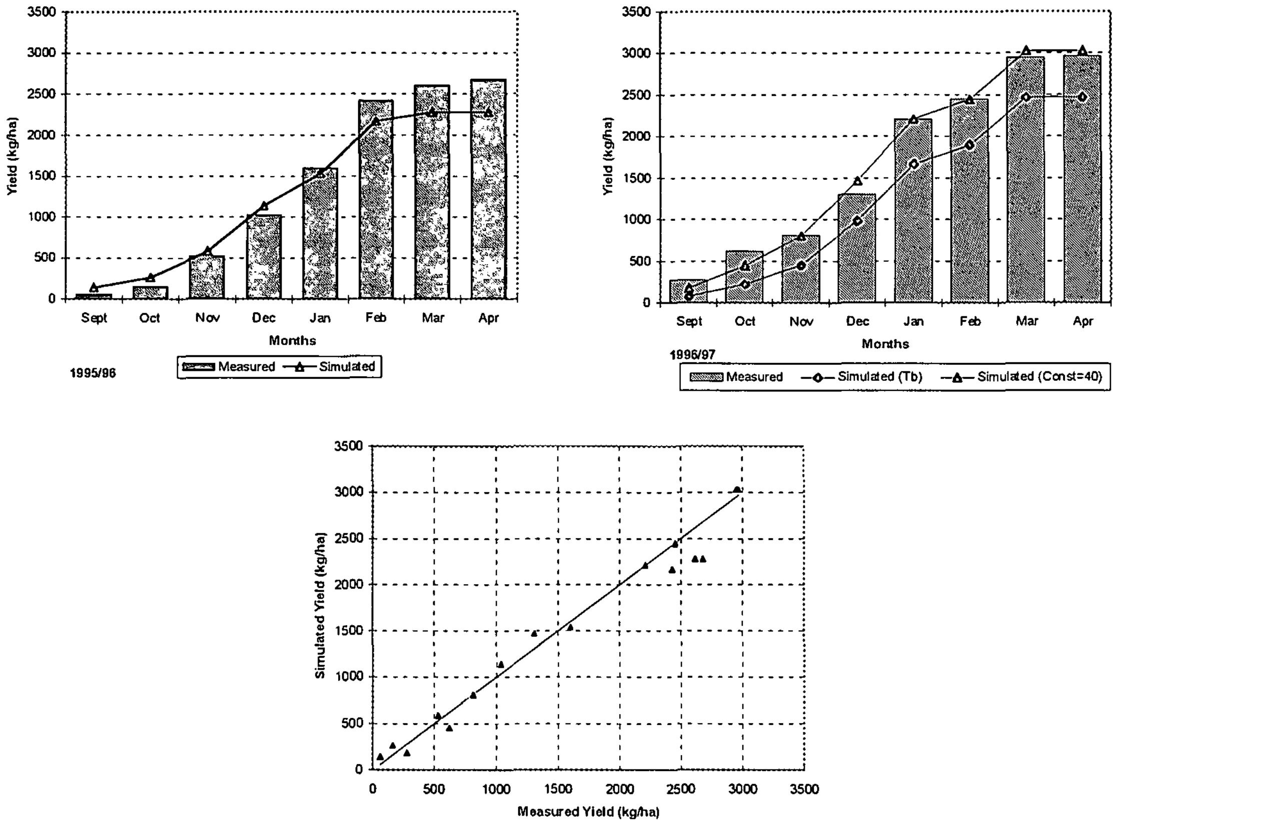

Figure 3.3 Measured and simulated biomass production (1995/96), indicating the implementation of resilience with $Const = 40$ during the 1996/97 growth season. Scatter plot of measured and simulated yields for the 1995/96 and 1996/97 season with $Const = 40$.

(b) Overall calibration :

Initially (subsection 3.3.1a) the parameters used in the exponential crop growth function were quantified. As mentioned in Chapter 2, special attention will now be given to physiological ageing (Eq 2.11). By applying this equation and assuming the values used by Johnson & Thornley (1983) for $T_{b,age} = 0$ and $\gamma 20 = 0.015$, the measured and simulated biomass yields obtained were compared (see Appendix C, Table 2).

Furthermore, using the technique by Walker (1997), Putu15 was optimised with respect to:

- Threshold thermal time ($T_{b,age}$), and
- rate constant $\gamma 20$

Yielding values of the rate constant $\gamma 20$ of 0.01, and the threshold thermal time ($T_{b,age}$) of 70°d. The significance of these parameter in Putu15 are given in Appendix C, Table 3. The statistical analyses of the results obtained by assuming the values used by Johnson & Thornley (1983) and using thermal time is presented in Table 3.5 and Figure 3.4.

Table 3.5 Statistical results of model tests for 20 seasons using assumed values given by Johnson & Thornley (1983) (Model 1) and by applying a thermal threshold temperature of $T_{b,age} = 70^{o}d$ and a rate constant $\gamma 20 = 0.01$ (Model 2). Number of observations (OBS), Mean absolute error (MAE, kg ha^{-1}), Root mean square error (RMSE, kg ha^{-1}), Systematic root mean square error (S.RMSE, kg ha^{-1}), Unsystematic root mean square error (U.RMSE, kg ha^{-1}), correlation (r^2), Willmot index of agreement (D), slope and intercept.

Model	OBS	MAE	RMSE	S.RMSE	U.RMSE	r^2	D	Slope	Intercept
1	20	379.9	437.1	388.1	201.0	.92	.92	.89	517.61
2	20	189.8	223.5	143.4	171.5	.93	.97	.82	259.54

By accepting the values obtained by Johnson & Thornley (1983) for Themeda veld, the model (1) produced a high systematic error, which is reflected in the high intercept (517 kg ha^{-1}). Using values for $T_{b,age} = 70^{o}d$ and $\gamma 20 = 0.01$ improved the performance of the model dramatically (Model 2). These values suggest that leaf growth and biomass accumulation starts after 70°d depending on the season.

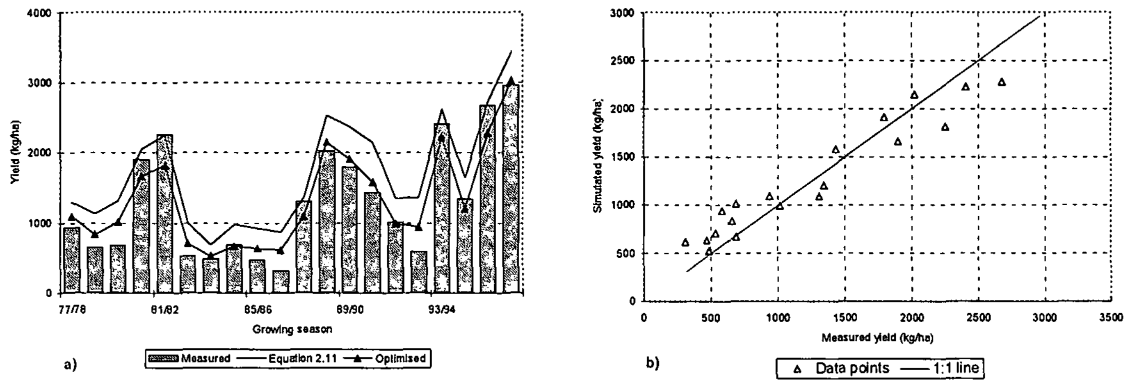

Figure 3.4 Measured and simulated biomass production (a) obtained by introducing equation 2.11 (Accepting values given by Johnson & Thornley, 1983) and the optimised values obtained by Model Maker for threshold thermal time and rate constant. (b) Scatter plot of measured versus yields simulated with Model Maker values of $T_{b,age} = 70^{o}d$ and $\gamma 20 = 0.01$.

(c) Variability in maximum growth rate Cm.

Independently, Van Niekerk, Blair, De Waal & Lategan (1983) have measured biomass production. Using data from the 1980/81 growing season, Cm was found to be approximately 19.5 kg ha^{-1} d^{-1}. Furthermore, Cm was computed using Putu11 (see Fouché, 1993) assuming that:

- Radiant flux density during mid-December is 27 Wm^{-2}.
- Average daily temperature is 25°C, and
- A leaf area index of 3.

Putu11 computed Cm for a full canopy to be 20.24 kg ha^{-1} d^{-1}.

3.3.2 Water balance

Measurements of the actual soil water content on the Shorrocks and Swartland ecotope were made by Glen Agriculture Research Institute during the 1987/88, 1988/89, 1989/90, 1995/96 and 1996/97 growth seasons. Data from the 1987/88 and 1988/89 season reflected high levels of soil water content (more than 1000 mm of rainfall were recorded for the growing season, during the floods of February and March 1988). Since the 1995/96 growing season was a good season in terms of rainfall distribution, it was decided to use this season for calibration of both ecotopes.

Drained upper and lower limits and soil rooting depth were determined for the ecotopes and are presented in Table 3.6.

Table 3.6 Measured drained upper and lower limit (mm) for each soil layer for the veld ecotopes Shorrocks and Swartland.

	Soil depth in metres							
Ecotope	0-0.3	0.3-0.6	0.6-0.9	0.9-1.2	1.2-1.5	1.5-1.8	1.8-2.1	Total
Shorrocks								
Upper	26	59	54	58	59	51	54	361
Lower	15	30	26	29	30	25	27	182
Swartland								
Upper	47	96	85	83				311
Lower	26	60	55	60				201

a) Shorrocks:

The amount of water available for plant growth in each level is affected by the amount of water extracted from the soil root zone and the amount of water flowing into the soil layer in the event of rainfall. Excess water (above DUL) drains freely to the layer below. In Putu15, this excess water is computed as $VCON$ (see equation 2.16).

$VCON$ may be computed from porosity and the drained upper limit. By calibration (trial and error) and after consultation with Dr. Hensley, the value of $VCON$ was held constant 0.2 for the full profile. Furthermore, the implementation of the water balance routines requires knowledge of the initial soil water content at onset of the growing season. Initial soil water content in each layer was equal to the lower limit (LL , Hensley 1997 *pers comm.*) because this was expected in practice. Results obtained from the model calibration are presented in Figure 3.5 and statistical analyses are given in Table 3.7

Table 3.7 Statistical results of testing modelled layer soil water content during the 1995/96 growing season. Number of observations (OBS), Mean absolute error (MAE, mm), Root mean square error (RMSE, mm), Systematic root mean square error (S.RMSE, mm), Unsystematic root mean square error (U.RMSE, mm), correlation (r^2), Willmot index of agreement (D), slope, intercept and 80 % accuracy frequency: **Shorrocks ecotope**

Layer	OBS	MAE	RMSE	S.RMSE	U.RMSE	r^2	D	Slope	Intercept	80%
1	13	6.41	8.28	3.54	7.3	0.56	0.86	0.73	10.51	69
2	13	7.8	9.7	7.6	5.9	0.78	0.83	1.09	3.7	62
3	13	2.13	2.9	2.5	1.5	0.87	0.92	0.7	7.6	100
4	13	1.4	1.8	1.7	0.6	0.27	0.62	0.25	0.95	100
5	13	1.9	1.9	0.73	0.74	0.08	0.59	0.27	22.4	100
6	13	0.93	1.1	0.79	0.77	0.01	0.48	0.11	22.9	100
7	13	0.63	0.87	0.44	0.73	0.05	0.54	0.28	20.3	100
Total	13	8.9	11.5	6	9.8	0.85	0.95	0.95	11.2	100
Overall	91	3.52	4.9	1.6	4.7	0.62	0.88	0.79	6.2	89

General discussion:

From the observed and simulated data, water extraction occurred mainly in the upper 900 mm of the soil profile where probably 90 % of roots are found. The model failed to predict soil water content accurately during the mid-season (February to March) for soil layers 300 to 600 mm (see Figure 3.5). Although the correlation (r^2) for layers 4 to 7 were 0.27 and lower, the mean error was less than 2 mm or 1% of total soil water content (amount of water between upper and lower limit). In these soil layers, change in soil water content due to drainage and water extraction did not occur.

Overall the model fitted observed data moderately well with a correlation coefficient $r^2 = 0.62$. Mean absolute error was less than 4 mm. Nearly 90 % of simulated values are accurate to within 20% of the measured values.

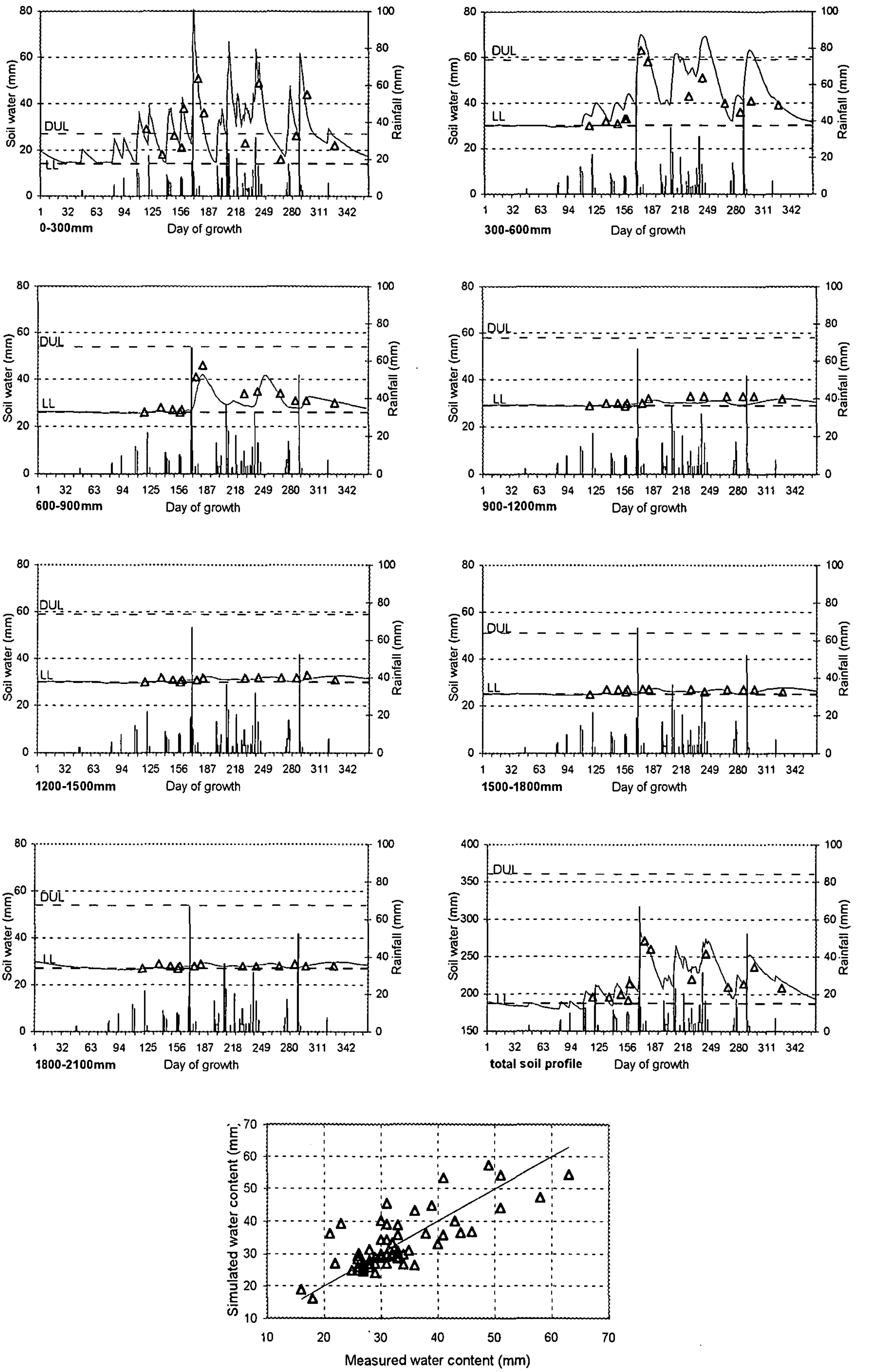

Figure 3.5 Measured and simulated water content for each soil layer for the 1995/96 growing season, and the scatter plot between measured and simulated soil water content for entire profile: **Shorrocks ecotope.**

***b) Swartland*:**

On the Swartland ecotope, the fraction of excess water above DUL drained ($VCON$) for layers 1 to 4 were 0.2, 0.5, 0.75 and 0.1, respectively. These values are the results of the calibration carried out by trail and error . The assumption was made that the initial soil water content on day one of simulation equalled lower limit (LL, Hensley 1997 *pers comm.*). Results obtained from model calibration are presented in Figure 3.6. Statistical analyses is given in Table 3.8

Table 3.8 Statistical results of testing modelled layer soil water content during the 1995/96 growing season. Number of observations (OBS), Mean absolute error (MAE, mm), Root mean square error (RMSE, mm), Systematic root mean square error (S.RMSE, mm), Unsystematic root mean square error (U.RMSE, mm), correlation (r^2), Willmot index of agreement (D), slope, intercept and 80 % accuracy frequency: **Swartland ecotope**

Layer	OBS	MAE	RMSE	S.RMSE	U.RMSE	r^2	D	Slope	Intercept	80%
1	12	9.4	11	6.8	8.7	0.67	0.88	0.69	15.26	58
2	12	8.1	11.2	7.8	8.0	0.68	0.75	1.5	-28.4	83
3	12	6.6	8.5	3.4	7.8	0.37	0.52	1.96	-56.8	83
4	12	1.9	2.4	2.4	0.14	0.33	0	-0.04	65.3	100
Total	12	13.2	16.4	5.1	15.5	0.73	0.91	0.93	21.65	100
Overall	48	6.5	9.0	1.2	8.9	0.60	0.86	0.98	1.95	81

General discussion:

On this ecotope problems were encountered in estimating the actual soil water content for soil layer depth of 600 to 900 mm. Frequent rainfall events during February and March resulted in the occurrence of deep drainage and consequently the over-estimation in the soil water content for soil layer 300-600mm and 600-900mm. Low levels of water extraction during May and June (dormant period) also contributed to this over-estimation of the actual soil water content (Fig 3.6). In the 4th soil layer (900-1200mm), no changes were predicted, apart from the water extraction which occurred during the first part of the growth season (see Figure 3.6). An overall mean absolute error of 6.5 mm with a correlation (r^2) of around 0.6 was achieved. Over 80 % of model predictions are accurate to within the 20 % of their measured values.

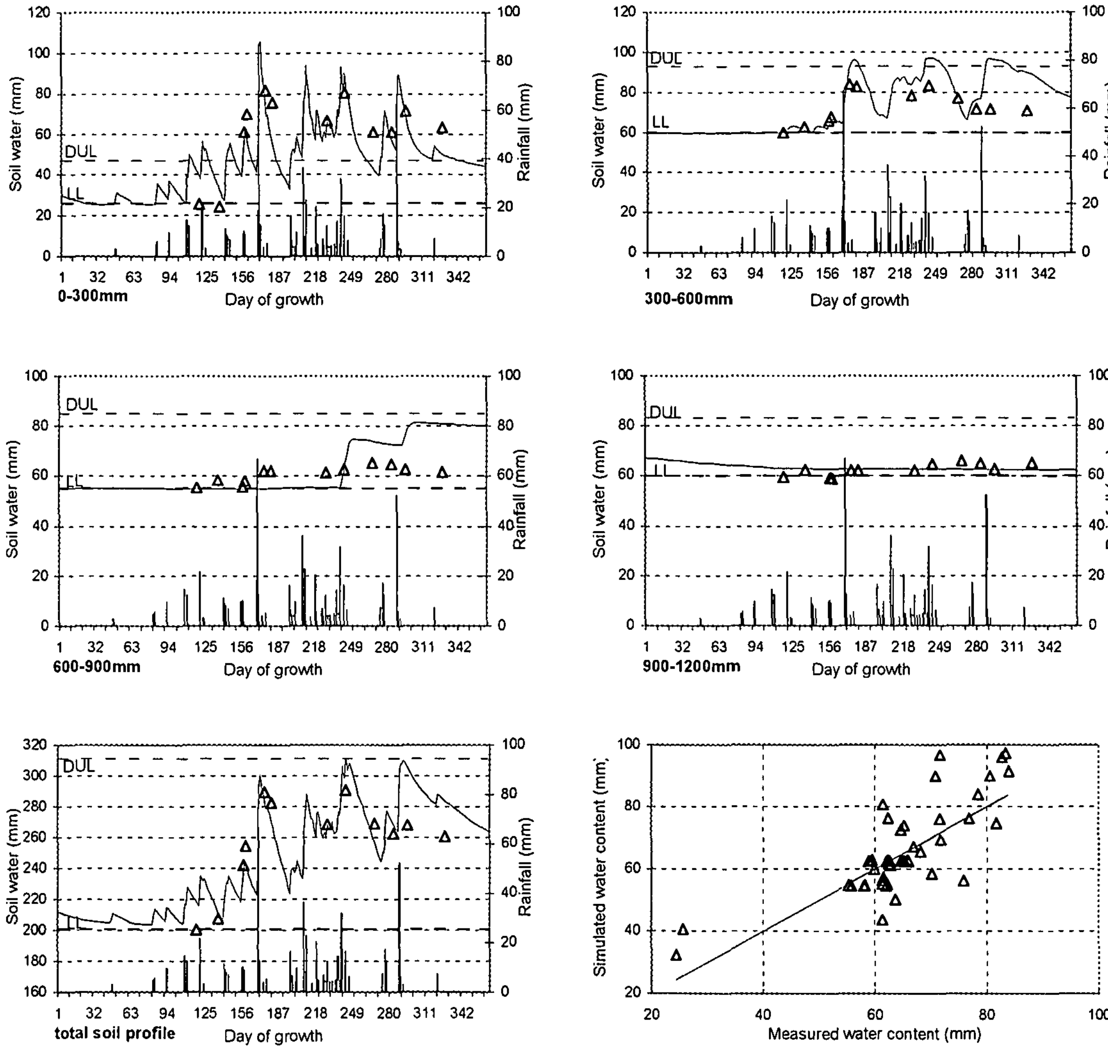

Figure 3.6 Measured and simulated water content for each soil layer for the 1995/96 growing season, and the scatter plot between measured and simulated soil water content for entire profile: **Swartland ecotope**

3.4 Model validation

3.4.1 Testing the water balance

The simulated values of the different components of the water balance equation (see equation 2.12, Chapter 2) for soil ecotopes Shorrocks and Swartland are given in Table 3.9.

Table 3.9 Deviation (%) from long-term mean rainfall (Dev), measured rainfall (P) and simulated total infiltration (I), - transpiration (E_V), - soil evaporation (E_S), - runoff (R), - deep drainage (D) and total water extraction from the root zone (ΔS) for the 1987/88, 1988/89, 1989/90 and 1996/97 growth season on the Shorrocks and Swartland ecotopes.

Ecotope	Season	Dev	P	I	E_V	E_S	R	D	ΔS
Shorrocks	1987/88	87	1024	891	510	172	88	144	-110
	1988/89	35	739	669	364	225	30	55	-65
	1989/90	3	563	514	474	210	18	0	139
	1996/97	35	738	653	373	206	49	0	-110
Swartland	1987/88	87	1024	891	396	260	88	140	-140
	1988/89	35	739	669	555	137	30	91	74
	1989/90	3	563	514	224	189	18	22	-110
	1996/97	35	738	653	395	245	49	0	-49

In general, total seasonal rainfall exceeded the long-term mean. For the 1987/88 growth season nearly 90 % more rainfall than the long-term mean was recorded. Total number of rainfall events that occurred for each growth season are presented in Table 3.10.

Table 3.10 Rainfall events for the 1987/88, 1988/89, 1989/90 and 1996/97 growth seasons

Rainfall (mm)	1987/88	1988/89	1989/90	1996/97
10 - 20	9	12	19	11
20 - 30	11	10	5	6
30 - 40	6	2	1	2
> 40	4	0	0	2

a) Shorrocks:

Statistical results testing the water balance model during growth seasons 1987/88 through to 1989/90 and 1996/97 are given in Table 3.11 and presented in Figure 3.7.

This soil is deep (1.8-2.1 m) and sandy. The water holding capacity is not very high and water moves freely through the soil profile. During the floods that occurred in February 1988, nearly 900 mm infiltrated the soil (see Table 3.9). This resulted in over-estimation of the soil water content and consequently a poor correlation ($r^2 = 0.23$) and a high mean absolute error (18.6 mm) compared to the overall-mean absolute error of 8.7 mm. Willmot index of agreement (D) was 64%, indicating a poor fit of simulated to measured values.

The Putu15 model estimated that 144 mm of deep drainage occurred (during the floods of February 1988) which were well within the range as reported by Snyman and Fouché (1991), viz. 261 mm during high rainfall events.

Putu15 simulated soil water content values most accurately for the 1996/97 growing season. A root mean square error of 5.3 mm and a correlation coefficient of $r^2 = 0.72$ was obtained. The rainfall was distributed evenly for the 1996/97 growing season. Over 88 % of the model predictions were accurate to within 20 % of their measured values.

Table 3.11 Statistical results of testing modelled layer soil water content during the 1987/88, 1988/89, 1989/90 and 1996/97 growing season. Number of observations (OBS), Mean absolute error (MAE, mm), Root mean square error (RMSE, mm), Systematic root mean square error (S.RMSE, mm), Unsystematic root mean square error (U.RMSE, mm), correlation (r^2), Willmot index of agreement (D), slope, intercept and 80 % accuracy frequency: **Shorrocks ecotope**

Year	OBS	MAE	RMSE	S.RMSE	U.RMSE	r^2	D	Slope	Intercept	80%
1987/88	28	18.6	22.0	7.8	20.5	0.23	0.64	0.71	11.57	36
1988/89	84	8.8	9.6	6.0	7.5	0.61	0.86	0.64	20.6	73
1989/90	63	8.2	10.1	4.2	9.2	0.45	0.81	0.69	14.2	49
1996/97	49	3.6	5.3	3.4	4.0	0.72	0.89	0.75	5.81	88
Overall	224	8.7	11.4	3.9	10.7	0.54	0.86	0.75	11.46	65

The overall systematic root mean square error produced is around 12 % of the root mean square error, which is well within the accuracy criterion of 60 %. The index of agreement (D) found across seasons was 86% satisfying the criterion of 80%. From this it is fair to assume that the water balance model fairly estimate measured soil water content values with the exception of the correlation coefficient (r^2) being 54%. Overall, 65 % of the model predictions were accurate to within 20 % of their measured values.

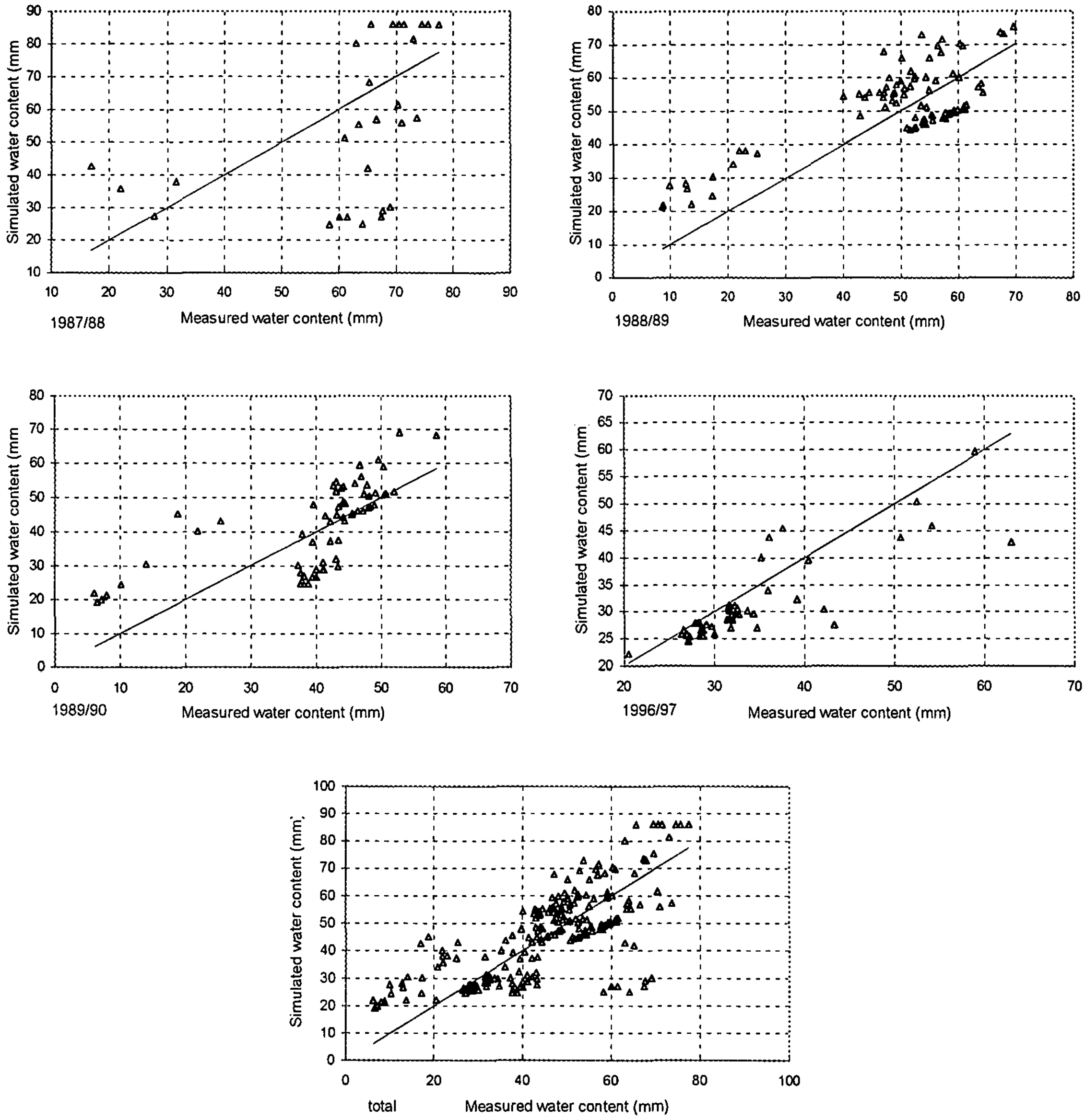

Figure 3.7 Scatter plot of measured and simulated soil water content for growing seasons 1987/88, 1988/89, 1989/90 and 1996/97 : **Shorrocks ecotope**

b) Swartland:

Statistical results testing the water balance model during growth seasons 1987/88 through to 1989/90 and 1996/97 on a Swartland soil are given in Table 3.12 and presented in Figure 3.8.

Table 3.12 Statistical results of model test for layered soil water content during the 1987/88, 1988/89, 1989/90 and 1996/97 growing season. Number of observations (OBS), Mean absolute error (MAE, mm), Root mean square error (RMSE, mm), Systematic root mean square error (S.RMSE, mm), Unsystematic root mean square error (U.RMSE, mm), correlation (r^2), Willmot index of agreement (D), slope, intercept and 80 % accuracy frequency: **Swartland ecotope**

Year	OBS	MAE	RMSE	S.RMSE	U.RMSE	r^2	D	Slope	Intercept	80%
1987/88	20	10.5	15.5	8.5	12.99	0.49	0.81	0.67	31.3	75
1988/89	44	10.0	13.1	9.1	9.47	0.61	0.87	0.60	25.2	73
1989/90	32	14.1	16.4	10.8	12.2	0.34	0.75	0.45	36.1	44
1996/97	28	9.4	13.7	1.2	13.6	0.18	0.56	0.97	0.92	64
Overall	124	11.03	14.5	7.1	12.6	0.43	0.81	0.61	26.6	64

The Swartland soil is considered to be a heavy clay soil and has a relatively high water holding capacity. The soil is representative of soil types found in the study area (see Figure 3.1). Simulated losses from surface runoff were between 18 and 88 mm, well within the range expected as reported by Snyman and Fouché (1991).

Water drained freely and deep percolation occurred during growth seasons 1987/88 through 1989/90 (see Table 3.9). This comes as no surprise, since:

- Annual rainfall exceeded mean rainfall
- 21, 12 and 6 rainfall events of more than 20 mm were recorded for 1987/88, 1988/89 and 1989/90 growth seasons (see Table 3.10) , respectively.

The high systematic error produced during the 1988/89 and 1989/90 season could be ascribed to the high infiltration simulated (891 and 669 mm for 1987/88 and 1988/89 growing seasons, respectively) and thus the over estimation of the soil water content. This high infiltration is more than the long-term average rainfall of 525 mm received for Glen.

Generally, the root mean square error and Willmot index of agreement produced was not significantly different over seasons. The correlation coefficient was low for all seasons with the exception of 1988/89 ($r^2 = 0.61$).

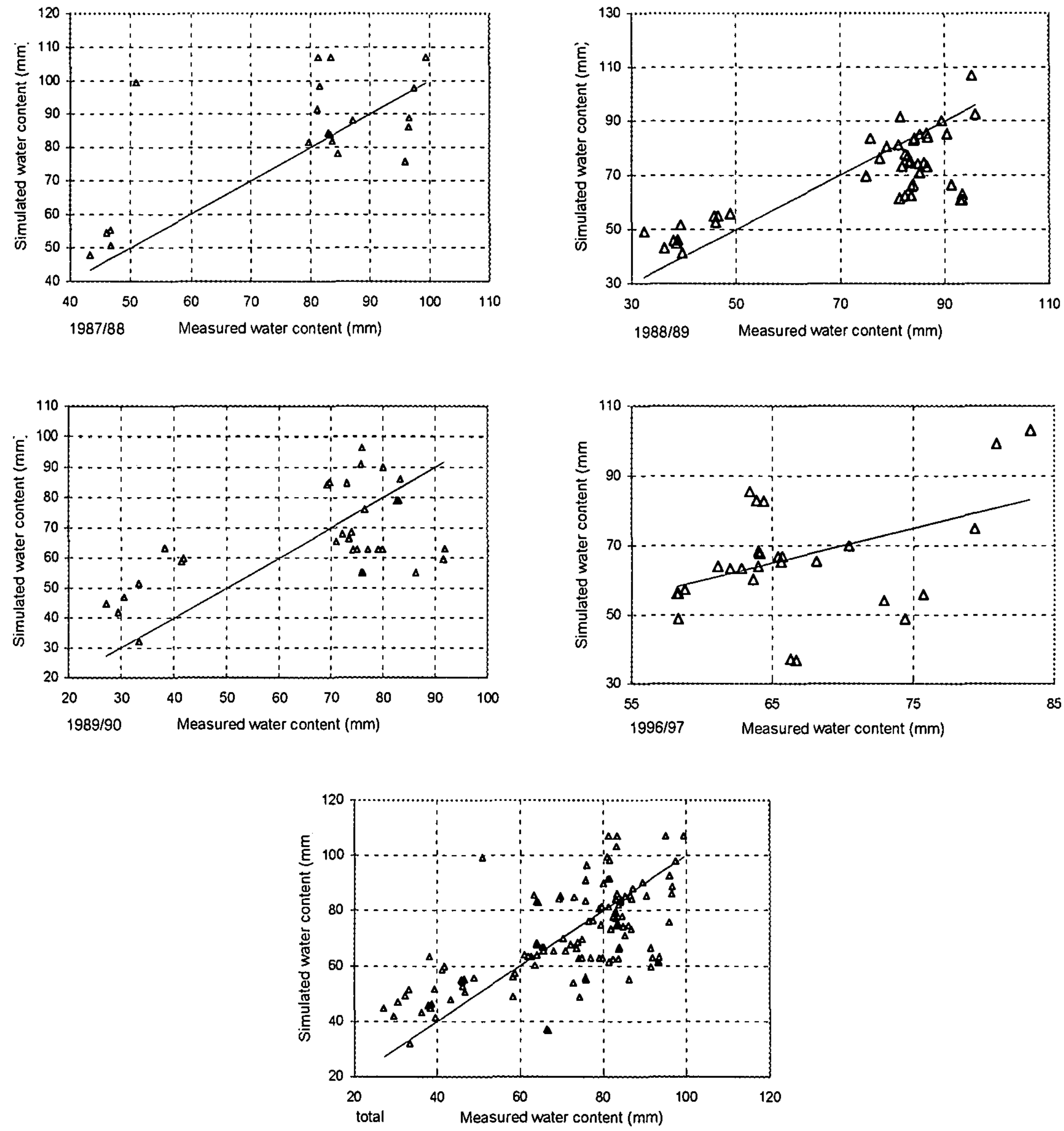

Figure 3.8 Scatter plot of measured and simulated soil water content for growing seasons 1987/88, 1988/89, 1989/90 and 1996/97:**Swartland ecotope**.

The overall systematic root mean square error is around 24% of the root mean square error, well within the criterion. The Willmot index of agreement (D) found is 81%. The low correlation coefficient $r^2 = 0.43$ found across seasons could be ascribed to an over-estimation of infiltration, which is reflected in the intercept (26.6 mm). 64 % of simulated values are accurate to within 20% of their measured values.

*c) **Conclusions*** :

From the tests conducted it does appear that the model over estimates soil water content particular on the Swartland ecotope. This is reflected in the intercept produced (Table 3.12, 26.6 mm). A probable cause for this overestimation could lie in estimating the amount of water infiltrating the soil. The solution to this would be :

- implementation of rainfall intensity data could improve these estimations dramatically, and secondly
- To look at relationships if any, between plant cover and total runoff as this could affect the amount of water that enters the soil in the end.

On both ecotopes (i.e. Shorrocks and Swartland) the overall systematic root mean square was less than 60% of the root mean square error which is well within the accuracy criterion. The overall Willmot index of agreement (D) was above 80% on both ecotopes meeting the criterion for the water balance. The criterion for the correlation coefficient (r^2) was not satisfied on all seasons at both ecotopes.

3.4.2 Biomass production

The objective of this section is to determine how accurately the model simulated biomass production. Data collected during the growing seasons of 1986/87 through to 1993/94 were used (van der Westhuizen, 1994 unpublished data, see Appendix D). The model was evaluated on serial harvest data from monitoring sites (benchmark ecotopes). This gives an indication of the reliability of the model for predicting biomass production within seasons and across environments. Where possible, shortcomings in the model were highlighted. Model output was also evaluated in terms of final seasonal maximum yields (across seasons and environments).

No description of the nature of each monitoring site will be given since Van der Westhuizen (1994) has provided this. Rainfall data obtained closest to the relevant sites were used (see Table 3.1), but climatological data from Glen were used at all the sites, since this was the only available data sets.

a) Serial harvest

Results obtained from comparison of simulated biomass against measured yield within seasons for ecotopes Shorrocks, Swartland, Mynrust and Franshoek are presented in Table 3.13. The scatter plot of measured and simulated biomass for these ecotopes is presented in Figure 3.9e.

Table 3.13 Statistical results of model performance at sites distributed in the Dry Sandy Highveld Grassland. Growing season (Season), Number of observations (OBS), Mean absolute error (MAE, kg ha^{-1}), Root mean square error (RMSE, kg ha^{-1}), Systematic root mean square error (S.RMSE, kg ha^{-1}), Unsystematic root mean square error (U.RMSE, kg ha^{-1}), correlation (r^2), Willmot index of agreement (D), slope, intercept (kg ha^{-1}), and 80 % accuracy frequency.

Site	Season	OBS	MAE	RMSE	S.RMSE	U.RMSE	r^2	D	Slope	Intercept	80 %
Shorrocks	1987/88	8	306.9	352.2	180.4	302.2	.0	.38	-0.03	952.0	25
	1988/89	8	463.4	515.6	197.0	476.5	.27	.68	0.73	115.4	13
	1989/90	10	215.9	283.9	133.8	250.3	.47	.78	0.86	-4.6	50
	1990/91	7	109.3	148.4 *	125.2	79.6	.95	.96	0.77	183.0	100
	1991/92	10	261.7	308.4	33.9	306.5	.36	.75	0.89	152.3	40
	1992/93	9	218.6	349.6	190.8	292.9	.39	.73	0.77	300.3	44
	1993/94	9	166.5	180.4 *	14.6	179.8	.78	.94	0.98	-3.7	56
	1994/95	4	93.3	124.9 *	124.9	3.1	.36	.16	-0.02	488.1	75
Overall		65	239.0	315.9	88.4	303.2	.50	.84	0.78	185.2	48
Swartland	1987/88	7	297.5	343.9	221.4	263.2	.04	.28	-0.41	1400.6	29
	1988/89	9	461.5	629.9	328.2	537.7	.53	.75	1.13	147.5	22
	1989/90	10	157.0	194.3 *	143.9	130.6	.80	.85	1.36	-73.2	30
	1990/91	6	149.2	208.4 *	201.9	51.7	.88	.80	0.51	576.2	67
	1991/92	10	315.0	452.9	412.1	188.1	.06	.55	0.14	547.7	60
	1992/93	10	144..4	181.9 *	141.7	114.1	.82	.84	1.44	-35.9	30
	1993/94	9	341.3	470.1	239.9	404.2	.40	.73	0.96	270.5	22
	1994/95	4	329.5	335.1	335.0	4.1	.38	.22	-0.10	675.4	0
Overall		65	272.0	389.5	135.2	365.2	.45	.79	0.84	236.4	34
Mynrust	1989/90	6	632.3	730.1	551.8	478.1	.19	.59	0.49	397.7	17
	1990/91	5	214.2	254.3	227.2	113.0	.77	.78	0.72	486.3	60
	1991/92	8	145.9	188.2 *	96.8	161.4	.50	.75	1.16	-16.7	50
	1992/93	7	331.4	374.0	350.8	129.7	.77	.50	1.92	133.2	0
	1993/94	4	100.2	142.6 *	45.1	135.3	.38	.75	0.79	102.4	50
Overall		30	291.0	402.7	267.5	301.1	.57	.85	0.57	387.3	33
Franshoek	1989/90	7	292.3	370.7	258.2	266.0	.54	.62	1.50	-286.8	57
	1990/91	7	207.3	257.1	223.3	127.4	.89	.93	0.65	362.0	71
	1991/92	9	316.3	426.0	279.9	321.0	.05	.30	-0.43	1235.5	56
	1992/93	9	732.7	791.6	750.7	251.1	.54	.25	2.51	487.0	0
	1993/94	9	903.3	1077.3	970.3	468.2	.48	.19	4.56	363.1	0
Overall		41	513.0	683.3	516.5	447.5	.15	.62	0.33	816.1	34
Lumped		201	313.7	448.1	230.9	383.9	.34	.76	0.57	446.6	38

*** Indicate results meeting the required criterion for accuracy.**

Shorrocks (3):

On the Shorrocks ecotope, measured yields varied between 160 and 1600 kg ha^{-1} (see Figure 3.9a, Appendix D). The root mean square error produced was the highest for growth seasons 1987/88 and 1988/89 which is reflected in the low correlation coefficient ($r^2 \leq 0.27$) obtained (see Table 3.13). Both these seasons were effected by the floods occurred during February 1988 (more than 87% and 35% of rainfall were recorded for growing season 1987/88 and 1988/89, respectively. Table 3.9). Simulated water extraction levels could be too low particularly during the 1988/89 season (see Table 3.9, $E_v = 364$ mm). This phenomena was highlighted by tests on the water balance (over-estimation of 14.2 mm occurred during the 1988/89 season).

For growth seasons 1990/91 and 1993/94 the highest correlation coefficient ($r^2 \geq 0.78$) were obtained. The mean absolute error was less than 170 kg ha^{-1} and the root mean square error less than 180 kg ha^{-1} for both these seasons.

The model produced an overall mean absolute error of less than 240 kg ha^{-1}. The root mean square error was 315 kg ha^{-1}. The model produced an overall correlation coefficient of $r^2 = 0.5$. For four out of the eight growing seasons the root mean square error was less than 300 kg ha^{-1}.

During the 1992/93 growing season, in the dormant stage (Mid May and June), Putu15 over estimated biomass yield by more than 600 kg ha^{-1}. This may be ascribed to an outlier in the observed yields (a decrease of nearly 600 kg ha^{-1} within 25 days occurred). Removing these outliers resulted in a overall root mean square error of 294 kg ha^{-1} and a correlation coefficient of $r^2 = 0.57$.

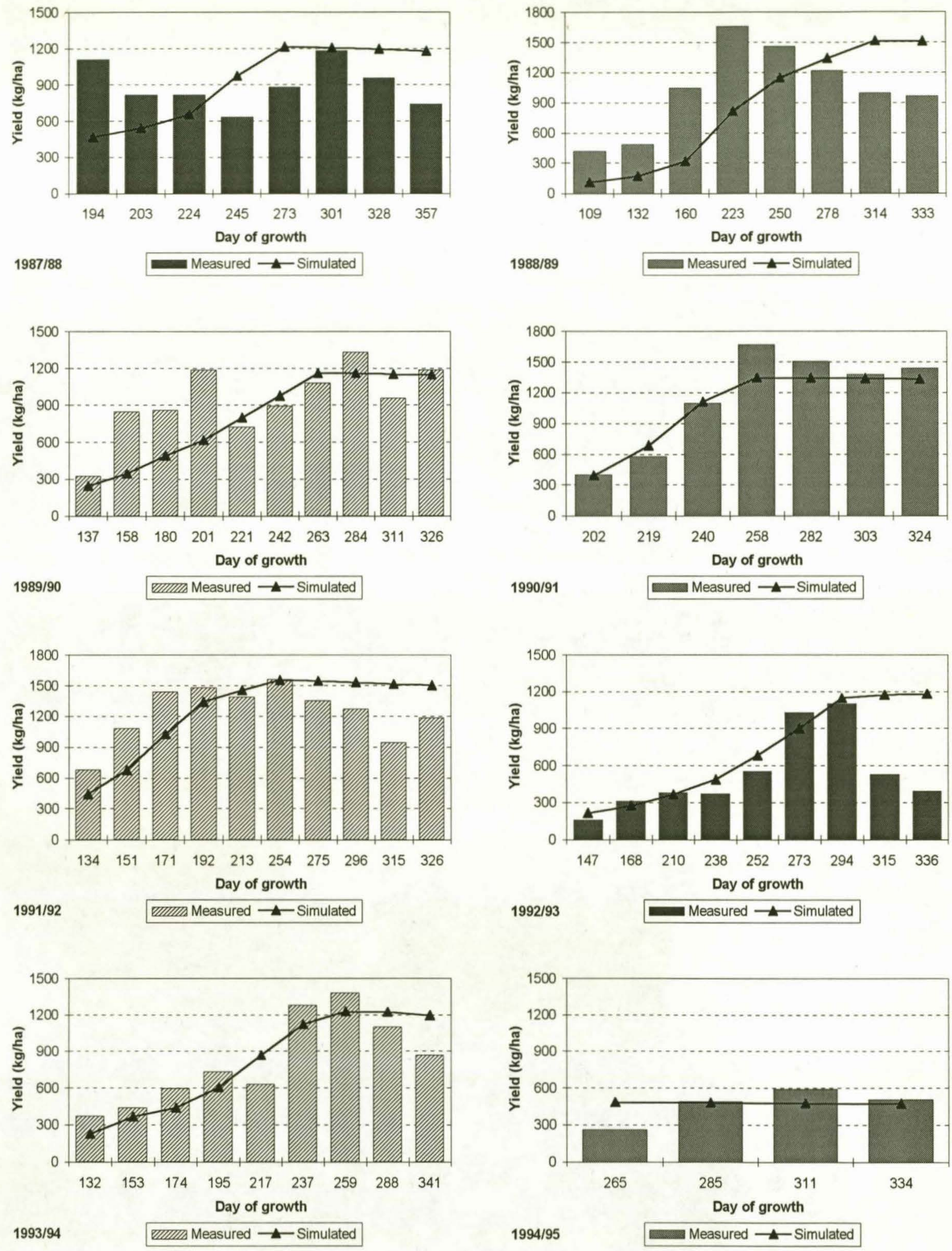

Figure 3.9a Measured and simulated yields for growing seasons 1987/88 through to 1994/95 on the Shorrocks ecotope.

Swartland (4):

On the Swartland ecotope, measured yields varied between 70 and 1800 kg ha^{-1}. For the 1987/88 and 1991/92 growing seasons, the model produced the lowest correlation coefficient. The root mean square error was unexceptably high for both these seasons. This is due to the floods which occurred during the 1987/88 season and outliers in measured biomass yield for the 1991/92 growth season. Observed yields in the early stages of growth (see Figure 3.9b, 1991/92) were high. Measured change of biomass was in the order of 63.5 kg ha^{-1} for 16 growing days. Optimum growth rate for Putu15 is around 25 kg ha^{-1} d^{-1}.

A correlation coefficient higher than 80% was recorded for growing seasons 1989/90, 1990/91 and 1992/93. The root mean square error was less than 208 kg ha^{-1} for all three these seasons. Willmot indexes of agreement was higher than 80%. This testifies to a good fit.

For five out of the eight growth seasons the root mean square error was less than 350 kg ha^{-1}. An over-all mean absolute error of 272 kg ha^{-1} was produced by the model. The overall correlation coefficient obtained was $r^2 = 0.45$ and the root mean square error was around 390 kg ha^{-1} (see Table 3.13).

Should the outliers in measured biomass yields (highlighted in Appendix D, Swartland) be removed, then a overall correlation coefficient of $r^2 = 0.7$ is obtained with a mean error of nearly 200 kg ha^{-1}. The root mean square error is 260 kg ha^{-1}.

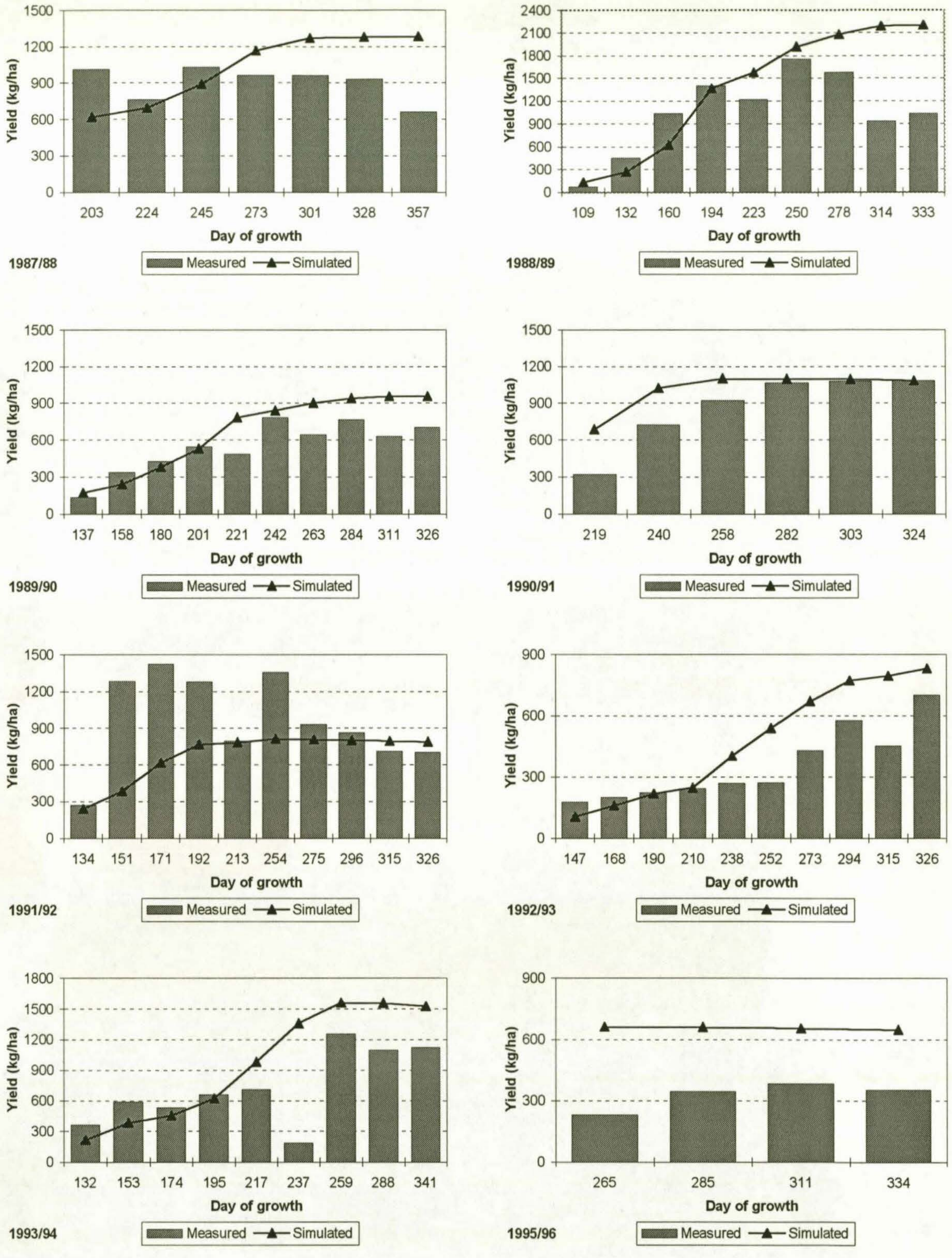

Figure 3.9b Measured and simulated yields for growing seasons 1987/88 through to 1994/95 on the Swartland ecotope.

Mynrust (34):

Measured yields varied between 100 and 2400 kg ha^{-1}. The model produced a root mean square error of less than 300 kg ha^{-1} (see Table 3.13) for three of the five growth season, viz. 1990/91, 1991/92 and 1993/94. The Willmot index of agreement was higher than 75 % for all three seasons.

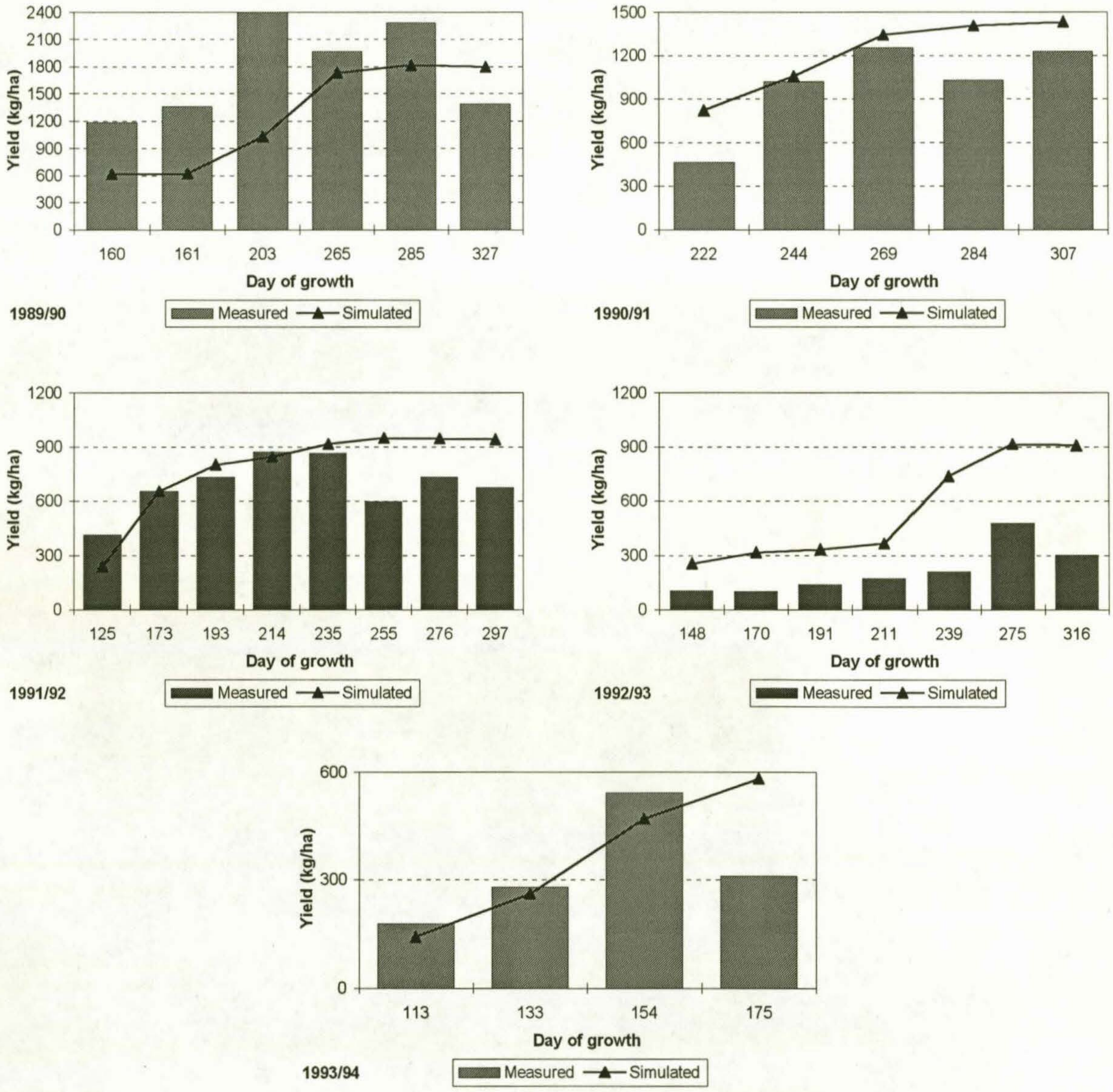

Figure 3.9c Measured and simulated yields for growing seasons 1989/90 through to 1993/94 at Mynrust.

An overall correlation coefficient of $r^2 = 0.57$ resulted, while the root mean square error (402 kg ha^{-1}) is unacceptably high. Based on the findings on the Shorrocks and Swartland ecotope, it is fair to assume that Putu15 should rather over-estimate the soil water content and hence biomass yields. This was not the case, an under-estimation of as much as 1200 kg ha^{-1} occurred during early growth period of the 1989/90 growth season (see Figure 3.9c). A probable cause for this would be:

- inability of the model to simulate high yields during the first part of the growth season;
- changes in specie composition to such an extent that the model is not capable of simulating high yields (nature of model calibration for Themeda veld);
- deviation in temperature at this site from temperatures at Glen;
- soil properties like (DUL, LL) might be incorrect for this site; or perhaps
- the use of rainfall data from the nearest rainfall station, which was 14 km away from the monitoring site (see Table 3.1).

By excluding observation during the 1989/90 growing season a overall correlation coefficient of $r^2 = 0.81$ resulted, while the root mean square error was 279 kg ha^{-1}.

Franshoek (63):

At Franshoek, measured yields varied between 30 and 2000 kg ha^{-1}. This benchmark ecotope is characterised by *Eragrostis* species and it comes as no surprise that the model performed badly ($r^2 = 0.15$, see Table 3.13). The model produced accurate results for the 1990/91 growth season (correlation coefficient was 89 %, root mean square error 257 kg ha^{-1} and Willmot index of agreement 93 %).

The root mean square error was for four out of the five growing seasons higher than 300 kg ha^{-1}. An overall high systematic error of 516.5 kg ha^{-1} (Table 3.13) indicates that the model consistently over-estimated yields, particularly during the 1992/93 and 1993/94 growth seasons (see Figure 3.9d).

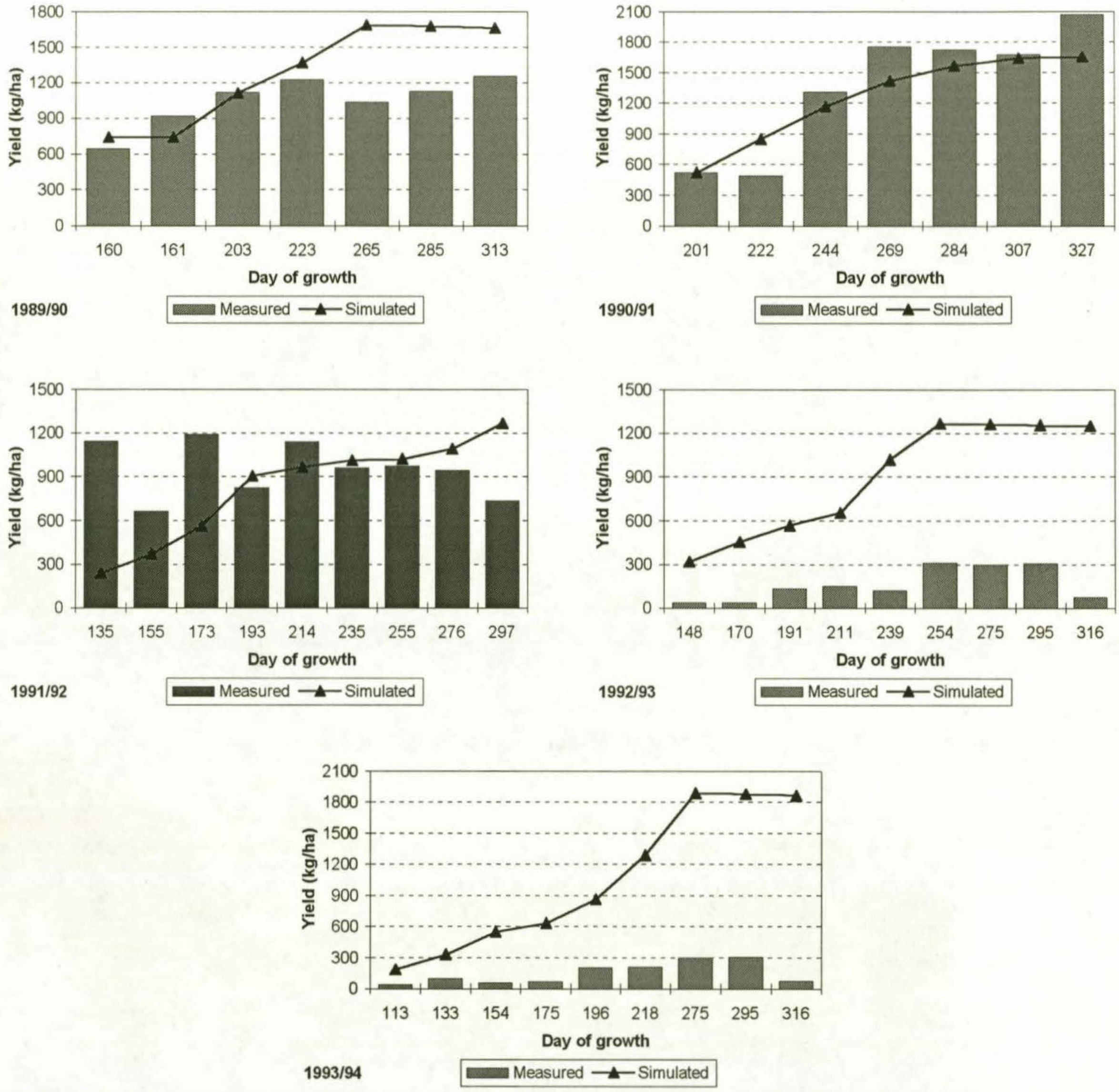

Figure 3.9d Measured and simulated yields for growing seasons 1989/90 through to 1993/94 at Franshoek.

The use of measured rainfall data from Smithfield that is 36 km away may explain many of the discrepancies.

Implementing the concepts of resilience particular for growth seasons 1992/93 and 1993/94 proved inadequate for this site. A change in specie composition as found here indicate a change in the overall resilience. Hence, the parameters found during the calibration may be inappropriate.

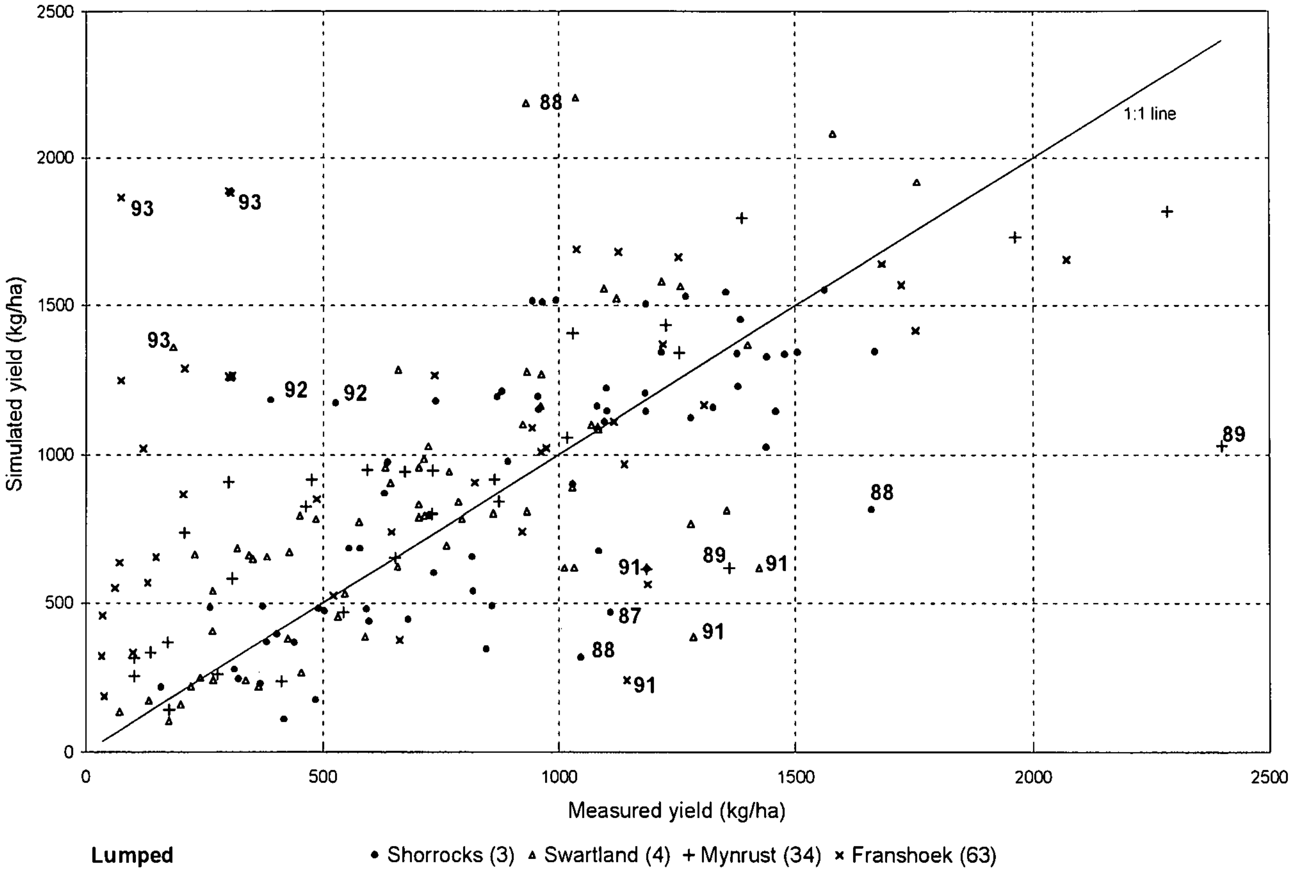

Figure 3.9e Scatter plot of measured yields versus simulated yields for monitoring sites at Glen (Shorrocks, Swartland), Mynrust and Franshoek.

Conclusion:

Lumping data on all sites (Shorrocks, Swartland, Mynrust and Franshoek) and seasons produced a mean absolute error of 313 kg ha^{-1} and a root mean square error of 448 kg ha^{-1}. The correlation coefficient (r^2) was 34 % (see Table 3.13). The moderate to poor performance found in some of the growing seasons may be ascribed to :

(1) The under estimation in biomass yields particularly in the early growth period which is due to the use of the expolinear crop growth function. This is the result of the parameters found during calibration, or,

(2) Outliers found in measured biomass yield particularly during the first part of the growing season. For example a growth rate of more than 45 kg ha^{-1} d^{-1} was measured for growing season 1991/92 on the Swartland ecotope (see Figure 3.9b), or,

(3) Sudden decrease in measured biomass during the active growth stage followed by a rapid increase (e.g. the 1989/90 growing season on the Shorrocks ecotope, see Figure 3.9a), the 1991/92 and 1993/94 growing seasons on the Swartland ecotope (see Figure 3.9b) and the 1991/92 growth season at Franshoek (see Figure 3.9d).

On the Shorrocks and Swartland ecotope, the model met the required criterion for accuracy for three of the eight seasons, respectively (see, Table 3.13). At Mynrust, the model satisfied the accuracy criterion for two out of five seasons. At Franshoek the criterion was not met for all seasons (see, Table 3.13).

Excluding data obtained at Franshoek from the analyses resulted in a correlation coefficient of nearly 50 %. The root mean square error was 360 kg ha^{-1}. Franshoek differs from the other three site in terms of specie composition.

By implementing the parameters found during calibration into the model and applying the model on benchmark ecotopes not suited (i.e. characterised mainly by *Eragrostis* species) will result in over estimating of biomass production during the growth season (e.g. Franshoek). Furthermore, the long-term production potential may also be overestimated.

b) Testing seasonal maximum yields :

Results obtained from testing final simulated yields against measured final yields are presented in Table 3.14 and Figure 3.10.

Table 3.14 Statistical results of model performance at sites distributed in the Dry Sandy Highveld Grassland. Number of observations (OBS), Mean absolute error (MAE, kg ha^{-1}), Root mean square error (RMSE, kg ha^{-1}), Systematic root mean square error (S.RMSE, kg ha^{-1}), Unsystematic root mean square error (U.RMSE, kg ha^{-1}), correlation (r^2), Willmot index of agreement (D), slope and intercept (kg ha^{-1}), and 80 % accuracy frequency.

Site name	OBS	MAE	RMSE	S.RMSE	U.RMSE	r^2	D	Slope	Intercept	80 %
Shorrocks	8	143	181.5	126.5	130.2	.83	.92	.77	167.8	88
Swartland	8	218	268.3	102.4	248.0	.64	.90	.78	267.3	50
Middelplaas	6	219	254.8	181.7	178.6	.82	.93	.68	340.7	50
Vacant	8	411	559.0	543.4	131.1	.83	.75	.35	619.6	50
Swaarkry	9	173	204.2	146.6	142.1	.93	.97	.85	257.1	44
Riviera	7	225	269.7	236.1	130.4	.93	.95	.67	393.3	57
Rama	8	149	202.4	140.8	145.4	.71	.88	.72	306.7	63
Voëlvlei	6	373	396.6	358.3	169.9	.52	.70	.34	741.9	17
Total	60	234	313.2	234.8	207.3	.76	.90	.61	410.7	53

The model produced accurate results at two monitoring sites viz.: Swaarkry and Riviera with a correlation coefficient $r^2 = 0.93$ and a root mean square error of 204 and 268 kg ha^{-1}, respectively. At Rama, Voëlvlei and on the Swartland ecotope the model obtained a correlation coefficient of less than 0.71. The Willmot index of agreement were more than 0.75 with the exception of Voëlvlei (D=0.7).

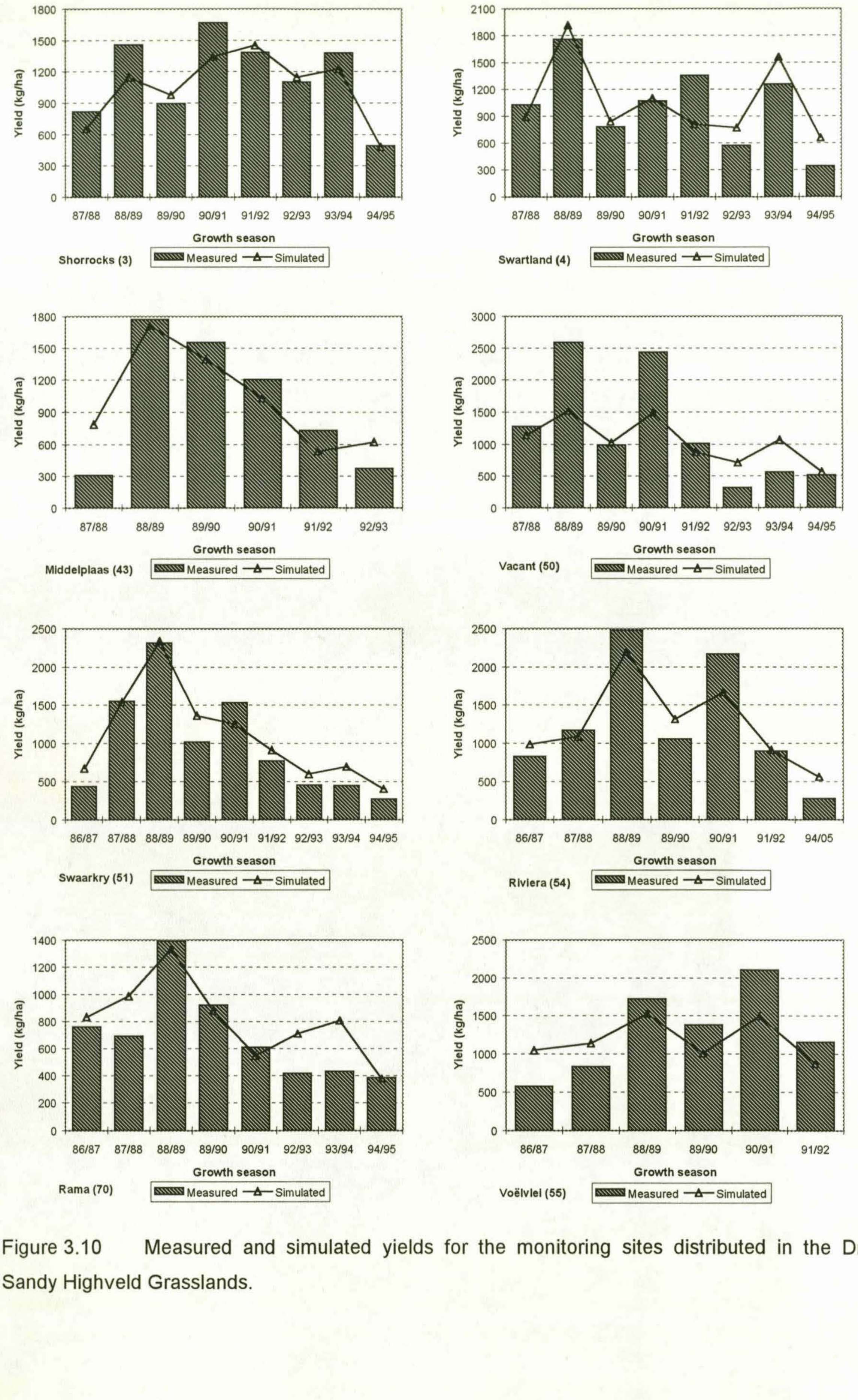

Figure 3.10 Measured and simulated yields for the monitoring sites distributed in the Dry Sandy Highveld Grasslands.

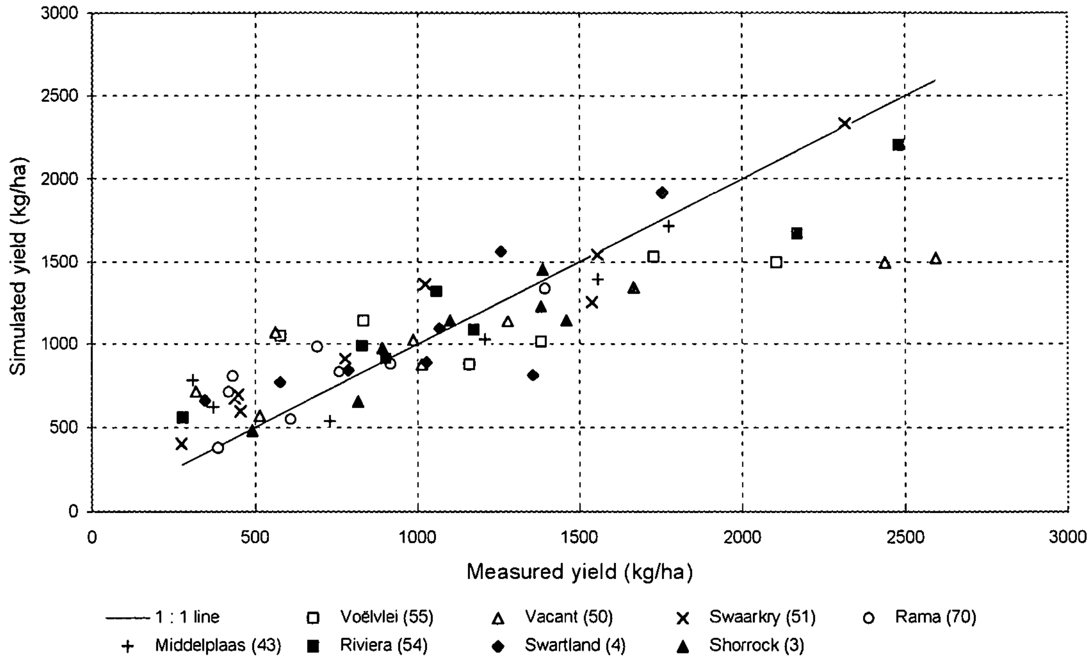

Figure 3.11 Scatter plot of measured and simulated final yields from monitoring sites.

All the data were lumped together and a mean absolute error of 234 kg ha^{-1} was produced with an correlation coefficient of 0.76 (see Table 3.14). When the data for Voëlvlei (55) and Vacant (50) was excluded from the statistical test then a overall mean absolute error of 185 kg ha^{-1}, root mean square error of 230 kg ha^{-1} and a correlation of 0.84 was produced.

Conclusion:

In terms of the accuracy criterion expected from the model, the model failed to predict final yields at two monitoring sites (see figure 3.11) viz. Voëlvlei (55) and Vacant (50). Both these sites form part of the Moist Cool Highveld Grassland (see Figure 3.1). The root mean square error produced at these two sites is higher than 300 kg ha^{-1}.

The model is accurate enough to be used for determining long-term yield potential for Themeda veld or Dry Sandy Highveld Grassland. Using the Putu15 model in locations outside the Dry Sandy Highveld Grassland may result in either the over or even under-estimation of its potential.

A serious limitation of this work was the use of estimated values for DUL, LL and soil rooting depths. Accurate determination of these parameters is necessary in future work. A shortcoming is using rainfall data not measured at the veld monitoring sites.

References

Acocks, J.P.H., 1988. Veldtypes of South Africa. Mem. Bot. Surv. S. Afr. NO. 58. Government Printer, Pretoria.

Fouché, J.H., 1992. Simulering van die produksie potensiaal van veld en die kwantifisering van droogte in die Sentrale Oranje-Vrystaat. Ph.D. proefskrif, UOVS, Bloemfontein.

ISCW-databank., 1997. Agriculture research council. Institute for Soil, Climate and Water. P/Bag X79, Pretoria.

Hensley, *per comm.* 1997. Institute for Soil Climate and Water. P.Bag X01. Glen 9360.

Johnson, I.R., and Thornley, J.H.M., 1983. Vegetative crop growth model incorporating leaf area expansion and senescence and applied to grass. *Plant, Cell and Environment.* 6: 721-729.

Le Houérou, H.N., Popov, G.F. and See, L., 1993. Agro-bioclimatic classification of Africa. Agrometeorology Series Working Paper. No 6. F-Ao Rome, Italy 228pp.

Le Roux, *per comm.* 1997. Department of soil science. University of Free State. P. Bag, 339, Bloemfontein. 9300.

Low, A.B. & Rebelo, A.G., 1996. Vegetation of South-Africa, Lesotho and Swaziland. Department of Environmental Affairs and Tourism. Pretoria.

Mostert, J.W.C., Roberts, B.R., Heslinga, C.F. & Coetzee, P.G.F., 1971. Veld management in the O.F.S. Region. Bulletin No. 391. Pretoria. The Government Printer.

Snyman, H.A., 1997a. The influence of range condition on the hydrological characteristic in a semi-arid rangeland. Proceedings XVIII International Grassland Congress, Canada. Vol.2 (23),1-2.

Snyman, H.A. 1997b. Dynamics and sustainable utilisation of rangeland in arid and semi-arid climate of southern Africa. Inaugural address. University of the Free State, Bloemfontein.

Snyman, H.A., and Fouché, H.J., 1991. Production and water-use efficiency of semi-arid grasslands of South-Africa affected by veld condition and rainfall. Water SA. Vol. 17 No 4.

Snyman, H.A., and Fouché, H.J., 1993. Estimating seasonal production of a semi-arid grassland based on veld condition, rainfall and evapotranspiration. *Afr. J. Range For Sci.* Vol. 10(1) 21-24.

Snyman, H.A., Opperman, D.P.J. and Van den Berg, J.A., 1980. Hydrological cycle and water use efficiency of veld in different successional stages. *Proc. Grassld. Soc. S. Afr.* 15 69-71.

Van der Westhuizen, H.C., 1994. Die kwantifisering van veldtoestand in die sentrale-Vrystaat. M.Sc.Agric.-verhandeling, UOVS, Bloemfontein.

Van Niekerk, J.P., Blair, A.R., De Waal, H.O. and Lategan, M., 1983. Aangeplante weiding: Die evaluasie van Cenchrusweiding vir beesvleisproduksie in die Sentrale Grasveld te Glen. Vorderingsveslag, Landbounavorsingsinstituut, Glen.

Walker, A., 1997. Model maker. One stop simulation and model analysis. Cherwell Scientific Publishing Limited. pp 306-310.

Wilmott, C.J., 1982. Some comments on the evaluation of model performance. *Bull. Am. Meteorol. Soc.* 63(11) 1309-1313.

CHAPTER 4

APPLICATION OF THE MODEL

"With several applications...Debate it at their leisure." W. Shakespeare

4.1 Introduction

In the subtropical regions of the earth, which are influenced by the semi-permanent high-pressure cells of the general circulation of the atmosphere, climates are characterised by a high degree of variability. The climate of southern Africa is no exception. Rainfall in particular is inconsistent in both time and spatial distribution (Tyson, 1986).

The *Themeda*-veld located between 25.24° to 27.30° latitude and -30.65° to -27.36° longitude form an integrated part of the semi-arid regions in southern Africa. Over this area, rainfall is highly seasonal and erratic. The correlation between number of days with rain and total annual rainfall is significant (Harrison, 1983).

The temperature spectrum of this region is flexible. Daily temperature is affected much less by local characteristics of topography than is minimum temperature, mainly due to atmospheric turbulence near the ground. Between 30 and 90 days of temperatures higher than 30°C are recorded per annum (Schulze, 1972).

4.2 Description of the problem

From observed results (see Snyman, 1997a), *Themeda*-veld is capable of producing nearly 3000 kg $ha^{-1}annum^{-1}$. This in turn could maintain 0.4 large stock unit per ha per annum (NRC, 1987). On the other hand this same veld could produce 300 kg ha^{-1} in poor rainy seasons (see Snyman, 1997a). High potential grazing is therefore associated with a high level of risk. Consequently planning decisions upon the mean annual yields at any one locality must be treated with caution. It is for this reason that medians and quartiles, as used by Jackson (1942) and Schulze (1984) and probabilities of the kind given by Zuchini and Adamson (1984) are useful.

The production potential of the *Themeda*-veld could be computed from measured annual harvest yields as did Snyman (1997a). The problem in assessing the overall potential of this veld lies in how to extrapolate results to other localities (e.g. Snyman and Fouché, 1993; Westhuizen, 1994; or Snyman, 1997a). Variation in not only rainfall and temperature exists but, also, variations in soils and specie composition are found. Deterministic models like Putu15; by taking these factors into account make extrapolation possible.

Precise and up to date information on the amount of fodder available for animal production is necessary for the implementation of the Drought Monitoring and Forecasting System (DMFS) in the Free State (see De Jager, Howard & Fouché, 1997). The Free State Department of Agriculture (FSDA) recognises the need to assess the impact and spatial distribution of drought. The Pasture Section of the FSDA has successfully implemented a Geographic Information System (GIS) to describe drought severity spatially. Lourens & de Jager (1997) have demonstrated the implementation of a GIS to determine drought severity for maize crops in the Free State.

The present study will demonstrate how Putu15 may be used in a GIS to describe the spatial distribution of the production potential of *Themeda*-veld. The production potential of a region is described here in terms of:

- the yield not expected to be exceeded 7% of the time (disaster drought conditions as defined by de Jager, Howard and Fouché, 1997);
- the long-term median yield; and
- the yield not expected to be exceeded 75% of the time (or upper wet condition yield).

The analyses assumed that variation in soils and meteorological factors determine year to year variation in veld production.

4.3 Method

Putu15 was used to compute veld growth on a daily basis. The daily weather data inputs required by the model are: maximum and minimum temperatures, rainfall and reference evaporation. Due to the scarcity of windspeed and radiation data, reference evaporation was computed from daily recorded sunshine hours (duration) and temperatures using the Priestley-Taylor equation compensated for high temperatures as described in Chapter 2.

4.3.1 Description of data:

Weather data

The South African Weather Bureau as well as the Agricultural Research Council (ARC) provided historic daily weather records. Within the long-term temperature, rainfall and sunshine duration records, several days, or even months of missing data occur which could account for up to 15% of the total record. This is illustrated in Table 4.1. During 1960 it was found for example that a total of 375 rainfall stations recorded rainfall for the whole year. Of these stations, only 368 measured rainfall during the month of July.

Table 4.1 Total number of weather stations recording temperatures, rainfall and sunshine duration in the Free State since 1960.

Year	Weather elements	Total	JUL	OCT	JAN	APR
1960	Temperature	24	23	23	21	21
	Rainfall	375	368	365	362	360
	Sunshine	11	9	10	11	11
1970	Temperature	18	16	17	18	18
	Rainfall	345	342	341	339	338
	Sunshine	13	11	12	13	13
1980	Temperature	40	33	34	35	37
	Rainfall	315	300	299	293	288
	Sunshine	33	26	27	28	30
1990	Temperature	59	57	58	57	54
	Rainfall	664	200	195	630	619
	Sunshine	41	38	37	36	35

Unfortunately not all stations recorded weather data over the entire period (see Table 4.2). All weather data irrespective of their duration were utilised.

Table 4.2 Duration percentage of total climatological stations found in the Free State since 1960.

Period (years)	Temperature	Rainfall	Sunshine
> 10	62	25	75
> 20	20	15	24
> 30	14	11	12

It was decided to create a GIS grid of 1308 points and apply the interpolation technique derived by Rautenbach (1996). Each grid square is approximately 10 km x 10 km. Each grid point was provided with interpolated daily weather data from the period 1960 to 1995/96. The methodology of interpolation will be discussed in sub-section 4.3.2.

Soil data:

Putu15 requires information on the soil depth and the soil water characteristic (see Chapter 2). The soil water characteristic is described in terms of the two-parameter exponential law, which requires values for the soil water content at -10 and -1500 kPa (i.e. $\theta_{10}, \theta_{1500}$). The value of θ_{10} and θ_{1500} were computed from the equations derived by Hutson (1984) and, or Bennie, Coetzee, Van Antwerpen, Van Rensburg and Burger (1988).

Furthermore, each grid-point was assigned a clay content and soil depth. The procedure followed when assigning a clay content and soil depth to each grid-point and locating weather stations is illustrated in Figure 4.1.

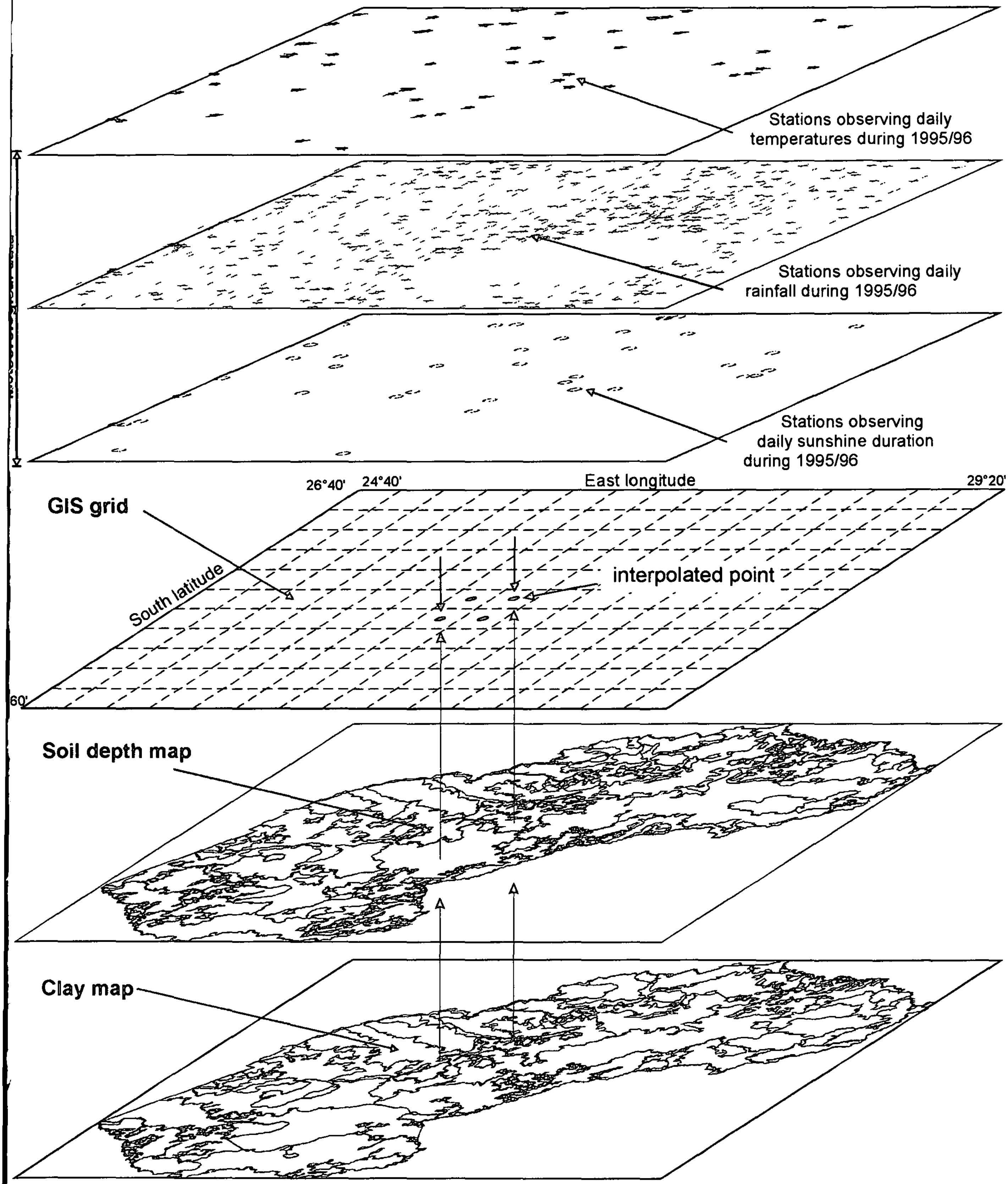

Figure 4.1 Point observation of depth and clay obtained from soil depth and clay content maps (Reproduced from Section of Information and Technology, Department of Agricultural, 1995).

4.3.2 Interpolation

a) Computation:

Interpolation is the process of estimating grid-point values from measured values. Values interpolated from the original point observations form a continuous, evenly spaced grid surface.

Daily weather data values for each grid-point were interpolated from the three nearest weather stations using the data-point concentration dependent weighting method of Rautenbach (1996). Briefly this method entails computing an interpolated value of a weather variable from the equation:

$$C_{ij} = \left[\frac{\sum_{k=1}^{3} W(r_{kij}) \bullet C_k}{\sum_{k=1}^{3} W(r_{kij})} \right] \quad [4.1]$$

Where, $W(r_{kij})$ is the weight function of the kth weather station data value C_k for $k = 1..3$ at grid-point (i,j). The distance between the position of any data-point value C_k and a grid-point value C_{ij} is denoted by r_{kij}. Subscripts (i,j) refer to the ith and jth grid-point in the x and y direction. The weight function is then given by:

$$W(r_{kij}) = b^{\left(\frac{r_{kij} - r_{(\min)ij}}{r_{(\min)ij}} \right)} \quad [4.2]$$

Where:

$r_{(\min)ij}$ is the distance from the grid-point ij to the nearest weather station

The radius of influence of a station's daily value decreases with an increase in the value of the parameter b and increases with an increase in the distance $r_{(\min)ij}$.

Rautenbach (1996) showed that the value of b could vary between 0.0003 and 0.2 depending on weather station concentration. Scrutiny of the weather station distribution in the Free State region revealed that weather stations are homogeneously spread over the province (particularly rainfall, see Figure 4.1) and hence a single value of b was adopted (0.0175) for the province.

Grid-points were allocated a long-term weather data series (i.e. from 1960/61 through to 1995/96). Putu15 was run for each of these grid-points. Each grid-point contained a cumulative distribution function (CDF) curve.

b) Plotting:

The results produced by the model for the grid-points were plotted by the Software package Vertical Mapper (VM). VM applied a smoothing routine (see Akima, 1978) to produce maps for the *Themeda*-veld in the Free State (see Figure 4.2). Of the three smoothing techniques available in VM, inverse distance weighting was selected because it is a type of moving average technique, which is usually applied, to highly variable data. Rectangular triangulation was considered but discarded because this method depicts discrete blocks and discontinuities, which are unrealistic in nature. Triangulation interpolation also produced unacceptable overshoot and distorted contours.

4.4 Results and discussion

Results of the simulations of production potential for the *Themeda*-veld are presented in Figure 4.2. A high level of spatial variability in biomass production is reflected in the maps of disaster drought yields, median yields and wet condition yields. The yield isolines generally follow the pattern of summer rainfall, diminishing with distance from East to West. The pronounced changes in predicted yield isolines in figure 4.2, show how markedly the production capacity of *Themeda*-veld is dominated by climatic variability. Alternatively, when viewed at a fixed location, there are massive changes in yield with risk level.

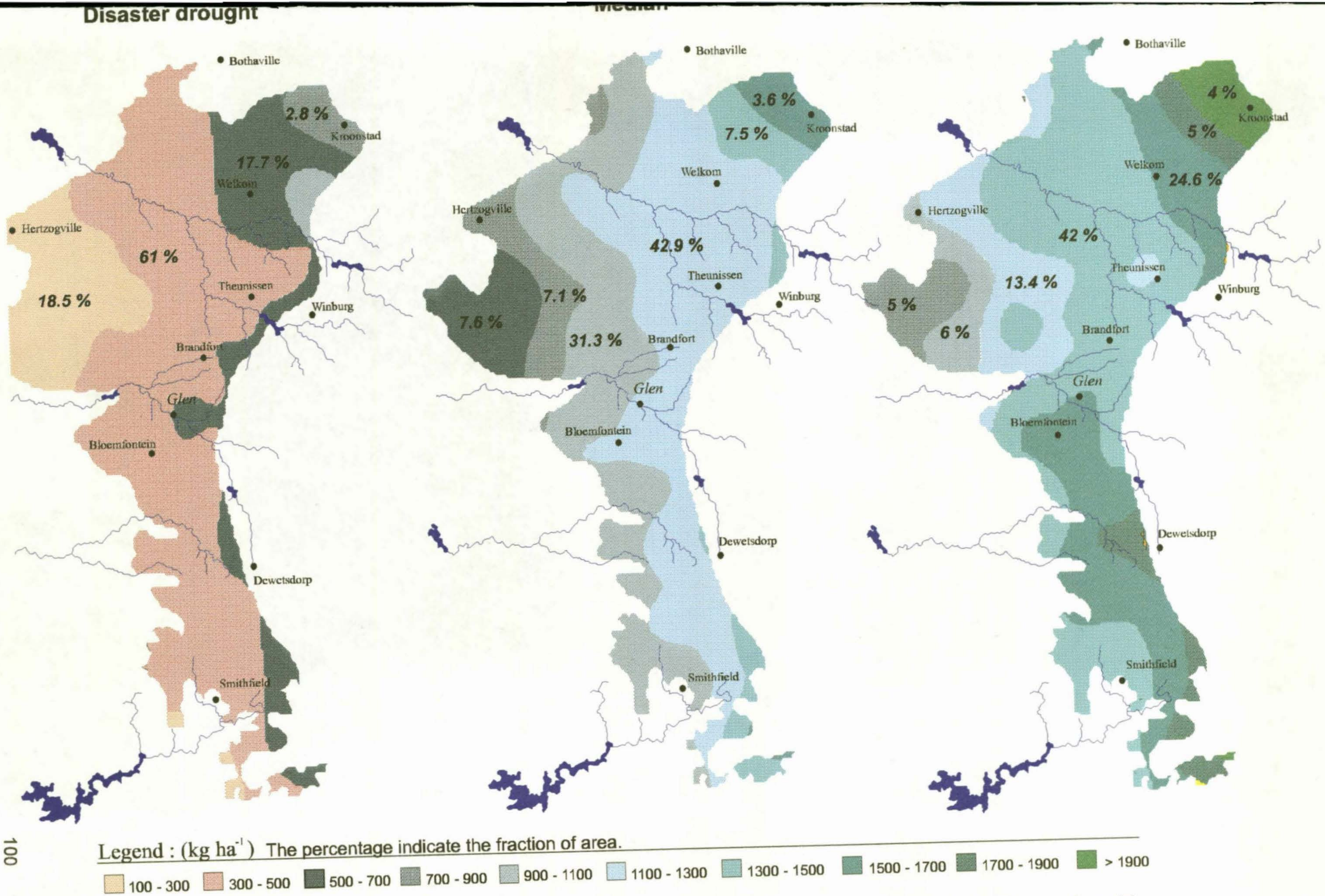

Figure 4.2. Spatial distribtuion of disaster drought, median and upper quartile (wet) yields in *Themeda*-veld.

In the event of disaster drought nearly 80% of the *Themeda*-veld will produce less than 500kgha^{-1}. In average seasons 75 % of *Themeda*-veld is capable of producing between 900 and 1300 kg ha^{-1}. Under most favourable rainfall conditions 80 % of the *Themeda*-veld could produce more than 1100 kg ha^{-1} annum^{-1}.

Implications:

The GIS and simulations provide a basis for examining the effect of climate on veld production. Results in Figure 4.2 quantify the climate risk faced by an individual farmer at any location.

Livestock farmers exposed to the risks illustrated in Fig 4.2 should take into account this wide variability in biomass yields when making management decisions. One example would be the manipulation of stock numbers depending upon what type of season is expected. Furthermore, the results provide scientifically dependable estimations of the overall carrying capacity of a specific farm.

The results presented in Figure 4.2, converted to cattle and sheep production could enable economic analyses, which also could be mapped in a GIS. This would provide a sound basis for production management planning at any location.

Planning as well as policy-making in relation to the livestock industry is facilitated by the analyses of climatic risk to the production capacity of *Themeda*-veld. Decisions on land use and provision of infrastructure could be more rationally based, as the potential value and viability of *Themeda*-veld could be mapped.

In considering land use, the massive geographical shifts in the yield isolines with risk level (see Figure 4.2), suggest that this general tendency may limit animal production to such a extent that greater adaptability in management decisions is required. That is, a range of agro-ecosystems (i.e. crop production like maize and, or wheat and cultivated pastures) need to be considered when farming in these areas. In some years, higher value crops would be appropriate, and in other years, a fodder or cultivated pasture may be suitable.

Putu15 was developed for the *Themeda*-veld. It was interesting to investigate how the model would perform over the entire Free State province. Hence, median yields for the entire Free State were computed and are presented in Figure 4.3. The results suggest that nearly 30 % of the total area in the Free State have the ability to produce more than 1700 kg ha^{-1} $annum^{-1}$. This high yielding area is found mainly in the Eastern Free State and in particular the Dry Clay Highveld grassland (see Figure 3.1). It needs to be emphasised that the high rainfall of the region changes the *Themeda*-veld to Highland sourveld. But Fig 4.3 illustrate what production may result was it possible to establish and maintain *Themeda*-veld in these other regions.

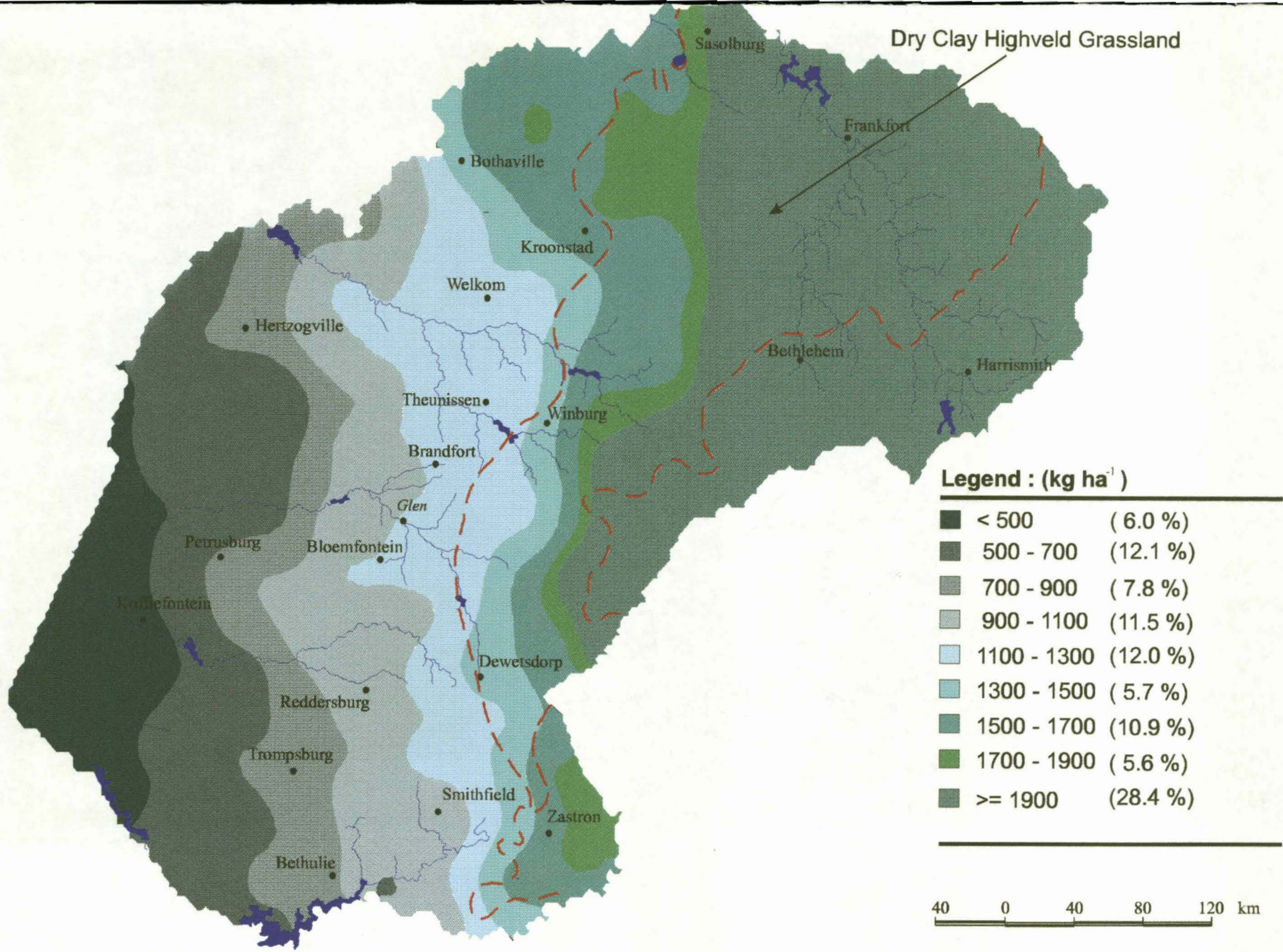

Figure 4.3 Long-term median production and % surface area for the Free state.

4.5 Model versatility.

Experimental data collected by Snyman and Fouché (1993) and later Snyman (1997a) were used to test how the model might be adapted to moderate veld conditions. This veld consists mainly of *Eragrostis lehmanniana* and *Eragrostis chloromelas* species. *Themeda triandra* are found in small quantities (Snyman and Fouché, 1993).

Using the same approaches as in Chapter 3, subsection 3.3.1, the magnitude of parameters Cm, k, Lo and $Const$ were found to be 1.86, 0.76, 0.6 and 35, respectively. These values were then implemented into Putu15. The results of simulation versus measured biomass are given in Appendix C (Table 4) and are presented in Figure 4.4.

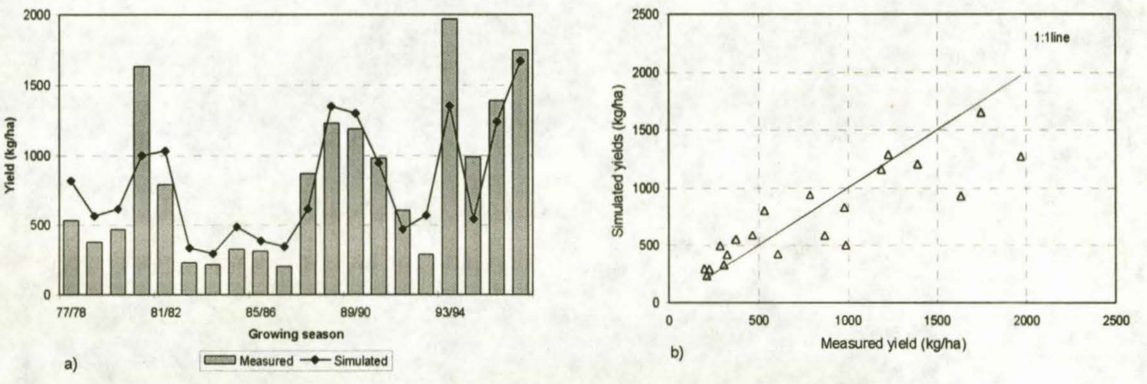

Figure 4.4 Measured and simulated biomass production (a) obtained by parameterisation of Putu15 for a moderate veld condition. Scatter plot of measured versus simulated yield (b).

The model produced an acceptable root mean square error of 270 kg ha^{-1}. A mean absolute error of 214 kg ha^{-1} and a correlation coefficient (r^2) of 77 % was found. The model estimated the variation in total biomass yield well with the exception of the 1980/81 and 1993/94 seasons, which were wet seasons. Implementing these four parameters (Cm, k, Lo and $Const$) in Putu15, makes it possible to examine the effects of veld condition on potential production and the associated risks.

Snyman and Fouché (1991) reported significant increases ($P<0.01$) in run-off due to changes in these veld conditions. Development of appropriate methodologies to consider these changes is important for future refinements.

4.6 Possibilities for improvements

It is important to be aware of the limitations of the GIS system.

Rautenbach (1996) quantified the criteria for the selection of stations to interpolate daily meteorological data from observation station to a grid-point. However, translating the criteria into an algorithm requires evaluation of the parameter b in Eq 4.2. Furthermore, interpolation results need to be compared with actual weather stations data.

Future modifications to this GIS should bear in mind:

Rainfall

The abundance and even distribution of rainfall stations in this study appear to provide sufficient data for the interpolation technique. In depth study is, however, needed as to what extent interpolated data compare with measured data.

Temperatures

Temperature is strongly affected by height above sea level as well as local topography. The western part of the Free State (Bloemfontein and further West) is characterised by a flat landscape. It is fair to assume that temperatures in this region could be extrapolated over large distances with a moderate level of accuracy. In the Eastern part of the Free State (Winburg and further East), topography plays an important role. Rapid temperature changes (in the Valleys and on the South side of the escarpments) can take place. Also, the few climatological stations actually monitoring temperature are a source of concern. Altitude data could be used as an additional component for interpolating temperatures.

Sunshine, solar irradiance

Recently, Lourens, Van Sandwyk, De Jager and Van den Berg (1995) have developed algorithms for accurately converting METEOSAT imagery values of cloud cover into daily solar irradiance values. The inclusion of such data into the GIS could enhance the accuracy of the output and deserves attention in future projects.

The CDF were computed from the model output. Use of interpolated weather data of varying length to compute the biomass growth and the CDF could cause problems. Future research on how the maps produced using fewer weather stations all with an equal length of data series will reveal the magnitude of such errors.

References

Akima, H., 1978. A method for Bivariate Interpolation and Smooth Surface Fitting for Irregularly Data Points. ACM Transactions on Mathematical Software, Vol. 4 (2) 148-159.

Bennie, A.T.P., Coetzee, M.J., Van Antwerpen, R., Van Rensburg, L.D. & Burger, R.DU T., 1988 *'n Waterbalansmodel vir besproeiing gebaseer op profielwatervoorsieningstempo en gewaswaterbehoeftes.* Report 144/1/88 by Department of Soil Science, University of the Orange Free State, to the WRC.

De Jager, J.M., Howard, M.D. and Fouché, H.J., 1997. Computing drought severity and forecasting its future impact on grazing in a GIS. In : Hazards and disaster : A series of definitive works. Volume on drought. Edited by Donald Wilhite of the International Drought Mitigation Centre, Univ. Nebraska, Lincoln (1997) Routledge Publishers.

Department of Agricultural and Environmental Affairs of the Free State (1995). Soil and clay maps digitised from the landtype data. By Section of Information and Technology. P/Bag X01, Glen. 9301.

Harrison, M.S.J., 1983. Rain day frequency and mean daily rainfall intensity as determinants of total rainfall over the eastern Orange Free state, *Journal of Climatology*, 3 : 35-45.

Hutson, J.L. 1984: Estimation of hydrological properties of South African soils. University of Natal, Pietermaritzburg, Department of soil Science and Agrometeorology. Unpublished Ph.D. Dissertation.

Jackson, S.P., 1942. Weather on the coasts of South-Africa, Meteorological Services of the Royal Navy and South African air Force, Parts 1-5, 372pp.

Lourens, U.W. and De Jager, J.M. 1997. A computerized Crop-specific Drought Monitoring System: Design Concepts and Initial Testing. Agricultural Systems, Vol. 53. Pp 303-315

Lourens, U.W., Van Sandwyk, C.M., De Jager, J.M. and Van den Berg, J. 1995. Accuracy of an emperical model for estimating daily irradiance in South Africa from METEOSAT imagery. *Agric. For. Meteorology.* 74, (1-2) : 75-86.

Rautenbach, C.J., 1996. Derivation of a data-point concentration dependent weighting function for the interpolation of rainfall grid-point fields. S.A. Journal for Natural Science and Technology 15,4, 168-171.

Schulze, B.R., 1972. South Africa, in Climates of Africa, Ed. Griffiths, J.F.World Survey of Climatology, Vol. 10, Elsevier, Amsterdam, 501-586.

Schulze, B.R., 1984. Climate of South Africa : Part 8: General Survey, WB28, South African Weather Bureau, 5th Edition, 330pp.

Snyman, H.A., 1997a. The influence of range condition on the hydrological characteristic in a semi-arid rangeland. Proceedings XVIII Int. Grassland Congress, Canada. Vol 2 (23),1-2.

Snyman, H.A., 1997b. Dynamics and sustainable utilization of rangeland in arid and semi-arid climate of southern Africa. Inaugural address. University of the Free State, Bloemfontein.

Snyman, H.A. and Fouché, H.J., 1993. Estimating seasonal herbage production of a semi-arid grassland based on veld condition, rainfall and evapotranspiration. *Afr. J. Range. For. Sci* 10(1): 21-24

Snyman, H.A. and Fouché, H.J., 1991. Production and water-use efficiency of semi-arid grasslands of South-Africa as affected by veld condition and rainfall. *Water S.A.* 17 (4): 263-268.

Tyson, P.D., 1986. Climatic change and variability in southern Africa. Oxford University Press. Cape Town. 1986.

Van der Westhuizen, H.C., 1994. Die kwantifisering van veldtoestand in die sentrale-Vrystaat. M.Sc.Agric.-verhandeling, UOVS, Bloemfontein.

Zuchini, W. and Adamson,P.T., 1984. The occurrence and severity of droughts in South Africa, WRC Report 91/1/84, Water Research Commission, Pretoria, 198pp.

CHAPTER 5

SUMMARY AND CONCLUSION

Models are a convenient tool to aggregate the multiple interactions between soil-plant-atmosphere. Incorporating these interactions into a model enables systematic analysis and testing of natural phenomena. The ability to interpret physiological processes in mathematical terms has led to a proliferation of computer models being developed and applied in agriculture.

In the semi-arid terrain's of South Africa, grassland production is affected strongly by the high variation in seasonal rainfall. These variations are accounted for in the Putu15 model.

The objectives of the present study were to :

1. Describe the algorithms and theory of Putu15;
2. Calibrate and validate the model;
3. Describe the spatial distribution in production potential of *Themeda*-veld and underlying climate risks using a Geographical Information System (GIS); and
4. Indicate the versatility of Putu15 to compute growth of a moderate veld.

Aspects of the fundamental principles on which the model is based, are highlighted and discussed in detail (Objective 1, Chapter 2). In its development, efforts from various scientists from all agricultural disciplines are combined. A literature survey was included as this facilitated model description. The source of the equations utilised was given, thereby meeting the needs of scientists interested in developing the model further. Where possible, changes from earlier versions of Putu (Putu11,12 and 14) have been flagged and include:

1. In Putu15, the expolinear crop growth function has been introduced. In this theory, the concept of lost time expressed as a function of final yields obtained from the previous season has improved simulation capability.

2. An innovation was the use of layered soil water balance routines specifically applied to grasslands. The concepts of evaporation coefficient theory have also been implemented into the model.

3. A feature of this model is the application of a function that shortens the active growth period should plant water stress occur. This numerical function plays a key role in the final yields obtained, especially in the arid regions for which this model has been developed.

In Chapter 3, specific attention has been given to meet objective 2. The method used to calibrate and validate the model were outlined. The model was first calibrated on 20 years of data. The model was then validated at ten different locations found in the Dry Sandy Highveld Grassland (see Low and Rebello, 1996) known as the Dry *Cymbopogon-Themeda* veld (Veldtype nr 50, see Acocks, 1988).

A thorough test of the water balance routines found in the model were conducted on two ecotopes at Glen (viz. Shorrocks and Swartland). Results indicate an over-estimation of the soil water content. The model achieved an overall root mean square error ($RMSE$) of 11.4 mm and 14.5 mm and a correlation (r^2) of 0.54 and 0.43 on the Shorrocks and Swartland ecotopes, respectively. Possibilities for future improvements have been highlighted.

Measured and simulated biomass yields were tested within seasons and over numerous seasons. Results from within season tests indicate a moderate fit with an overall correlation coefficient (r^2) of 45 % and higher for veld ecotopes Shorrocks, Swartland and Mynrust. Overall Willmot index of agreement (D) were 79% and higher. On Shorrocks, Swartland and Mynrust ecotopes, the overall root mean square error ($RMSE$) obtained was 315 kg ha^{-1} and higher. This may raise some concern when applying the model to estimate the amount of feed available for utilisation by animals at a given time. Shortcomings in the model were discussed. By lumping all the data for ecotopes Shorrocks, Swartland and Mynrust, a correlation coefficient of nearly 50 % was obtained and the $RMSE$ was 360 kg ha^{-1}.

Tests of model accuracy to compute seasonal maximum yields across seasons and environments, produced accurate results. For *Themeda*-veld an overall r^2 of 0.84 with a root mean square error of 230 kg ha^{-1} at eight locations were obtained.

The methodology used to determine the overall production potential of *Themeda*-veld and underlying climate risks were discussed in Chapter 4 (Objective 3). Due to the high variability in seasonal rainfall, the production potential of *Themeda*-veld was expressed in terms of :

- the yield not expected to be exceeded 7% of the time (disaster drought conditions as defined by de Jager, Howard and Fouché, 1997);
- the long-term median yield; and
- the yield not expected to be exceeded 75% of the time (or upper wet condition yield).

In the event of disaster drought, nearly 80 % of the *Themeda*-veld produces less than 500 kg ha^{-1}. In the long-term 75 % of *Themeda*-veld is capable of producing between 900 and 1300 kg ha^{-1}. Under most favourable conditions, 80 % of the *Themeda*-veld could produce more than 1100 kg ha^{-1} $annum^{-1}$.

The versatility of Putu15 was illustrated in Chapter 4 (Objective 4). Putu15 was adapted to simulate growth of a veld characterised with *Eragrostis* species. Four parameters were adjusted, which indicated model flexibility and capability for computing growth of other species. This was achieved through:

- keeping the number of input parameters required by the model to a minimum;
- using conservative parameters that require only small adjustment for different environments; and
- not including parameters difficult to derive from field studies.

Results from measured versus simulated yields on 20 years of data indicated a correlation (r^2) of 77%. The root mean square error was 270 kg ha^{-1}. The mean absolute error was 214 kg ha^{-1}. These results obtained for a veld characterised with *Eragrostis* species, testify to a good fit.

This approach reduces unintentional calibration of model parameter values, and makes simulations more stable when used in a wide range of environmental conditions.

Climatic variability makes sheep and beef cattle farming from dry-land conditions risky in the *Themeda*-veld. Rainfall variability dominates these production systems and is so great that the concept of an average year is meaningless. Climatic risk can only be adequately quantified by linking simulation models to long-term weather data. To consider the spatial variability in risk, models could be incorporated in a GIS by coupling soil attributes to weather data.

CONCLUSIONS

The work from this thesis provides a simplified and versatile grassland modelling capability applied to the semi-arid regions of South Africa. This was achieved through thorough testing of the water balance and yield equations (expolinear crop growth function). Since natural veld is one of the most important natural resources in these areas, the model will enable extension officers to make sound recommendations and management decisions regarding the expected carrying capacity of farms.

In terms of the criterion for model accuracy on the water balance equations, the systematic root mean square error of less than 60% of the root mean square error was met on both ecotopes under study (i.e. Shorrocks and Swartland). The overall Willmot index of agreement (D) was also achieved. The criterion for the correlation coefficient (r^2) was not satisfied for all seasons for both ecotopes.

On final seasonal yields, the model satisfied the criterion at all sites found in the Dry Sandy Highveld Grassland (see Low and Rebello, 1996) known as the Dry *Cymbopogon-Themeda* veld (Veldtype No 50, see Acocks, 1988).

Testing accumulative biomass yields within seasons, the model met the required criterion for accuracy, for three of the eight seasons on the Shorrocks and Swartland ecotope. At Mynrust, the model satisfied the accuracy criterion for two out of five seasons. The criterion was not met on all seasons at Franshoek.

Conclusive evidence showed that using parameters found in the expolinear crop growth function for *Themeda*-veld and applying this model on benchmark ecotopes not suited (i.e. characterised mainly by *Eragrostis* species) will result in overestimating of biomass production during the growth season (e.g. Franshoek) and thus the overestimation of the long-term production potential.

By simple calibration procedures (adjusting four parameters) it is possible to accurately compute growth of a moderate veld i.e. where *Eragrostis*-species are the dominant key specie in the sward.

Putu15 will speed up the development and application of simulation models in a GIS which accounts for variation in not only climate and soils, but also for species composition. Future model improvement should concentrate on:

1. improving simulation of transformation of veld condition from one state to another, and
2. including rainfall intensity data into the model.

Recent advances in long-range rainfall forecasting allow a pre-season evaluation of likely growing conditions. By using Putu15, improved yield outcomes and drought severity maps could be generated for the Free State especially in the *Themeda*-veld.

The Putu15 model offers great potential to investigate the effects of climatic variability and anticipated climatic change.

APPENDIX A.1 : SOURCE CODE FOR Putu15

SUB : INITIALISE VARIABLES AND CALL SUB'S

```
// Include header files
#include <stdio.h>
#include <stdlib.h>
#include <dos.h>
#include <fcntl.h>
#include <math.h>
#include <graph.h>

// Set up structure for weather data
typedef struct CLIMATE
{
        int DOG;
        float Rad;
        float Tmax;
        float Tmin;
        float Rain;
        float Eo;
} CLIMATE;
 CLIMATE Data[366];

// Define and initialise routines
int Initialise(float DISFv[], float *HUCFULC, float CRITthmlperd[],float W[],float DZRT[],float
        SILTFRAC[], float CLAYFRAC[],float BULKDENS[],float SWUL[], float DUL[], float V01[],
float
        VCON[],float b[],float V15[], float V16[],float W16[], float PAW[], float TPAW,float *TDZRT,
        float KSPO[], float LL[],float ClayVal, float SiltVal);
int TempRoutine(float *T, float TTmx, float BO, float *DELHU, int DOG);
int EnvironmentallVar(int DOG, float T, float T0, float *Ffac, float Fv, float *HU, float DELHU, float
        *GAMMA, float GAMMA20, float MinHu, float DevidHu, float dT, float *TIMEthml, float V01[],
         float V[], float LAIg, float LAIst, float Kvo, float *PTRANS, float Kso, float *SOILVAP);
int RootDevelpment(int DOG, int Stge,float TIMEthml, float HUCFULC, float ROOTZO,float *ZEFF,
        float AP, float ZEFFO,float RPROP[], float DZRT[], float *NOLAY);
int SoilwaterPot(float PSIS[],float b[],float V[], float V15[]);
int SoilRootCond(float KSPO[], float RPROP[], float RM, float V[],float V16[], float V01[], float PSIS[],
        float PTRANS,float *Fv, float TPAW,float W[], float SOILVAP, float W16[], float DZRT[], float
        PAW[], float DUL[],float LL[], float TDZRT, float NOLAY, int DOG);
int PsicLeaf(int DOG, float *Psic);
```

```
int ReWetSoil(int DOG, float SWUL[], float V[], float DZRT[], float DUL[],float VCON[],
        float W[], float PSIS[],float P0[],float b[],float V15[]);
int Development(float *WWeight, float CM, float k, float TIMEthml, float Tb,float *W1,float *W2,float
        *W3,float *W4,float *W5,float *WeightM,float LAR, float Lamda,float GAMMA, float
        PercTrash, float HU,float Tpgrowth,float *dLAI, float *LAI, float DELHU, float Ffac, float
        *LAI1, float *LAI2,float *LAI3,float *LAI4,float *LAI5,float *LAIg, float *LAIst, float *WM,
        int DOG);
int SeasMeans(int DOG, float Tpgrowtho, float *Tpgrowth, float Fv,float DELHU);
float far VinitRead(int *Year, float VINIT[], float V[], float W[],float DZRT[], float *WM);
float far VinitWrite(int *Year, float V[],  float WM);
int MID(char str1[],char str2[],int pl,int aan);
float far VinitWrite(int *Year, float V[],  float WM);
int ReadWeatherFile(int *Year);                    /* Function to read weather data from disk  */


// Define and initialise functions
float FuNEXPOLIN (float CM, float k, float TIMEthml, float Tb, float LAR);
float FuNINITINTCP (float k, float Lo);
float FuNLostTIME (float RM1, float Fo);
float FuNTION2 (float PSI, float Psic);
float FuNTION6 (float T, float T0);
float FuNTION9 (float LAI, float CONSTfig);
float FuNTION11 (float LAI);
float FuNTION15 (float P0L, float ML, float VL, float V15L);
float FuNTION16 (float V15L, float PL, float P0L, float ML);
float FuNTION18 (float V, float V16, float V01);
float FuNTION19 (float TIMEthml, float HUCFULC, float ROOTZO);
float FuNTION21 (float V1DEF);
float FuNTION22 (int DOG);
float FuNTION24 (float Kvo, float FI);


// Entry level for program
int main()
        {

         int StartYr, n;
         float MAE,R2,slopeYX,intercept;
         float GAMMA20,BO,Tpgrowtho,CM,k,LAR,Lo,MinHu,DevidHu;
         float CUTFS[5][20];
```

```
_clearscreen(_GWINDOW);
StartYr =77;

int DOG;
// Soil proporties
float DZRT[10] = {0,0.1F,0.3F,0.3F,0.3F,0.3F,0.3F,0.3F,0.3F,0.3F};
float VINIT[10] = {0,238,324,324,324,149,149,149,149,149};
float V15[10] = {0,196,196,196,196,196,196,196,196,196,};
float CLAYFRAC[10] = {0,0.1F,0.1F,0.17F,0.18F,0.18F,0.18F,0.2F,0.2F,0.2F};
float SILTFRAC[10] = {0,0.02F,0.02F,0.02F,0.02F,0.02F,0.02F,0.02F,0.02F,0.02F};
float BULKDENS[10] = 0,1.65F,1.65F,1.65F,1.65F,1.65F,1.65F,1.65F,1.65F,1.65F};
float V[10] = {0,0,0,0,0,0,0,0,0,0};
float W[10] = {0,0,0,0,0,0,0,0,0,0};
float DUL[10],LL[10];
float ROOTZO = 2;
float ZEFFO = 1;
float ClayVal = 55;
float SiltVal = 20;

// Crop factors file
float DISFv[10] = {0,0,0,0.3F,0.35F,0.55F,1.0F,0.9F,0.45F,0.2F};
float CRITthmlperd[10] = {0,0,2150,2150,2150,2150,2150,2150,2150,2150};

float Kvo = 1.1F;
float Kso = 1.0F;
float TTmx = 30.0F;
float HUCFULC;

// Parameters
float TPAW = 0;
float TDZRT;
float P0[10] = {0,1500,1500,1500,1500,1500,1500,1500,1500,1500};


// Set initially to zero
float SWUL[10] = {0,0,0,0,0,0,0,0,0,0};
float V01[10] = {0,0,0,0,0,0,0,0,0,0};
float PSIS[10] = {0,0,0,0,0,0,0,0,0,0};
float VCON[10] = {0,0,0,0,0,0,0,0,0,0};
```

```
float b[10] = {0,0,0,0,0,0,0,0,0,0};
float V16[10] = {0,0,0,0,0,0,0,0,0,0};
float W16[10] = {0,0,0,0,0,0,0,0,0,0};
float PAW[10] = {0,0,0,0,0,0,0,0,0,0};
float KSPO[10] = {0,0,0,0,0,0,0,0,0,0};
float T0 = 20;                  /* the optimal temperature for crop growth */
float AP = 0.021F;              /* % OF TOTAL ROOTS FOUND BELOW 0.97 */

// Grass parameters
float PercTrash = .05F, Lamda = 2;
float WM, BO;
float RM1;
float dT = 0;
float Fo, Tb1,A,Tb,HU;
int Stge;

// Temperature declaration routine parameters
float T, DELHU;
float TIMEthml;

// Environmental declarations
float Ffac, Fv, GAMMA, PTRANS, SOILVAP;

// Root Development declarations
float RM = 15;
float RPROP[10];
float ZEFF;
float NOLAY;

// Development Parameters
float WWeight;
float WeightM;
float Tpgrowth;
float dLAI;
float LAI, LAI1,LAI2, LAI3,LAI4,LAI5, LAIg, LAIst;
float W1,W2,W3,W4,W5;

// Now read the parameters
ClayVal = 55;
SiltVal = 20;
```

```
    BO = 10;
    LAR= 0.002;
    CM = 2.49;
    k = 0.9;
    GAMMA20 = 0.0229;
    Lo = 0.0722;
   Tpgrowtho = 2165;
   MinHu = 90;
   DevidHu = 1150;

   // Vinit File
   VinitRead(&StartYr,VINIT,V,W,DZRT,&WM);

   // Initialise variasbles for grass crop
   RM1 = LAR * CM * k;
   Fo = FuNINITINTCP(k, Lo);
   Tb1 = FuNLostTIME(RM1, Fo);
   A = 40 * (1237 - WM) / 1250;
   Tb = Tb1 * (1 + A / 100);
   LAI = Lo, HU = 0, LAI1 = Lo, LAI2 = 0, LAI3 = 0, LAI4 = 0;
   LAIg = 0, LAIst = 0;

   // Reset the Variables at beginning of season
   WM = 0, Tpgrowth = Tpgrowtho, TIMEthml = 0;
   W1 = 0, W2 = 0, W3 = 0, W4 = 0, W5 =0, Stge = 2;

   ReadWeatherFile(&StartYr);          /* Read the weather file data (BINARY File)  */

   Initialise(DISFv,&HUCFULC,CRITthmlperd,W,DZRT,SILTFRAC,CLAYFRAC,BULKDENS,
   V0,DUL,V01,VCON,M,V15,V16,W16,PAW,TPAW,&TDZRT,KSPO,LL, ClayVal, SiltVal);

   for(DOG = 1; DOG <= 365; DOG++)
        {
        TempRoutine(&T, TTmx, BO, &DELHU, DOG);
        EnvironmentallVar(DOG, T, T0, &Ffac, Fv, &HU, DELHU, &GAMMA, GAMMA20,
        MinHu, DevidHu, dT, &TIMEthml, V01,V,LAIg,LAIst,Kvo,&PTRANS, Kso, SOILVAP);
        RootDevelpment(DOG, Stge,TIMEthml, HUCFULC,ROOTZO,&ZEFF,AP,
        ZEFFO,RPROP, DZRT,&NOLAY);
        SoilwaterPot(PSIS,M,V,V15);
        SoilRootCond(KSPO, RPROP, RM, V, V16, V01, PSIS, PTRANS, &Fv, PAW, W,
```

```
                    SOILVAP, W16, DZRT, PAW, DUL, LL, TDZRT, NOLAY, DOG);
                    ReWetSoil(DOG, V0, V, DZRT, DUL, VCON, W, PSIS, P0, M, V15);
                    Development(&WWeight,CM,k,TIMEthml,Tb,&W1,&W2,&W3,&W4,&W5,
                    &WeightM,LAR,Lamda,GAMMA,PercTrash,HU,Tpgrowth,&dLAI,&LAI,
                    DELHU,Ffac,&LAI1,&LAI2,&LAI3,&LAI4,&LAI5,&LAIg,&LAIst,&WM,DOG);
                    SeasMeans(DOG, Tpgrowtho, &Tpgrowth, Fv, DELHU);
                    }
            VinitWrite(&StartYr,V,WM);
return 0;
        }


                                // INITIALISE THE VARAIABLES

int Initialise(float DISFv[], float *HUCFULC, float CRITthmlperd[],float W[],float DZRT[],float
        SILTFRAC[], float CLAYFRAC[],float BULKDENS[],float SWUL[], float DUL[], float V01[],
float
        VCON[],float b[],float V15[], float V16[],float W16[], float PAW[], float TPAW,float *TDZRT,
        float KSPO[], float LL[],float ClayVal, float SiltVal);

 {

        int NFULCAN = 0;
        int count, I;
         float AWLIM, KSPOO;
         float ITAW = 0;
         float PORO[10] = {0,0,0,0,0,0,0,0,0,0};
         float W01[10] = {0,0,0,0,0,0,0,0,0,0};
         float W15[10] = {0,0,0,0,0,0,0,0,0,0};
         float IAW[10] = {0,0,0,0,0,0,0,0,0,0};

         float SWULpress[10], PSIS1500[10],V1500[10];

        *TDZRT = 0;
        *HUCFULC = 0;
        // Crop factors file
        for (count = 3; count <= 10; count++)
        {
         if ( (DISFv[count] <= DISFv[count - 1]) && (DISFv[count] > 0))
                    {
```

```
                        break;
                        }
        }
        NFULCAN = (count-1);

        for (count = 1; count <= NFULCAN; count++)
         {
                *HUCFULC += CRITthmlperd[count];
         }

        // Parameter routine

         for(I = 1; I<=9; I++)
         {

          CLAYFRAC[I] = ClayVal;
          SILTFRAC[I] = SiltVal;
          BULKDENS[I] = 1.4F;
          SWULpress[I] = -10;
          PSIS1500[I] = -1500;


          if(CLAYFRAC[I] > 27)
                {
                 V01[I] = (.0558 + .00365 * CLAYFRAC[I] + .00554 * SILTFRAC[I] + .0303 *
                        BULKDENS[I]) * 1000;
                 V1500[I] = (.0602 + .00322 * CLAYFRAC[I] + .00308 * SILTFRAC[I] - .026 *
                        BULKDENS[I]) * 1000;
                }
          else
                {
                 V01[I] = (.0345 * pow((CLAYFRAC[I] + SILTFRAC[I]), .611)) * 1000;
                 V1500[I] = (.00385 * (CLAYFRAC[I] + SILTFRAC[I]) + .013) * 1000;
                }
          b[I] = log(-10 / PSIS1500[I]) / (log(V01[I] / V1500[I]));
          DUL[I] = V1500[I] * pow((-30 / PSIS1500[I]),(1 / b[I]));
          PORO[I] = (1 - BULKDENS[I] / 2.65) * 1000;
          VCON[I] = (PORO[I] - DUL[I]) / PORO[I];

          SWUL[I] = V1500[I] * pow((SWULpress[I] / -1500),(1 / b[I]));
```

```
            V01[I] = V1500[I] * pow((-10 / -1500),(1 / b[I]));
            V15[I] = V1500[I] * pow((-1500 / -1500), (1 / b[I]));
            V16[I] = V1500[I] * pow((-1600 / -1500), (1 / b[I]));
            LL[I] = V1500[I];

            W01[I] = V01[I] * DZRT[I];
            W15[I] = V15[I] * DZRT[I];
            W16[I] = V16[I] * DZRT[I];
            IAW[I] = W[I] - W16[I];
            ITAW = ITAW + IAW[I];
            PAW[I] = DUL[I] * DZRT[I] - W15[I];
            TPAW = TPAW + PAW[I];
            *TDZRT = *TDZRT + DZRT[I];
            if( *TDZRT <= 1)
                {
                    /* TPAW1 = TPAW1 + PAW[I];  */
                }
           AWLIM = (1 - .1 / DZRT[1]) * (W01[1] - W15[1]);
           if( AWLIM < .2 * (W01[1] - W15[1]))
                {
                 AWLIM = .2 * (W01[1] - W15[1]);
                }
        }


        KSPOO = -.05;      /* MAX CONDUCTANCE OF ROOT ZONE  mm/(d kPa m3)  */
        for(I=1; I<=9; I++)
        {
         KSPO[I] = KSPOO * DZRT[I];
        }
  return 0;
  }


                         // DEFINE THE FUNCTIONS CALLED

// Expo linear growth function
float FuNEXPOLIN (float CM, float k, float TIMEthml, float Tb, float LAR)
  {
```

```
        return 1 / (k * LAR) * log(1 + exp(k * LAR * CM * (TIMEthml - Tb)));
}


float FuNTION2 (float PSI, float Psic)
        {
         return 1 - exp(-8.000001E-3 * (PSI - (Psic - 400)));
        }


float FuNTION16 (float V15L, float PL, float P0L, float ML)
        {
         return V15L * pow(PL / P0L,1 / ML);
        }


float FuNINITINTCP (float k, float Lo)
{
        return 1 - exp(-k * Lo);
}


float FuNLostTIME (float RM1, float Fo)
{
        return -log(Fo / (1 - Fo)) / RM1;
}

float FuNTION6 (float T, float T0)
        {
         return exp(-.00277777 * pow((T - T0), 2));
        }

float FuNTION19 (float TIMEthml, float HUCFULC, float ROOTZO)
        {
         return ROOTZO * (1 / (1 + 44.2 * exp(-8.5 * TIMEthml / HUCFULC)));
        }

float FuNTION21 (float V1DEF)
        {
         return exp(-.03 * V1DEF);
```

```
        }

float FuNTION9 (float LAI, float CONSTfig)
        {
         return  (1 - exp(-CONSTfig * LAI));
        }

float FuNTION11 (float LAI)
        {
         return (1 - exp(-.7 * LAI));
        }

float FuNTION15 (float P0L, float ML, float VL, float V15L)
 {
        return -P0L * pow(VL / V15L, ML);            /* PSIS  */
 }

float FuNTION18 (float V, float V16, float V01)
 {
        return (log(V / V16)) / log(V01 / V16);
 }

float FuNTION22 (int DOG)
        {
                                return -1600 - 11.7 * ((float)DOG - 50);
        }

float FuNTION24 (float Kvo, float FI)
        {
         return Kvo * FI;
        }


                                // READ THE WEATHER FILE

int ReadWeatherFile(int *Year)
         {

          FILE *f21;
          int LENGTHyear, a;
```

```
          float b,c,d,e;
          char buf[7] = "SYDN.W";
          char FileWeath[9];

          sprintf( FileWeath, "%s%d", buf, *Year );  /* Get filename */

          LENGTHyear = 365;
        // Test for leap year
          if((*Year%4)==0) LENGTHyear = 366;

    f21=fopen(FileWeath,"r");

        do
        {
          fscanf(f21,"%d %f %f %f %f",&a,&b,&c,&d,&e);
          Data[a].Tmax = b;
          Data[a].Tmin = c;
          Data[a].Rain = d;
          Data[a].Eo = e;
         }
        while ( a < LENGTHyear );
     fclose(f21);

         return 0;
         }


      // READ VOLUMETRIC WATER CONTENT PRIOR TO SIMULATION i.e. ON DAY ONE

float far VinitRead(int *Year, float VINIT[], float V[], float W[],float DZRT[], float *WM)

         {
        FILE *f21;
        char teks[12];
        char LINE[12];
        static char Fvinit[12] = "watervin.w";
        int a,b,c,d,e,f,g,h,i,l,dat;
        int Yrcrnt;

        Yrcrnt = *Year;
```

```
          MID(teks,Fvinit, 1, 10);
          sprintf( LINE, "%s%d", teks, Yrcrnt );

           f21=fopen(LINE,"r");
           fscanf(f21,"%d %d %d %d %d %d %d %d %d %d",&a,&b,&c,&d,&e,&f,&g,&h,&i,&dat);
          VINIT[1]=(float)a;VINIT[2]=(float)b;VINIT[3]=(float)c;
          VINIT[4]=(float)d;VINIT[5]=(float)e;VINIT[6]=(float)f;
          VINIT[7]=(float)g;VINIT[8]=(float)h;VINIT[9]=(float)i;
           for (l=1;l<= 9; l++)
          {
           V[l] = VINIT[l];
           W[l] = V[l] * DZRT[l];
          }
           fclose(f21);
          *WM = (float)dat;

           return 0;
           }


            // WRITE VOLUMETRIC WATER CONTENT ON LAST DAY OF SIMULATION

float far VinitWrite(int *Year, float V[],  float WM)

           {
            FILE *f21;

          char teks[12];
          char LINE[12];
          static char Fvinit[12] = "watervin.w";
          int Yrcrnt;

          Yrcrnt = *Year+1;
          MID(teks,Fvinit, 1, 10);
          sprintf( LINE, "%s%d", teks, Yrcrnt );

           f21=fopen(LINE,"w");
           fprintf(f21,"%5.0f %5.0f %5.0f %5.0f %5.0f %5.0f %5.0f %5.0f %5.0f %5.0f\n",
                    V[1], V[2], V[3], V[4], V[5], V[6], V[7], V[8], V[9], WM);
           fclose(f21);
```

```
            return 0;
            }



int MID(char str1[],char str2[],int pl,int aan)
           {
           int i;
           char *pt1,*pt2;
           pt1=str1;
           pt2=str2;

           for(i=pl-1;i<pl+aan-1;i++)
          {
          *pt1=str2[i];
          pt1++;
          }
           *pt1='\0';
           return 0;
           }
```

```
                // COMPUTE DAILY AVERAGE TEMPERATURE EFFECTING GROWTH

int TempRoutine(float *T, float TTmx, float BO, float *DELHU, int DOG)
        {
        /* Subroutine calculating daily avg temperatures   */
        float UPRT,EFFGT;

        *T = (Data[DOG].Tmax + Data[DOG].Tmin) / 2;
        UPRT = Data[DOG].Tmax;
        if ( Data[DOG].Tmax > TTmx )
                {
                UPRT = TTmx;                    /* Maximum temperature for growth */
                }
        EFFGT = (UPRT + Data[DOG].Tmin) / 2;
        if ( EFFGT < BO )
                {
                EFFGT = BO;                     /* Minimum temperature for growth */
                }
        *DELHU = EFFGT - BO;
        return 0;
        }

                // ENVIRONMENTAL VARIABLES AND LIMITING FACTORS

int EnvironmentallVar(int DOG, float T, float T0, float *Ffac, float Fv, float *HU, float DELHU, float
        *GAMMA, float GAMMA20, float MinHu, float DevidHu, float dT, float TIMEthml, float V01[],
        float V[], float LAIg, float LAIst, float Kvo, float *PTRANS, float Kso, float *SOILVAP)
        {
        float FTP, V1DEF, FG, CONSTfig, FIg, FIst, Eo, Kvg, Ks;
        float Mu = 1;

         FTP = FuNTION6(T, T0);
         *Ffac = (FTP * Fv) * 100;
         *HU = *HU + DELHU;
         *GAMMA = GAMMA20 * (*HU - 90) / 1150;
         if ( *GAMMA < 0 )
                {
```

```
            *GAMMA = 0;
            }

    dT = DELHU * *Ffac / 100;
    *TIMEthml = *TIMEthml + dT;

    /* Calculate potential and crop evaporation  */

    V1DEF = V01[1] - V[1];
    if( V1DEF < 0 )
            {
             V1DEF = 0;
            }
    FG = FuNTION21(V1DEF);
    CONSTfig = .7 - .3 * FG;
    Flg = FuNTION9(LAIg, CONSTfig) + .001;
    Flst = FuNTION11(LAIst) + .001;
    Eo = Data[DOG].Eo;
    Kvg = FuNTION24(Kvo, Flg) * Mu;
    *PTRANS = Kvg * Eo;
    Ks = Kso * FG * (1 - Flst);
    *SOILVAP = Ks * Eo;
    return 0;
    }
```

// COMPUTE NORMALISED ROOT GROWTH

```
int RootDevelpment(int DOG, int Stge,float TIMEthml, float HUCFULC, float ROOTZO,
        float *ZEFF, float AP, float ZEFFO,float RPROP[], float DZRT[], float *NOLAY)
        {
         int I;
        float RDEVF, A, ZBOT, RMASS, ZTOP;
        float ZBOTT[10];

        if (DOG > 0 )
        {
         RDEVF = FuNTION19(TIMEthml, HUCFULC, ROOTZO);
         if( RDEVF < .3 )
                {
                 RDEVF = .3;
                }
         *ZEFF = RDEVF;
         if( RDEVF > ZEFFO )
                {
                 *ZEFF = ZEFFO;
                }
         *ZEFF = ZEFFO;                  /* Only for natural grasslands */
         A = -log(AP) / (.97 * RDEVF);
         RMASS = 0;
                for(I=1; I<=9; I++)
                {
                        RPROP[I] = 0;
                        if( I == 1 )
                         {
                                ZTOP = 0;
                                ZBOT = DZRT[1];
                                ZBOTT[1] = ZBOT;
                                RPROP[I] = (exp(-A * ZTOP) - exp(-A * ZBOT)) / .979;
                                RMASS = RMASS + RPROP[I];
                         }
                        else
                         {
```

```
                                ZTOP = ZTOP + DZRT[I - 1];
                                ZBOT = ZTOP + DZRT[I];
                                ZBOTT[I] = ZBOT;
                                RPROP[I] = (exp(-A * ZTOP) - exp(-A * ZBOT)) / .979;
                                RMASS = RMASS + RPROP[I];
                        }
                }


        if( *ZEFF <= ZBOTT[1])
                {
                 *NOLAY = 1;
                }
                else
                {
                 for( I=2; I<=9; I++)
                        {
                                if (( *ZEFF > ZBOTT[I - 1])&&( *ZEFF <= ZBOTT[I]))
                                 {
                                        *NOLAY = I;
                                 }
                        }
                }


        for( I = 1; I<=9; I++)
                {
                        RPROP[I] = RPROP[I] / RMASS;
                        if( I > *NOLAY )
                         {
                                RPROP[I] = 0;
                         }
                }

        }
return 0;
}

                                   // SOILWATER POTENTIAL
```

```
int SoilwaterPot(float PSIS[],float b[],float V[], float V15[])
        {
        int I;
        for(I =1; I <= 9; I++)
                {
                PSIS[I] = -1500 * pow((V[I]/V15[I]),b[I]);
                }
        return 0;
        }


                // SOIL ROOT CONDUCTANCE AND LEAF WATER POTENTIAL

int SoilRootCond(float KSPO[], float RPROP[], float RM, float V[],float V16[],float V01[], float
        PSIS[], float PTRANS,float *Fv, float TPAW, float W[], float SOILVAP, float W16[],
        float DZRT[], float PAW[],float DUL[],float LL[], float TDZRT, float NOLAY, int DOG)
        {

        int I;
        static float Psic, PSIL, PSIHI, PSILO, PSIT, TRANS, TEST, FTAW;
        static float TDEFICIT, PAWC, TAW, wtest, PPAW, FW;
        static float TS[10];
        static float AW[10];
        static float PAWL[10];
        static float DEFICIT[10];
        static float FAW[10];
        static float KSP[10];

        float KSPEFF = 0;
        float PSIST = 0;
        float WMPSIS = 0;

        for( I=1; I<=9; I++)
        {
        KSP[I] = KSPO[I] * pow((RPROP[I] * RM),0.5) * FuNTION18(V[I] + 1, V16[I], V01[I]) / 10;
        KSPEFF = KSPEFF + KSP[I];
        WMPSIS = WMPSIS + KSP[I] * PSIS[I];
        }
```

```
PSIST = WMPSIS / KSPEFF;                    /* WEIGHTED MEAN PSIS */
PsicLeaf(DOG, &Psic);

PSIL = PSIST + PTRANS / KSPEFF;

PSIHI = 0, PSILO = -3500;
PSIT = (PSIHI + PSILO) / 2;
*Fv = 1 - exp(-8.000001E-03 * (PSIT - (Psic - 400)));
if(*Fv > 1) *Fv = 1;

if(*Fv < 0) *Fv = 0;

TRANS = *Fv * PTRANS;
PSIL = PSIST + TRANS / KSPEFF;
TEST = PSIL - PSIT;

while (TEST > 5 || TEST <= -5)
{
        PSIT = (PSIHI + PSILO) / 2;
        if( PSIT <= -3500)
         {
        // printf(" ULTRA-STRESS, PSIL = -3000, ON DOY %d\n",  DOY);
         }

        *Fv = 1 - exp(-8.000001E-03 * (PSIT - (Psic - 400)));
        if(*Fv > 1) *Fv = 1;
        if(*Fv < 0) *Fv = 0;
        TRANS = *Fv * PTRANS;
        PSIL = PSIST + TRANS / KSPEFF;
        TEST = PSIL - PSIT;

        if(TEST > 5) PSILO = PSIT;
        if(TEST <= -5) PSIHI = PSIT;
}


                // EXTRACT WATER FROM EACH SOIL LAYER

FTAW = 0;
```

```
for( I=1; I<=9; I++)
{
 TS[I] = -(PSIS[I] - PSIL) * KSP[I];
}

TDEFICIT = 0;TRANS = 0; PAWC = 0; TPAW = 0; TAW = 0;
wtest = W[1] - TS[1] - SOILVAP;
if( wtest < W16[1] )
 {
        TS[1] = W[1] - W16[1];
        W[1] = W16[1];
        goto L13828;
 }
W[1] = wtest;

L13828:
V[1] = W[1] / DZRT[1];
TRANS = TS[1];
AW[1] = W[1] - W15[1];
TAW = TAW + AW[1];
PAWL[1] = AW[1] / PAW[1] * 100;
TPAW = TPAW + PAW[1];
PAWC = ((DUL[1] - LL[1]) / 2) * DZRT[1];
TDZRT = DZRT[1];
if( V[1] > V01[1] )
 {
        DEFICIT[1] = 0;
 }
 else
 {
        DEFICIT[1] = V01[1] * DZRT[1] - W[1];
 }
TDEFICIT = TDEFICIT + DEFICIT[1];


for( I=2; I<=9; I++)
        {
         TDZRT = TDZRT + DZRT[I];
         wtest = W[I] - TS[I];
         if( wtest < W16[I] )
```

```
                {
                 TS[I] = W[I] - W16[I];
                 W[I] = W16[I];
                 goto L13850;
                }

        W[I] = wtest;
        V[I] = W[I] / DZRT[I];

        L13850:
        TRANS = TRANS + TS[I];
        if( I > NOLAY )
                {
                 goto L13866;
                }
        if( V[I] > V01[I] )
                {
                 DEFICIT[I] = 0;
                }
         else
                {
                 DEFICIT[I] = V01[I] * DZRT[I] - W[I];
                }
                 TDEFICIT = TDEFICIT + DEFICIT[I];
        AW[I] = W[I] - W15[I];
        PAWC = ((DUL[I] - LL[I]) / 2) * DZRT[I] + PAWC;
        TAW = TAW + AW[I];
        /* Total available soilwater and maximum available water in the root zone */
        TPAW = TPAW + PAW[I];
        PAWL[I] = AW[I] / PAW[I] * 100;

        L13866:
        FAW[I] = W[I] - W16[I];
        FTAW = FTAW + FAW[I];
       }

PPAW = TAW / TPAW * 100;
*Fv = TRANS / PTRANS;
if( *Fv > 1 )
       {
```

```
                *Fv = 1;
                }
        if( *Fv < 0 )
                {
                *Fv = 0;
                }


        FW = (1 - TRANS / PTRANS);          /* FW = (1 - FNTION3(PSIL, PSIC))  */
        if( FW > 1 )
                {
                FW = 1;
                }
        if( FW < 0 )
                {
                FW = 0;
                }

        return 0;
        }

                        // CRITICAL LEAF WATER POTENTIAL

int PsicLeaf(int DOG, float *Psic)
        {
        *Psic = FuNTION22(DOG);

        if( *Psic > -1600 )
                {
                *Psic = -1600;
                }
        if( *Psic < -2300 )
                {
                *Psic = -2300;
                }

        return 0;
        }
```

```
            // DISTRIBUTION OF INFILTRATION WATER THROUGH SOIL PROFILE

int ReWetSoil(int DOG, float SWUL[], float V[], float DZRT[], float.DUL[],float VCON[],float W[],
                float PSIS[],float P0[],float b[],float V15[])
        {

         int I;
        float RUNOF, INFIL, PINF, HOLD, DRAIN, DEEPERC;


        if( Data[DOG].Rain < 3 )
                {
                 Data[DOG].Rain = 0;
                }
        RUNOF = .2;             //      RUNOF = .2;
        INFIL = Data[DOG].Rain;
        if( INFIL < 50 )
                {
                 RUNOF = .1;    //              RUNOF = .1;
                }
        if( INFIL < 25 )
                {
                 RUNOF = .05;  //               RUNOF = .05;
                }
        if( INFIL < 15 )
                {
                 RUNOF = 0;
                }

        PERC[1].= (Data[DOG].Rain) * (1 - RUNOF);
        RUNOF = (Data[DOG].Rain) * RUNOF;

       for( I=1; I<=9; I++)
        {
            W[I] = W[I] + PERC[I];
            V[I] = W[I] / DZRT[I];
            if( W[I] > (SWUL[I] * DZRT[I]))
              {
               PERC[I + 1] = W[I] - (SWUL[I] * DZRT[I]);
              W[I] = SWUL[I] * DZRT[I];
```

```
                V[I] = SWUL[I];
                }
              else
                {
                  if( W[I] > (DUL[I] * DZRT[I])
                   {
                    PERC[L + 1] = (VCON[I] * (V[I] - DUL[I])) * DZRT[I];
                    W[I] = W[I] - PERC[L + 1];
                    V[I] = W[I] / DZRT[I];
                    }
                   else
                    {
                     PERC[I + 1] = 0;
                    }
                 }
         }

        DEEPERC = DEEPERC + PERC[10];
       for( I=1; I<=9; I++)
        {
         PERC[I] = 0;
         PSIS[I] = FuNTION15(P0[I], b[I], V[I], V15[I]);
        }


return 0;
 }
```

```
    // DISTRIBUTION OF DRY MASS THROUGH PLANT ORGANS W(1..4) and LAI(1..4)

int Development(float *WWeight, float CM, float k, float TIMEthml, float Tb,float *W1,float *W2,
            float *W3,float *W4,float *W5,float *WeightM,float LAR, float Lamda,
            float GAMMA, float PercTrash, float HU,float Tpgrowth,float *dLAI, float *LAI,
            float DELHU, float Ffac,float *LAI1, float *LAI2,float *LAI3,float *LAI4,
            float *LAI5,float *LAIg, float *LAIst, float *WM,int DOG)
    {
    float DMGWeight, gain, loss;
    static float WPREV;
     if (DOG == 1 ) WPREV = 0;
     if( HU <= Tpgrowth )
    {
     *WWeight = FuNEXPOLIN(CM, k, TIMEthml, Tb, LAR);
     DMGWeight = (*WWeight - WPREV);
     WPREV = *WWeight;
     *dLAI = (1 - exp(-k * *LAI)) * LAR * CM * k * DELHU * Ffac / 100 * pow(Tpgrowth,10) /
            (pow(HU,10) + pow(Tpgrowth,10));
    }
    else
    {
    *dLAI = 0; DMGWeight = 0;
    }
    loss = Lamda * GAMMA * *W1;
    *W1 = *W1 + DMGWeight - loss,gain = loss, loss = GAMMA * *W2;
    *W2 = *W2 + gain - loss, gain = loss, loss = GAMMA * *W3;
    *W3 = *W3 + gain - loss, gain = loss;
    loss = PercTrash * GAMMA * *W4 * pow(HU,10) / (pow(HU,10) + pow(Tpgrowth,10));
    *W4 = *W4 + gain - loss, gain = loss;
    *W5 = *W5 + gain;
     if( W4 < 0 ) W4 = 0;
     *WeightM = *W1 + *W2 + *W3 + *W4;


     // Leaf growth change
    gain = *dLAI, loss = Lamda * GAMMA * *LAI1;
    *LAI1 = *LAI1 + gain - loss, gain = loss, loss = GAMMA * *LAI2;
```

```
        *LAI2 = *LAI2 + gain - loss, gain = loss, loss = GAMMA * *LAI3;
        *LAI3 = *LAI3 + gain - loss, gain = loss, loss = PercTrash * GAMMA * *LAI4 * pow(HU,10) /
                                                        (pow(HU,10) + pow(Tpgrowth,10));
        *LAI4 = *LAI4 + gain - loss, gain = loss, loss = GAMMA * *LAI5;
        *LAI5 = *LAI5 + gain;
        if( *LAI4 < 0 ) *LAI4 = 0;

         *LAI = (*LAI1 + *LAI2 + *LAI3);
         *LAIg = (*LAI1 + *LAI2 + *LAI3);
         *LAIst = (*LAI1 + *LAI2 + *LAI3 + *LAI4);

         if( *WeightM > *WM )
               {
                *WM = *WeightM;
               }

        return 0;
        }


          // EFFECT OF DAILY WATER STRESS ON LENGTH OF GROWTH SEAONS

int SeasMeans(int DOG, float Tpgrowtho, float *Tpgrowth, float Fv, float DELHU)
        {
         static float DayDev, SeasTFv;
         float SeasMFv;

         if(DOG == 1 )
         {
               DayDev = 0;
               SeasTFv = 0;
               SeasMFv = 0;
         }
         if(DELHU > 0 && DOG > 40)
         {
               DayDev = DayDev + 1;
               SeasTFv = SeasTFv + Fv;
               SeasMFv = SeasTFv / DayDev;
               *Tpgrowth = Tpgrowtho * (1 - (1 - SeasMFv) * .3);
         }
```

APPENDIX A.5

FORMAT OF WEATHER FILE

DOG	MaxT	MinT	Rain	Evap
1	12.20	-2.00	0.00	2.46
2	13.00	-1.70	0.00	2.08
3	16.00	0.00	0.00	2.72
4	21.40	3.30	0.00	2.67
5	20.00	5.20	0.00	3.04
6	18.90	4.50	0.00	2.50
7	19.50	6.80	0.00	3.06
8	20.20	-3.00	0.00	2.21
9	21.00	3.80	0.00	3.28
10	16.70	0.60	0.00	2.28
11	18.00	2.50	0.00	2.91
12	20.60	4.00	0.00	2.59
13	15.00	2.50	0.00	2.76
14	17.00	-6.30	0.00	1.98
15	17.00	1.00	0.00	2.60
16	21.00	2.40	0.00	2.39
17	21.50	2.00	0.00	3.13
18	21.00	6.40	0.00	2.58
19	17.00	0.20	0.00	2.63
20	17.00	-4.00	0.00	1.96
21	16.00	6.00	0.00	2.72
22	16.00	4.00	0.00	2.30
23	19.00	3.20	0.00	2.82
24	20.00	0.00	0.00	2.21
25	21.00	0.40	0.00	3.07
26	23.00	3.00	0.00	2.84
27	19.00	0.20	0.00	2.81
28	15.50	4.50	0.00	2.38
29	17.00	7.50	3.00	2.88
30	17.70	1.00	0.00	2.28
31	18.50	1.00	0.00	2.86

DOG	= Day of growth	[DOG = 1 on 1st of Jully]
MaxT	= Maximum daily temperature	[°C]
MinT	= Minimum daily temperature	[°C]
Evap	= Daily reference evaporation	[mm]
Rain	= Daily total rainfall	[mm]

APPENDIX B

Measured and simulated soil content water for Shorrock and Swartland ecotope in mm
Day of growth (DOG)

Shorrocks (1987)

	Layer 1		Layer 2		Layer 3		Layer 4	
DOG	Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated
239	27.8	27.4	75.6	86.0	70.4	61.5	73.7	57.4
246	31.5	37.9	77.5	86.0	71.4	86.0	74.5	86.0
261	22.0	35.8	71.0	56.0	66.6	56.9	70.5	86.0
273	16.9	42.7	63.5	55.3	61.0	51.3	65.6	86.0

	Layer 5		Layer 6		Layer 7	
DOG	Measured	Simulated	Measured	Simulated	Measured	Simulated
239	69.0	30.1	64.1	25.0	61.4	27.1
246	73.0	81.4	67.6	29.0	67.4	27.1
261	69.5	86.0	63.0	80.1	65.3	68.3
273	65.0	42.1	58.3	25.0	60.0	27.1

Shorrocks (1988)

	Layer 1		Layer 2		Layer 3		Layer 4	
DOG	Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated
7	17.20	24.60	64.00	58.30	57.40	48.00	61.10	50.90
19	13.70	22.10	63.50	57.20	57.90	47.80	61.20	50.70
71	12.70	28.40	60.20	60.10	55.60	47.30	59.60	49.60
84	12.90	26.80	59.10	61.30	54.60	51.40	58.60	49.40
91	8.70	21.80	56.10	59.10	53.60	51.80	58.30	49.20
110	23.00	38.10	57.20	71.70	48.70	55.20	55.00	56.30
131	20.80	34.10	67.30	73.60	49.00	55.40	53.70	72.90
146	8.60	21.30	54.40	60.20	47.00	54.10	51.80	62.00
159	9.90	27.70	48.10	59.90	43.80	54.00	49.30	57.90
197	17.30	30.40	60.80	69.70	42.80	55.00	47.10	67.80
225	25.00	37.40	57.00	67.50	40.10	54.50	44.50	55.40
246	21.90	38.20	69.60	75.20	64.40	55.50	67.90	73.00

	Layer 5		Layer 6		Layer 7	
DOG	Measured	Simulated	Measured	Simulated	Measured	Simulated
7	61.50	51.90	54.40	46.00	55.40	48.90
19	61.10	51.70	54.10	45.90	55.60	48.80
71	59.90	50.50	52.70	45.20	54.20	47.60
84	59.30	50.30	51.10	45.10	54.10	47.50
91	59.30	50.10	52.40	44.90	54.00	47.30
110	57.80	49.60	51.70	44.50	53.80	46.80
131	56.50	69.70	50.60	54.90	52.60	48.20
146	55.10	65.90	50.00	59.00	52.50	60.40
159	52.40	59.70	48.60	53.20	51.70	57.40
197	50.20	65.90	46.30	55.50	50.70	56.80
225	47.20	55.40	43.00	48.50	47.30	51.20
246	60.30	70.40	47.60	57.20	49.30	52.40

Shorrock (1989)

	Layer 1		Layer 2		Layer 3		Layer 4	
DOG	Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated
123	7.2	19.9	47.3	51.0	44.4	48.2	49.1	51.4
133	25.3	43.1	58.6	68.3	43.0	51.9	48.1	50.5
137	18.7	45.3	52.9	69.2	43.0	54.8	47.8	53.6
158	8.0	21.4	50.3	59.0	42.6	53.6	46.7	59.4
180	6.1	22.0	44.1	53.4	39.6	48.0	43.8	52.8
202	21.8	40.2	46.9	56.1	37.8	39.3	42.1	43.1
245	6.5	19.3	43.4	37.7	37.6	28.0	41.0	31.1
284	14.0	30.5	43.4	47.4	37.8	25.7	41.1	28.8
326	10.2	24.5	43.1	45.1	37.2	30.1	41.0	28.8

	Layer 5		Layer 6		Layer 7	
DOG	Measured	Simulated	Measured	Simulated	Measured	Simulated
123	52.0	51.8	46.4	46.0	48.9	47.9
133	50.7	51.0	45.6	45.4	48.3	47.3
137	50.5	50.7	45.4	45.1	48.0	47.1
158	49.5	61.0	44.1	48.7	47.2	46.0
180	45.9	54.0	41.3	44.8	44.3	43.0
202	44.1	44.2	39.4	37.1	42.1	37.3
245	43.0	32.1	38.1	26.9	40.0	28.8
284	43.3	29.8	37.6	24.7	39.4	26.7
326	43.3	29.8	38.8	24.7	40.0	26.7

Shorrock (1995)

	Layer 1		Layer 2		Layer 3		Layer 4	
DOG	Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated
118	29.0	24.1	30.0	34.5	26.0	26.0	29.0	28.9
136	18.0	16.4	32.0	34.4	28.0	26.3	30.0	29.3
149	26.0	28.6	31.0	40.3	27.0	26.3	30.0	29.3
157	21.0	37.8	33.0	38.8	26.0	26.5	29.0	29.5
159	38.0	38.3	33.0	42.9	27.0	26.6	30.0	29.6
175	51.0	47.5	63.0	70.1	41.0	33.8	30.0	30.5
182	36.0	28.4	58.0	63.1	46.0	42.1	32.0	31.2
228	23.0	40.7	43.0	53.0	34.0	29.0	33.0	30.0
243	49.0	58.1	51.0	67.7	35.0	32.5	33.0	30.4
268	16.0	19.7	40.0	38.9	34.0	32.6	33.0	30.5
285	26.1	29.6	36.0	42.8	31.0	27.9	33.0	29.5
297	44.0	35.6	41.0	62.9	31.0	31.7	33.0	30.1
328	22.0	25.7	39.0	39.8	30.0	30.7	32.0	31.7

	Layer 5		Layer 6		Layer 7	
DOG	Measured	Simulated	Measured	Simulated	Measured	Simulated
118	30.0	29.9	25.0	25.0	27.0	27.0
136	32.0	30.3	27.0	25.3	29.0	27.3
149	31.0	30.3	27.0	25.3	28.0	27.3
157	30.0	30.5	26.0	25.5	27.0	27.5
159	31.0	30.6	27.0	25.6	28.0	27.6
175	31.0	31.5	27.0	26.5	28.0	28.5
182	32.0	32.2	27.0	27.2	29.0	29.2
228	32.0	31.0	27.0	26.0	28.0	28.0
243	32.0	31.4	26.0	26.4	28.0	28.4
268	32.0	31.6	27.0	26.5	28.0	28.5
285	32.0	30.5	27.0	25.4	29.0	27.4
297	33.0	31.1	27.0	26.1	28.0	28.1
328	31.0	32.7	26.0	27.7	28.0	29.7

Shorrock (1996)

	Layer 1		Layer 2		Layer 3		Layer 4	
DOG	Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated
79	20.5	22.2	39.2	32.4	29.7	27.3	31.7	30.3
130	52.5	50.5	63.0	42.9	34.7	27.1	31.8	30.2
159	40.4	39.6	59.0	59.6	43.3	27.6	33.7	30.2
205	36.0	34.0	37.6	45.5	31.8	27.1	34.4	29.7
248	50.7	43.8	35.2	40.1	28.4	25.6	32.0	28.6
372	54.2	46.0	36.1	43.8	28.8	25.6	31.7	28.6
329	31.6	30.8	42.2	30.5	28.4	25.6	31.4	28.6

	Layer 5		Layer 6		Layer 7	
DOG	Measured	Simulated	Measured	Simulated	Measured	Simulated
79	31.7	31.32	26.4	25.94	27.94	27.94
130	32.3	31.16	27.0	25.88	28.4	27.89
159	32.3	31.16	30.0	25.88	28.2	27.89
205	32.6	30.72	27.3	25.54	29.1	27.55
248	32.7	29.63	27.2	24.64	28.8	26.63
372	31.9	29.63	27.2	24.64	26.63	26.63
329	32.4	29.63	27.1	24.64	28.5	26.63

Swartland (1987)

	Layer 1		Layer 2		Layer 3		Layer 4	
DOG	Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated
240	50.9	99.3	99.4	107.0	87.0	88.0	79.6	81.4
261	46.1	54.5	97.3	97.8	83.4	107.0	81.3	107.0
268	46.7	55.3	96.4	86.0	83.2	83.9	81.4	98.3
273	43.3	47.9	95.9	75.7	83.6	81.9	81.0	91.4
287	46.8	50.7	96.5	88.7	84.5	78.0	82.9	84.3

Swartland (1988)

	Layer 1		Layer 2		Layer 3		Layer 4	
DOG	Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated
7	38.8	46.3	93.1	61.2	83.9	66.7	82.4	77.8
20	39.6	41.4	93.4	61.2	83.7	66.0	82.9	77.3
72	38.5	44.9	93.4	63.2	83.6	62.7	83.2	74.7
84	38.4	45.8	91.4	66.5	82.4	62.5	84.8	74.3
110	46.6	55.1	89.4	90.3	81.3	61.6	81.8	73.4
131	46.2	52.8	95.1	107.0	85.2	85.2	86.8	84.2
146	36.2	43.2	90.4	85.5	84.2	83.8	86.5	85.6
159	32.4	49.3	83.5	75.3	81.2	81.2	84.1	83.2
197	39.4	51.8	81.4	91.6	75.7	83.6	78.9	80.7
225	45.9	55.0	86.7	73.3	74.9	69.8	77.6	76.4
246	48.9	55.8	95.9	92.6	85.2	71.0	86.0	74.7

Swartland (1989)

	Layer 1		Layer 2		Layer 3		Layer 4	
DOG	Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated
123	33.4	32.1	91.5	59.6	86.2	55.2	91.8	63.0
133	41.7	59.9	83.0	79.2	76.0	55.1	79.0	62.9
137	38.2	63.4	83.3	86.2	75.8	55.1	79.8	62.9
158	29.5	42.0	80.0	90.0	73.9	68.5	77.0	62.9
182	27.2	44.8	76.5	76.2	72.2	67.9	74.9	62.9
202	41.3	58.7	82.7	79.1	70.9	65.3	74.1	62.8
284	33.3	51.6	75.9	96.5	69.7	85.2	73.5	66.5
326	30.6	47.0	75.7	91.0	69.3	84.3	73.0	84.9

Swartland (1995)

	Layer 1		Layer 2		Layer 3		Layer 4	
DOG	Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated
118	25.7	40.6	59.8	60.0	55.3	54.8	59.5	63.0
136	24.4	32.4	62.7	61.1	58.2	54.8	62.3	62.8
157	61.3	56.4	65.8	62.9	55.8	54.7	59.0	62.5
159	70.1	58.6	68.0	65.5	58.0	54.7	58.8	62.5
175	81.7	74.7	83.9	91.6	62.0	54.7	62.0	62.5
181	75.8	56.2	82.7	95.9	62.1	55.3	62.1	62.5
228	66.8	67.2	78.4	84.1	61.3	55.3	62.1	62.4
243	80.5	89.9	83.3	97.3	62.5	61.6	64.5	62.4
268	61.3	43.8	76.9	76.2	65.2	74.0	65.9	62.4
284	61.4	57.3	71.6	76.1	64.6	72.7	64.9	62.4
296	71.7	69.5	71.6	96.7	62.4	76.4	62.6	62.4
328	63.6	50.2	70.8	90.0	61.4	80.8	65.2	62.4

Swartland (1996)

	Layer 1		Layer 2		Layer 3		Layer 4	
DOG	Measured	Simulated	Measured	Simulated	Measured	Simulated	Measured	Simulated
79	66.7	36.8	70.4	69.9	61.1	64.1	64.1	67.9
142	79.4	75.0	83.3	103.2	63.6	60.3	65.7	66.8
158	74.4	48.8	80.9	99.4	63.9	83.1	65.4	66.8
207	58.3	48.9	68.1	65.4	62.0	63.5	65.6	65.3
253	72.9	54.1	64.0	68.4	58.8	57.3	64.0	64.0
281	75.7	55.9	63.4	85.7	58.3	56.2	62.8	63.5
324	66.3	37.2	64.4	82.9	58.2	56.2	62.8	63.5

Table 1. Measured biomass yields obtained at the University of the Free-state for the 1995/96 and 1996/97 season.

		1995/96		1996/97	
Month	DOG	Climax	Sub-climax	Climax	Sub-climax
Sept	93	61.3	23.1	275.8	256.2
Oct	124	160.4	133.5	622.4	322.3
Nov	154	529.2	401.6	812.7	586.6
Dec	185	1036.0	516.3	1309.8	851.6
Jan	216	1601.6	1051.4	2209.1	1238.0
Feb	243	2428.0	1353.3	2452.1	1399.4
March	274	2611.6	1374.6	2947.55	1679.4
April	305	2677.6	1389.6	2963.5	1747.0

Table 2. Measured and simulated total yields for 20 years using values for $T_{b,age} = 0$ and $\gamma 20 = 0.015$ (Johnson & Thornley, 1983), and optimised values at University of Free state.

Year	Measurement	Optimised	Johnson & Thornley, 1983
1977/78	937.9	1093.26	1300.61
1978/79	656.1	837.00	1131.74
1979/80	685.9	1014.69	1315.70
1980/81	1900.0	1662.77	2048.77
1981/82	2255.6	1816.92	2246.75
1982/83	537.4	711.63	1003.09
1983/84	491.1	525.11	690.60
1984/85	687.3	667.66	974.18
1985/86	471.3	633.85	922.20
1986/87	313.4	616.20	868.33
1987/88	1307.0	1094.49	1367.03
1988/89	2020.7	2149.47	2530.02
1989/90	1794.9	1911.92	2373.91
1990/91	1433.8	1581.01	2146.69
1991/92	1015.5	994.03	1350.50
1992/93	586.1	938.48	1366.21
1993/94	2407.3	2223.76	2616.89
1994/95	1342.5	1203.77	1641.37
1995/96	2677.0	2281.14	2726.29
1996/97	2963.0	3028.69	3443.87

Table 3. Output produced by model maker for the determination of rate constant $\gamma 20$ and threshold thermal time $T_{b,age}$.

	Degrees of Freedom	Weighted sum of squares	Mean Square	F-value = 176.55
Model	1	1.154e+11	1.154e+11	P-value <0.001
Residual (X^2)	18	1.176e+10	6.53e+8	Q-value=0
Total	19	1.12e+11		
r^2 = 0.93				

Table 4. Measured and simulated total yields for 20 years at University of Free state on moderate veld conditions.

Year	Measured	Simulated
1977/78	534.0	816.18
1978/79	373.0	565.84
1979/80	467.0	614.13
1980/81	1633.0	999.18
1981/82	788.0	1028.84
1982/83	229.0	334.01
1983/84	213.0	291.75
1984/85	327.0	486.42
1985/86	311.0	385.75
1986/87	200.0	344.77
1987/88	870.0	616.43
1988/89	1226.0	1344.25
1989/90	1186.0	1296.58
1990/91	980.0	944.86
1991/92	608.0	468.19
1992/93	290.0	571
1993/94	1968.0	1351.95
1994/95	989.0	543.61
1995/96	1389.0	1235.36
1996/97	1747.0	1670.64

Shorrock (3)

1987/88		
DOG	Measured	Simulated
194	**1109.5**	**468.8**
203	817.9	540.7
224	815.5	656.6
245	636.1	974.7
273	879.2	1213.7
301	1183.7	1207.5
328	956.2	1196.8
357	738.5	1179.9

1988/89		
DOG	Measured	Simulated
109	418.3	109.8
132	485.1	173.4
160	**1047.3**	**317.0**
223	**1659.6**	**814.6**
250	1459.7	1144.9
278	1216.9	1345.0
314	994.3	1517.3
333	964.9	1511.2

1989/90		
DOG	Measured	Simulated
137	322.8	244.8
158	846.7	345.1
180	858.6	490.5
201	**1186.6**	**615.8**
221	724.9	797.5
242	891.9	977.1
263	1081.0	1162.9
284	1327.6	1160.0
311	956.9	1152.4
326	1184.7	1146.1

1990/91		
DOG	Measured	Simulated
202	403.3	393.3
219	579.3	684.7
240	1097.0	1112.8
258	1666.7	1346.4
282	1505.2	1343.5
303	1378.7	1338.1
324	1440.4	1329.2

1991/92		
DOG	Measured	Simulated
134	679.8	444.5
151	1084.1	676.3
171	1439.3	1023.5
192	1478.5	1337.7
213	1385.8	1452.4
254	1561.4	1551.7
275	1354.0	1544.1
296	1270.0	1531.4
315	944.4	1515.2
326	1184.7	1503.9

1992/93		
DOG	Measured	Simulated
147	159.9	216.7
168	314.4	275.8
210	381.8	367.7
238	374.2	487.9
252	556.1	685.0
273	1030.7	900.0
294	1101.6	1147.4
315	**526.5**	**1173.5**
336	**391.0**	**1183.3**

1993/94		
DOG	Measured	Simulated
132	368.6	228.0
153	440.3	366.5
174	597.1	438.5
195	734.2	602.2
217	630.4	869.3
237	1280.3	1124.1
259	1380.3	1229.4
288	1101.4	1222.9
341	869.2	1195.0

1994/95		
DOG	Measured	Simulated
265	263.0	483.4
285	490.3	481.9
311	591.5	478.2
334	504.2	473.2

Swartland (4)

1987/88		
DOG	Measured	Simulated
203	1011.73	618.62
224	761.16	694.69
245	1027.96	890.23
273	961.21	1164.43
301	962.92	1271.06
328	932.31	1279.34
357	657.65	1284.94

1988/89		
DOG	Measured	Simulated
109	71.01	134.36
132	454.32	265.92
160	1032.32	619.35
194	1400.65	1368.57
223	1217.10	1579.25
250	1755.16	1917.48
278	1577.42	2083.56
314	**930.10**	**2187.18**
333	**1035.54**	**2204.42**

1989/90		
DOG	Measured	Simulated
137	133.98	170.57
158	337.9	239.53
180	426.27	380.83
201	545.85	531.18
221	484.78	785.33
242	786.42	841.66
263	642.08	903.76
284	766.43	942.40
311	631.15	957.21
326	701.51	957.21

1990/91		
DOG	Measured	Simulated
219	319.83	686.83
240	722.47	1027.19
258	923.11	1101.97
282	1068.00	1099.07
303	1082.39	1094.00
324	1083.95	1085.92

1991/92		
DOG	Measured	Simulated
134	269.74	241.09
151	**1285.09**	**384.60**
171	**1423.99**	**616.89**
192	1279.70	768.41
213	794.47	785.21
254	1355.26	812.79
275	932.74	809.04
296	860.72	802.80
315	713.13	794.82
326	701.51	789.30

1992/93		
DOG	Measured	Simulated
147	176.07	104.03
168	201.79	158.87
190	222.68	218.17
210	242.35	247.25
238	267.87	404.56
252	269.03	539.31
273	429.98	671.64
294	575.31	773.25
315	451.29	794.49
326	701.51	831.54

1993/94		
DOG	Measured	Simulated
132	364.13	218.82
153	588.76	385.80
174	530.49	454.60
195	657.05	623.01
217	712.52	985.29
237	**184.81**	**1359.62**
259	1257.43	1563.25
288	1095.34	1556.13
341	1123.22	1522.87

1994/95		
DOG	Measured	Simulated
265	230.98	662.85
285	345.16	660.89
311	382.63	656.09
334	352.41	649.44

Mynrust (34)

1989/90		
DOG	Measured	Simulated
160	**1185.63**	**613.66**
161	**1361.12**	**617.66**
203	**2400.25**	**1028.97**
265	1962.04	1730.04
285	2284.55	1816.63
327	1387.75	1795.19

1990/91		
DOG	Measured	Simulated
222	464.69	824.58
244	1017.55	1057.35
269	1255.07	1342.96
284	1028.92	1405.14
307	1227.13	1434.37

1991/92		
DOG	Measured	Simulated
125	413.15	236.48
173	651.72	652.21
193	730.49	799.76
214	872.06	842.02
235	862.33	915.98
255	593.34	947.56
276	731.89	946.37
297	672.08	940.77

1992/93		
DOG	Measured	Simulated
148	103.51	253.33
170	101.80	315.05
191	138.08	331.72
211	174.10	365.96
239	208.49	736.59
275	476.49	915.28
316	301.22	905.87

1993/94		
DOG	Measured	Simulated
113	177.4	141.58
133	278.69	260.76
154	543.15	468.61
175	310.04	582.52

Franshoek (63)

1989/90		
DOG	Measured	Simulated
160	643.61	741.23
161	922.94	742.36
203	1117.10	1111.5
223	1221.08	1370.6
265	1037.43	1688.51
285	1125.44	1680.49
313	1254.77	1661.83

1990/91		
DOG	Measured	Simulated
201	522.64	523.86
222	487.21	850.58
244	1308.13	1168.16
269	1752.68	1416.72
284	1722.30	1569.03
307	1680.87	1639.41
327	2069.86	1653.75

1991/92		
DOG	Measured	Simulated
135	**1144.27**	**241.47**
155	661.31	374.07
173	**1187.84**	**563.53**
193	821.74	905.86
214	1139.00	967.19
235	962.09	1010.33
255	973.44	1022.62
276	943.74	1091.00
297	735.38	1267.51

1992/93		
DOG	Measured	Simulated
148	33.19	320.74
170	35.67	456.75
191	131.10	567.70
211	148.64	654.98
239	122.36	1019.69
254	309.39	1265.47
275	300.95	1262.49
295	305.41	1257.28
316	**72.61**	**1248.69**

1993/94		
DOG	Measured	Simulated
113	38.67	186.63
133	99.97	331.98
154	60.45	550.90
175	70.31	637.09
196	206.45	866.05
218	208.95	1289.58
275	**300.95**	**1887.69**
295	**305.41**	**1878.92**
316	**72.61**	**1864.70**

Vacant (50)

Year	DOG	Measured	Simulated
1987/88	340	1278.8	1141.18
1988/89	357	2593.99	1520.88
1989/90	333	987.71	1028.48
1990/91	333	2437.33	1495.66
1991/92	309	1013.86	877.33
1992/93	307	317.39	716.10
1993/94	360	561.28	1072.08
1994/95	341	514.06	569.07

Voelvlei (55)

Year	DOG	Measured	Simulated
1986/87	343	578.4	1049.61
1987/88	336	835.12	1142.78
1988/89	341	1729.68	1529.75
1989/90	360	1382.37	1014.64
1990/91	333	2105.44	1495.66
1991/92	309	1160.38	877.33

Swaarkry (51)

Year	DOG	Measured	Simulated
1986/87	340	435.90	676.09
1987/88	334	1555.53	1544.31
1988/89	340	2315.39	2335.56
1989/90	334	1023.18	1367.20
1990/91	361	1538.27	1255.98
1991/92	311	777.50	914.40
1992/93	307	453.75	597.72
1993/94	360	447.98	697.86
1994/95	241	273.75	404.23

Rama (70)

Year	DOG	Measured	Simulated
1986/87	347	759.09	833.65
1987/88	337	691.02	986.52
1988/89	356	1393.53	1335.93
1989/90	332	917.48	880.69
1990/91	331	609.59	549.24
1992/93	310	418.55	710.31
1993/94	360	431.13	807.00
1994/95	340	385.40	378.70

Midelplaas (43)

Year	DOG	Measured	Simulated
1987/88	343	306.92	786.29
1988/89	343	1774.85	1714.60
1989/90	318	1556.03	1396.61
1990/91	317	1208.21	1031.26
1991/92	322	728.46	536.91
1992/93	308	370.86	621.36

Riviera (54)

Year	DOG	Measured	Simulated
1986/87	344	829.19	989.06
1987/88	336	1175.41	1089.13
1988/89	341	2480.30	2202.29
1989/90	333	1057.72	1322.00
1990/91	333	2168.38	1668.40
1991/92	309	903.31	913.47
1994/95	340	278.77	560.21