MODELLING THE WATER BALANCE ON BENCHMARK ECOTOPES

M Hensley[*1], JJ Anderson[*1], JJ Botha[*1], PP van Standen[*1]
A Singels[*2], M Prinsloo[*3], & A du Toit[*3]

[*1] ARC - Institute for Soil, Climate and Water
[*2] University of the Free State
[*3] ARC - Grain Crops Institute

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EXECUTIVE SUMMARY

There is much evidence to support the contention that reliable plant growth models can make an important contribution towards promoting improved rainfall use efficiency, and therefore sustainable land use and food security. It is known that the water balance subroutines of the main crop models currently used in South Africa are relatively unreliable. The aim of this project was to attempt to improve their reliability, and then use them to make long-term predictions to quantify risk. The following were the detailed aims as set out in the original project:

1. To obtain the necessary data over a period of three years at eight benchmark crop ecotopes to test and adapt selected crop models so that they are capable of making reliable long-term predictions of the water balance and of crop yield.
2. To use the calibrated models together with long-term climatic data, to obtain for each benchmark ecotope,
   (a) long-term cumulative distribution functions of yield - to serve as quantitative estimates of risk;
   (b) long-term predictions of runoff and deep drainage - to provide surface and subsurface hydrological information.
3. To accumulate knowledge about how to adapt crop models to give reliable results for ecotopes with a wide range of characteristics - to improve the efficiency of extrapolation to unknown ecotopes.

The following benchmark ecotopes were selected for the study. The first name of the ecotope, because it is geographical, provides for most readers a general description of prevailing climate, and the second name identifies the soil in terms of the South African Soil Classification System. The maize ecotopes were Setlagole/Clovelly, Wolmaransstad/Hutton, Kroonstad/Avalon, Bethal/Hutton, Bethal/Avalon and Ermelo/Longlands. The wheat ecotopes were Bultfontein/Clovelly and Petrusburg/Bloemdal. Yield and detailed water balance measurements were made at each ecotope over three growing seasons.

Comparisons between measured and simulated results showed that although both the DSSAT3 and PUTU maize and wheat models sometimes gave reliable yield predictions, they were also sometimes very unreliable. Soil water content predictions were better than those of yield, but also at times unsatisfactory. Adjustments are needed to improve reliability. The following are important model weaknesses that have been exposed: (a) the lack of a subroutine to deal with waterlogging in maize ecotopes; (b) the lack of a subroutine for the absence of secondary roots in wheat; (c) the inability of PUTU to predict high yields on the Bethal/Hutton and Bethal/Avalon ecotopes; (d) the excessive maize root water extraction rate frequently simulated by DSSAT3 during the last part of the growing season; (e) unsatisfactory runoff subroutines for both models; (f) unsatisfactory stress prediction subroutines, especially in DSSAT3; (g) the lack of a subroutine to cater for lateral water movement in the root zone.

Due to frequent waterlogging at some of the maize ecotopes it was possible to make some valuable observations about the ability of maize to withstand this hazard. Where a water table remained at a depth of about 500 mm at the Ermelo/Longlands ecotope for most of a growing season the yield was very poor. At the Bethal/Avalon ecotope where the water table was maintained at a depth of about 700 mm for the first 75 days of the growing season, there were virtually no adverse effects, the final yield being 10 575 kg ha^{-1} . A provisional threshold water table depth for maize can therefore be set at about 600 mm.

Long-term cumulative functions (the same thing as cumulative probability functions or CPF's) of yield were computed as follows. Four CPF's were computed for each ecotope using each of the following root zone water contents at planting viz. ¼, ½, ¾, and full. This was done to avoid the problem of not knowing what the actual water content was during each of the growing seasons for which rainfall data was available. Predicted grain yields (t ha^{-1}) at 50% probability, starting with a full root zone at planting, and presented in the order of the ecotopes listed in paragraph two, are as follows: 2,3; 3,8; 4,9; 6,8; 6,8; 6,8; 2,1; 3,0. The equivalent values, starting with a ¼-full root zone at planting, are, 1,7; 3,5; 2,4; 6,0; 4,9; 5,0; 1,1; 0,6. Although these results indicate that water content of the root zone at planting may not be important in the last three relatively high rainfall maize ecotopes, the economic importance of this factor in the case of Setlagole/Clovelly and Kroonstad/Avalon, and the two wheat ecotopes, is identified. The CPF's clearly reflect the relative production risks between the ecotopes studied. The absolute value of the CPF's need to be confirmed when the reliability of the models has been improved.

Long-term predictions of runoff and deep drainage have been computed for selected ecotopes. Deep drainage estimates have been excluded on the three ecotopes at which considerable lateral water movement occurs in the root zone, as it is considered that long-term estimates in these cases would be meaningless at this stage. The value of the long-term predictions to provide useful surface and subsurface hydrological information is doubtful at this stage because of lack of model reliability.

The potential strengths of the models have been demonstrated, as well as their amenability to improvement, and therefore the closeness of this technology to becoming a powerful practical tool for agriculture.

It is recommended that further research be undertaken, preferably by a multidisciplinary team, to provide the measurements and modelling expertise needed to rectify the model weaknesses identified. The fairly wide occurrence of considerable lateral hillside water movement which this project has exposed shows clearly that any multidisciplinary approach needs to include comprehensive hydrological studies, including catchment hydrology and groundwater recharge. The overall results of such holistic multidisciplinary studies could make a valuable contribution towards the growing need for integrated resource management.

A great deal has been learned about the functioning of the water balance processes at the ecotopes studied, about how to measure them, and the long-term influence of these processes during pedogenesis on soil physical, chemical and morphological characteristics. Expertise with regard to the latter will be a valuable aid for transferring information from ecotopes where measurements have been made, to those at which measurements have not yet been made, and so facilitate future practical applications of crop model technology for promoting improved rainfall use efficiency.

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1. INTRODUCTION

1.1 MOTIVATION

The importance of the water balance, the ecotope, and crop modelling

Figure 1.1 diagrammatically represents the atmosphere-plant-soil (APS) system. This system is the nucleus of nature's factory for the production of all the land grown food, natural fibre, wood, and paper used by mankind. The six water balance processes identified in Figure 1.1 play an important role in the functioning, productivity and stability of the system. It is these processes which form the focal point of the present study. Hence the term "water balance" in the title of this project.

Optimal management of the APS system to the benefit of mankind requires that its functioning be well understood. Good understanding will make it possible to quantify the processes, and therefore to model the system as a whole. Because of large annual fluctuations in the climate component of the system, it is necessary to be able to describe how the system functions in the long-term. A reliable model makes it possible to do this. Hence the term "modelling" in the title of this project.

The characteristics, productivity, and stability of the APS system depend on three natural resource factors, i.e. climate, topography and soil. All these factors are depicted in two dimensions in Figure 1.1. The diagram can be considered to represent the modal unit of a specific three-dimensional system (as it occurs in the landscape) in which the atmosphere (climate), topography, and soil are reasonably homogeneous. The boundaries of such a system are determined by points in the landscape at which the characteristics of one or more of the factors climate, topography or soil change significantly. The specific three-dimensional unit of the landscape outlined by these boundaries describes an **ecotope** as defined by MacVicar, Scotney, Skinner, Niehaus & Loubser, (1974). The broader national framework into which the ecotope fits has already been created for South Africa by the Institute for Soil Climate and Water in the form of the Land Type Survey. Ecotopes are subdivisions of these Land Types. The ecotope is an appropriate land unit for agronomic research and extension.

Returning to the APS system in Figure 1.1, and now considering it to represent a particular ecotope, it is logical that in order to understand the functioning of the water balance processes it will be necessary to first characterize the system in detail, and then to monitor the water balance processes over several growing seasons. This is a laborious task and can obviously only be carried out on a relatively small fraction of the hundreds of crop ecotopes present in South Africa. To obtain results which can be extrapolated as efficiently as possible, benchmark ecotopes, representing a wide range of ecotope characteristics, were selected for this study. Hence the term "benchmark ecotopes" used in the title of this project.

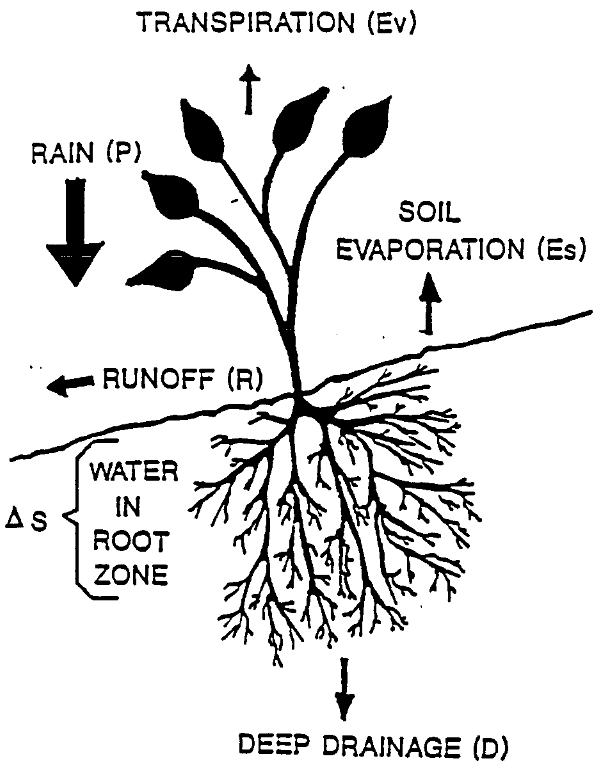


Figure 1.1. A diagrammatic representation of the atmosphere-plant-soil system, showing the important water balance processes

The water balance describes the relationship between the main water related processes in the APS system. Equation 1 is a slightly adapted form of the equation by Bennie (1984) for rainfed cropping.

water for yield = water gains - water losses

$$Ev = (P + \Delta S) - (Es + R + D) \quad \text{.........................(1)}$$

where:
- Ev = evaporation from the crop (transpiration) (mm)
- P = precipitation (mm)
- ΔS = water extracted from the root zone (mm)
- Es = evaporation from the soil (mm)
- R = runoff (mm)
- D = deep drainage (mm)

There are a number of practical reasons why it is important that the processes identified in Figure 1.1, and their interrelationships as described in Equation 1, be well understood, and that they be quantified at selected sites. Firstly, water is the most important limiting factor in rainfed crop production in the RSA - hence the value of determining Ev. Secondly, because of the overall shortage of water in the RSA it is important to quantify runoff (R) -

since this contributes to the water which can be stored in dams. R is also related to soil erosion. Thirdly, it is important to quantify deep drainage (D) because of its contribution to groundwater recharge and also because of the possibility of this water carrying pollutants (e.g. nitrates) into the groundwater.

Technological advances in recent years have made it possible to measure or estimate all the processes identified in Equation 1 with a reasonable degree of accuracy. These advances include automatic weather stations, the neutron water meter (NWM), tipping bucket runoff meters, and improved understanding regarding how the water balance processes function under different conditions. Being able to quantify the water balance at a particular site during a particular growing season is however by itself not of great value. Mainly because of the large variations in annual rainfall generally experienced in our cropping areas, it is necessary to be able to make reliable long term predictions about the water balance. This will ensure maximum usefulness of the results with regard to aspects such as crop management recommendations, surface hydrology and ground water recharge. To do this models are needed. It is clear that when they have been tested and adapted to give reliable results they will be valuable tools for the purposes mentioned.

Experience has shown that the water balance sub-routines of crop models currently being tested in the RSA frequently give unsatisfactory results. In particular, simulation of the processes ΔS, Es, R and D are unsatisfactory. The main reasons for this seem to be firstly, an inadequate understanding regarding these processes in different soils, and secondly, the absence of the necessary wide range of measured field data with which to improve the models.

1.1.1 The value of reliable models for making land use decisions

Land currently cultivated in South Africa can be divided into three categories viz.:

A Good arable land: sustainable long-term productivity easily possible with a relatively wide range of production techniques.

B Marginal arable land: sustainable long-term productivity only possible with specific production techniques efficiently employed.

C Poor arable land: land on which an acceptable level of sustainable long term productivity is not possible for a variety of reasons; rainfall too low, and/or erratic; water storage capacity too low in relation to rainfall amount and distribution; soil too frequently waterlogged.

Before crop models were available, land use decisions in relation to these categories had to be based on the results of field experiments at a limited number of sites and generally over relatively few seasons. This procedure has serious limitations which can be largely overcome by the judicious use of crop models, providing they are reliable. An important advantage of models is their ability to simulate long-term results. Another is the ability to extrapolate results to ecotopes on which measurements have not been made. Success in this respect will depend on the extent to which efficient mechanistic description of the relevant processes has been achieved. Field experiments retain their importance as they provide the means of testing and adapting the models.

A reliable crop model can be a valuable tool for decision making in relation to each of the named categories of cultivated land. In all cases the water balance is of fundamental importance. Because economic conditions and the level of technology (e.g. availability of new cultivars etc.) vary with time, decisions regarding the most suitable production techniques in categories A and B also vary. In these categories crop models can be used together with long-term climate data to identify the most profitable production techniques under current economic and technology conditions, e.g. which crop, best planting date, best population, best variety, best rotation etc. Identification of the best production techniques is critical in category B.

The cultivation of relatively large areas of land in category C in South Africa and other countries has led to serious degradation and economic problems. The well known "dust bowl" which developed in the USA due to the cultivation of unstable land is a good example. If quantitative long-term data is not available it is difficult to demarcate these areas convincingly. Impressive financial successes during a few above average seasons inevitably act as an irresistible temptation to farmers to throw caution to the winds. Reliable crop models can play a valuable role in identifying these unsuitable areas. Modelling degradation processes (e.g. water and wind erosion) mechanistically is difficult, and reliable models do not seem to be widely available yet. However, it should be possible to deal with yields, and therefore the economic aspects of low potential areas, with the present crop models, once the necessary tests and adaptations have been done.

With regard to long-term simulations an important weakness which both the PUTU and CERES/DSSAT3 models still have is their inability to accurately simulate the water balance during the fallow season. This is indicative of weaknesses particularly in their soil evaporation and runoff sub-routines. This weakness detracts from the reliability of long-term simulating with long-term climate data. For crops which grow during the rainy season, the assumption that the available water in the root zone is at 50% of capacity at planting each year, will probably give an answer close enough to the truth. With winter wheat grown in the summer rainfall area of South Africa the problem is more serious since the root zone water content at planting often has an important influence on yield. In this case a valuable strategy to define the yield potential of a particular ecotope is to make four separate runs with long-term weather data. For the first, second, third and fourth runs the available water in the root zone is assumed to be at ¼, ½, ¾ and full capacity, respectively. Ecotopes which cannot produce satisfactory long-term yields using the last two water contents clearly have a very low potential. The use of this strategy is demonstrated in Chapter 7.

1.1.2 The value of crop models for promoting efficient agronomic research

Because of the complexity of the processes in the APS system, current crop models still contain many assumptions which may or may not be valid over a wide range of ecotopes. Because of this a model is therefore, in a sense, a hypothesis with a holistic focus. This focus has unfortunately often been absent in agronomic research in the past. Agrometeorlogists, agronomists and soil scientists each tended to focus on their part of the APS system, whereas the farmer has to manage the system as a whole. The hypothesis which the model presents identifies those aspects which need to be researched. The model then provides a suitable vehicle for testing the research results.

1.1.3 The need to maximise rainfall use efficiency on all agricultural and forestry land

The water balance for South Africa as a whole can very approximately be described by Equation 2.

$$P = ET + R + Ss \text{ ....(2)}$$

where (all units mm)
P = precipitation
ET = evapotranspiration from vegetated or bare areas
R = runoff (includes runoff from the soil surface and from groundwater baseflow)
Ss = storage in the soil

Ss will generally be very low at the end of the growing season in most parts of South Africa. Therefore, in the long-term, and if one specifies that the time of assessment is at the end of the growing season, Ss probably becomes negligible. It is also reasonable to assume that in the long-term groundwater storage remains fairly constant (Personal communication, H. Maaren, 1996), making it possible to exclude this component of the water balance. Equation 2 can therefore be rewritten as follows:

$$P = ET + R$$

Data is available which makes it possible to make reasonable estimates for each of these components. Based on data from all their weather stations over a period of 30 years the Weather Bureau finds that the overall mean annual rainfall for South Africa is 501 mm. (Personal communication, Weather Bureau, 1996). R amounts to approximately between 8.4% and 8.5% of the rainfall (Personal communication, Department of Water Affairs, 1996, and H. Maaren, 1996).

Based on these estimates the water balance can be written as follows, with percentages given below each component.

$$\begin{aligned} P &= ET + R \\ 100 &= 91.5 + 8.5 \end{aligned}$$

The major portion of the country's rainfall is therefore used in evapotranspiration from the atmosphere-plant-soil system. This is the study realm of agricultural and forestry scientists. From a national perspective considerable responsibility therefore rests on them to ensure that rainfall use efficiency on their lands is as high as possible. The ever increasing demands on the country's limited water supplies accentuates this need. Because of the valuable ability of growth models to produce long term quantitative water-balance predictions, increasing their reliability to do this can, if properly employed, contribute towards increasing rainfall use efficiency on agricultural and forestry land.

1.2 AIMS

1.2.1 To obtain the necessary data over a period of 3 years at 8 benchmark crop ecotopes to test and adapt selected crop models so that they are capable of making reliable long-term predictions of the water balance and crop yield.

1.2.2 To use the calibrated models together with long-term climate data, to obtain for each benchmark ecotope:
- (a) Long-term cumulative distribution functions of yield - to serve as quantitative estimates of risk;
- (b) Long-term predictions of runoff and deep-drainage - to provide surface and sub-surface hydrological information;

1.2.3. To accumulate knowledge about how to adapt crop models to give reliable results for ecotopes with a wide range of characteristics and thus to improve the efficiency of extrapolation to unknown ecotopes.

1.3 HYPOTHESIS

With the expertise currently available, and with a suitable set of measurements on selected benchmark ecotopes over a number of seasons, it will be possible to adapt the maize and wheat models of the CERES/DSSAT3 and PUTU families of models to give satisfactory long-term predictions of the water balance and of yield on these ecotopes.

2. REVIEW OF LITERATURE

The focus here will be on a crop modified upper limit of available water (CMUL), the drained upper limit (DUL), deep drainage (D in Equation 1), and on the lower limit of available water (LL). These terms are defined as follows

CMUL: The maximum amount of water available from the root zone of a particular crop at a particular growth stage and at a particular evaporative demand. CMUL is always more than DUL because water can be taken up by plants while drainage is occurring. The critical factor is the drainage rate of the root zone and how it changes with time, i.e. the shape of the drainage curve. Although crop models make allowance for the available water above DUL, estimated values are generally used for the drainage rate. CMUL is based on a field measured drainage curve.

DUL: The highest field measured water content of a soil after it had been thoroughly wetted and allowed to drain until drainage became practically negligible i.e. when the water content decrease in the soil profile was about 0.1 to 0.2% water content per day. (Ratliff, Ritchie & Cassel,1983). Since the DUL plot is free of vegetation, and is covered by a plastic sheet to prevent evaporation, DUL depends solely on the properties of the soil profile. Crop and climate influence are excluded. For practical use the DUL value for the effective root zone of the relevant crop should be reported.

LL: The lowest field-measured water content of a soil after plants had stopped extracting water and were at or near premature death or became dormant as a result of water stress (Ratliff, Ritchie & Cassel,1983).

The drainage curve

Simple formulae are available (Hutson, 1983; Ritchie, Godwin & Singh, 1989), founded on texture based regression equations, to obtain estimates of DUL or an equivalent value. Although these estimates may be reasonably reliable for soils approximately within the range of the data base used, they are not necessarily applicable elsewhere. In a handbook for the CERES model (Ritchie, 1985) it is recommended that DUL be determined in the field by means of a drainage curve. Local experience has shown this to be a wise recommendation. However, because field determinations of DUL (and LL) are so laborious, a model of some sort for estimating values for these parameters, based on some simple measurements, is needed to facilitate the application of crop model technology at farm level. Although this matter is receiving attention no solution is available yet.

A suitable procedure for taking into account the water available to crops held temporarily above DUL (i.e. to give CMUL) has been described by Hattingh (1993); Hensley, Hattingh & Bennie (1993), and further information in this connection has been presented by Hensley (1996). Relevant results for selected benchmark ecotopes are presented in Table 9.2 Similar results for other soils are presented by Bennie, Hoffman, Coetzee and Vrey (1994). All these results assume that the drainage curve being used is a true reflection of what actually happens under field conditions after enough rain has fallen to fill the root zone to far above DUL. Problems in this connection in soils with impeded subsurface drainage are dealt with in section 5.5.2

The lower limit of available water

Crop models are currently not designed to accommodate an algorithm to describe a stress-curve for a specific crop ecotope. For determining total root water uptake (TRWU) in the SOYGRO, CERES-MAIZE and the CERES-WHEAT models, the procedure being used is based on Ritchie's water-balance model (Ritchie, 1985), in which Equation 3 is of basic importance.

$$Qr = 2.64 \times 10^{-3} \exp(62 \times (\theta-\theta_l))/6.68 - \ln Lv \text{ ....(3)}$$

Where:

Qr = rate of water-uptake through roots [cm^3 water (cm root)$^{-1}$ d^{-1}]
θ = water content of the root-zone at a specific time (cm^3 water cm^{-3} soil)
θ_l = lower limit of available water for the root-zone (cm^{-3} water cm^{-3} soil)
$(\theta-\theta_l)$ = volume of water-content above LL (cm^3 water cm^{-3} soil)
Lv = root length density (cm roots cm $^{-3}$ soil)

Equation 3 is based on certain suppositions. Some of these may not be valid for certain soils. To enable the use of Equation 3 in modelling, Ritchie (1985) incorporated a set of measured values for $(\theta-\theta_l)$ and Lv from Taylor and Klepper (1975) and Gregory, McGowan & Biscoe (1978). The relationship between Qr and $\theta-\theta_l$ could thus be described for various Lv values. Taylor and Klepper (1975) worked on Cahaba fine-loam-sand soil in a lysimeter in Alabama (USA). Gregory *et al*, (1978) worked on an Astley sandy-loam soil in Suffolk in England. The Ritchie (1985) results are depicted in Figure 2.1. Clearly Lv had a relatively small influence on Qr, despite the fact that Qr is plotted on a log-scale (Y-axis). Figure 2.3 shows the Ritchie (1985) results for an Lv value of 1, together with comparable results of other researchers. A linear scale is now used on the Y-axis and the relationship is clearly curvilinear.

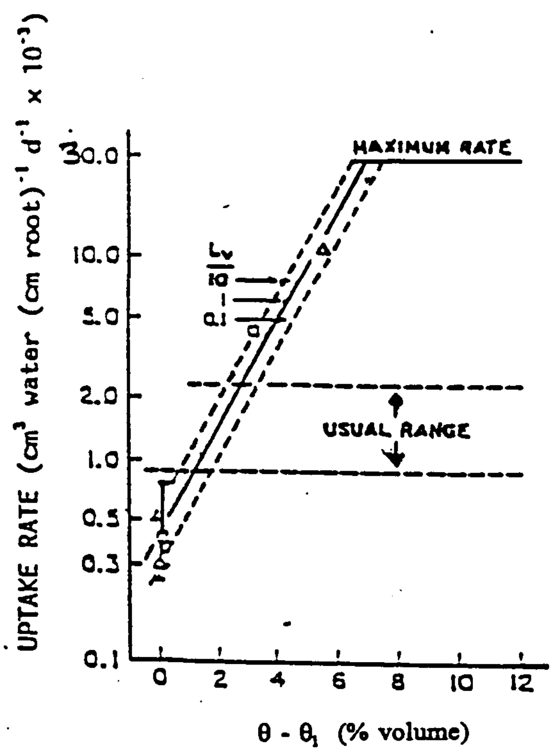


FIGURE 2.1: A graphic representation of the relationship between Qr and θ-θ_l with various Lv values (after Ritchie, 1985)

In the CERES models Lv is estimated for a specific crop at a specific age by a partitioning of photosynthate procedure. Qr is apparently obtained as follows: to begin the simulation specific values for θ_l and for θ are needed. θ-θ_l will then be available for the first day of the growing season. With the estimated Lv, a Qr value can be obtained for that day using Equation 3. This causes a reduction in θ thus giving a value for θ-θ_l for the following day, and thus also for each day after that. Plant growth results in increased root density and total root length. This process is simulated day by day by the photosynthate partitioning procedure. For each new day a value for Lv is supplied together with the relevant θ-θ_l values, thus enabling that day's Qr to be estimated. The estimated Qr values, and total root-lengths makes it possible to estimate total root water uptake (TRWU) (which can be considered to be equal to Ev).

Notice the important role played by root length density and total root-length when estimating TRWU. The following observations are therefore important:

* Root-distribution is difficult to determine (Stone, Teare, Nickell & Mayaki, 1976 and Gregory, *et al,* 1978).
* About 30% error may occur when determining root-density (Taylor & Klepper, 1975).
* Ritchie (1985) comments that "It should be mentioned that a weak part of CERES, and of crop models in general, is the simulation of the dynamics of root growth in the soil. More quantitative root growth information is needed

before major improvement can be made in the root growth part of CERES".

In the CERES family of models the stress index is defined as TRWU/EP, where EP = potential evapotranspiration. Figure 2.2 describes the relationship between TRWU/EP and the physiological processes of a crop, used in these models. The relative rate of progress of the processes are considered to start declining when SWDF1 and SWDF2 fall below 1. An incorrect estimate of TRWU will therefore lead to an inaccurate estimate of yield. Notice that the influence of stress on physiological processes is considered to be linear, and the same for a variety of crops.

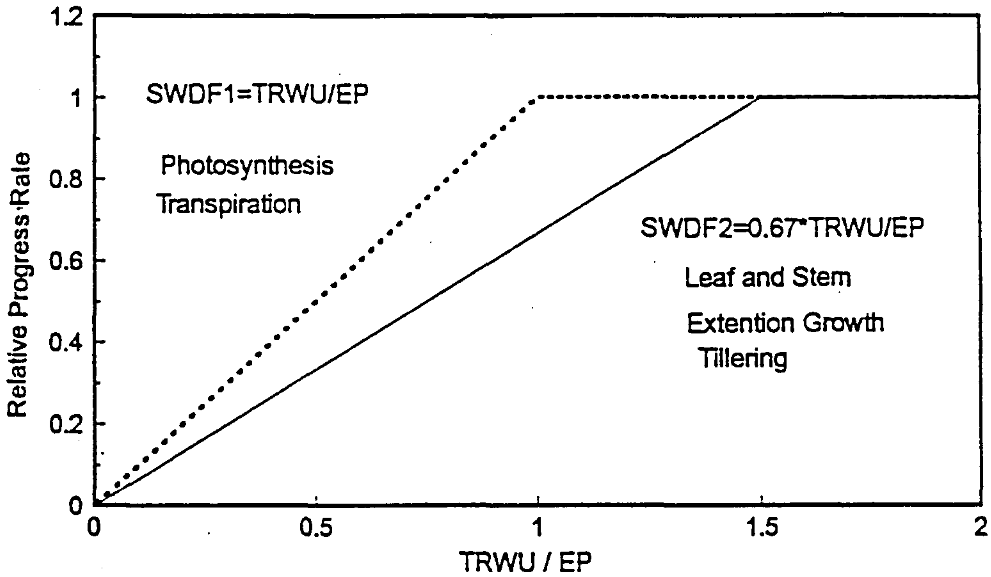


FIGURE 2.2: The relationship that is used to estimate the soil-water deficit factors SWDF1 and SWDF2 in the CERES family of models (after Johnson & Ritchie, 1989)

Bennie, Coetzee, Van Antwerpen, Van Rensburg & Burger, (1988) carried out a crop water use investigation in the Bloemfontein, Ramah, Sandvet and Vaalharts areas. The range of soils studied included Hutton Form (Shorrocks and Mangano series); Clovelly Form (Annandale, Vaalbank and Bleskop series); Oakleaf Form (Vaalrivier, Limpopo and Jozini series). The studies included four crops at 50 sites. The clay percentage in the B_1 horizons of the soils usually ranged between 5% and 20%. Measured values of Bennie, *et al*, (1988) were used to determine Qr using Equation 3. The average rooting density over the entire root-zone was used. Van Rensburg (1996) investigated the crop water-use on a deep soil of the Bainsvlei Form, Amalia Family with 16-20% clay in the B_1 horizon. Their results are presented in Figure 2.3, together with those of Ritchie (1985).

The aim of Figure 2.3 is to show that different climates, crops and soils give different relationships of Qr to $(\theta-\theta_l)$. It is clearly unsatisfactory to use only one relationship, as proposed by Ritchie (1985). Although the curves are influenced to a certain degree by the relevant Lv, Figure 2.1 indicates that this influence will be small over the range of values involved here.

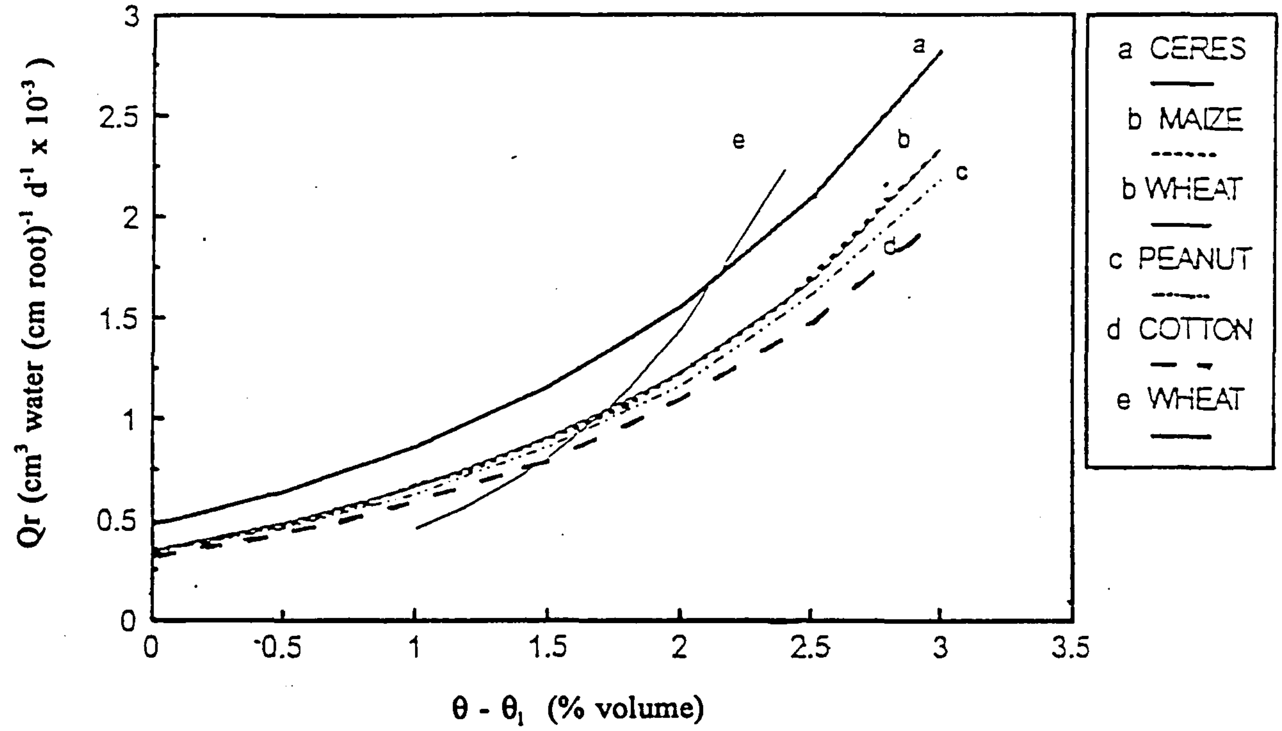


FIGURE 2.3: A graphic representation of the relationship between Qr and θ-θ_l based on the results of various researchers: Ritchie (1985), Lv = 1.0 cm cm^{-3} [graph a]; calculated data based on field results obtained by Bennie, *et al* (1988), [graphs b, c and d], and Van Rensburg (1996) [graph e]. The Lv values for the latter two studies were approximately between 0,2 and 0,7 cm cm^{-3} for the study by Bennie *et al*, and 0.5 cm cm^{-3} for Van Rensburg (1996).

The stress algorithms used by PUTU-MAIZE and PUTU-WHEAT are described by Equations 4 and 5 respectively (A. Singels, 1996. Personal communication).

$$Ev/Evp = 1 - \exp^{(0{,}005 \times (PSIL + 1600)} \quad \text{.........................} \quad (4)$$

Where:

Ev = transpiration (mm d^{-1})
Evp = potential transpiration (mm d^{-1})
PSIL = leaf-water potential (KPa)

$$Ev/Evp = 1 - \exp^{(-0.0017*(PSI - (PSIC - 300)))} \quad \text{................} \quad (5)$$

Where:

Ev and Evp are the same as in equation 4
PSI = leaf-water potential (KPa)
PSIC = critical leaf water potential (-1200 KPa)

These algorithms are graphically portrayed in Figure 2.4. It is important to note that there is a specific algorithm for a specific crop, and also that the relationships are curvilinear.

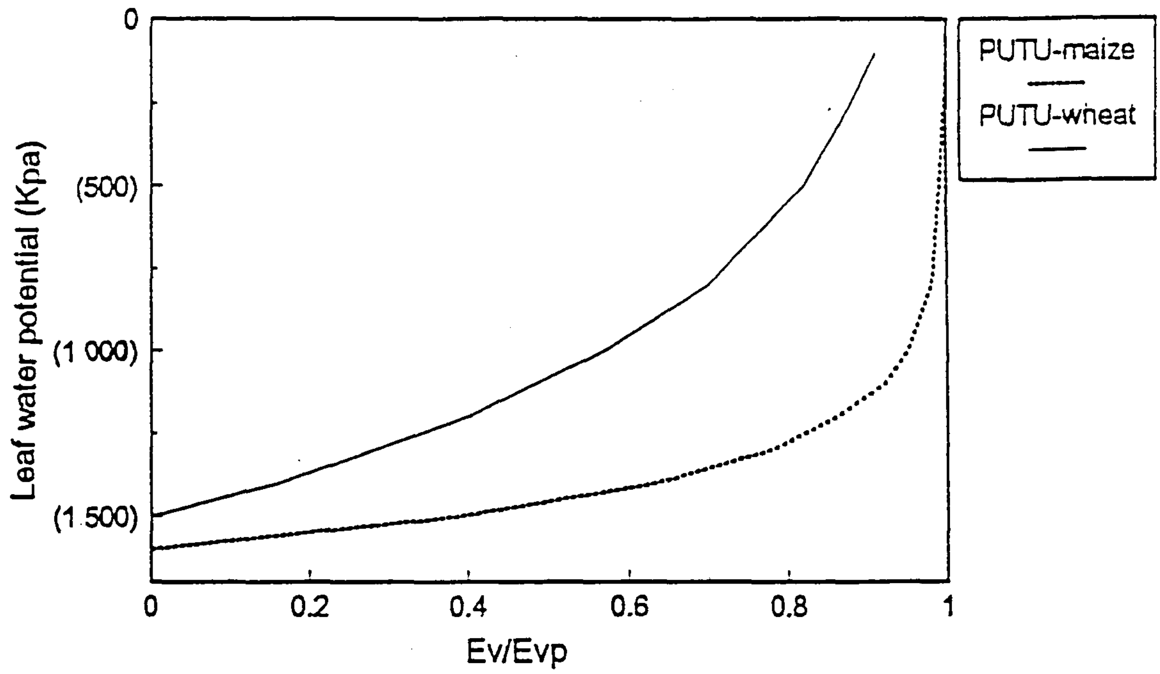


FIGURE 2. 4: A diagrammatic representation of the algorithms (Equations 4 and 5) which are used in PUTU to define increasing stress (A. Singels, 1996. Personal communication).

3. PROCEDURE

3.1 Measurements

The soil component of each ecotope was characterised in detail by means of a soil profile description, analytical data, bulk density and saturated hydraulic conductivity determinations on each horizon, a field determined drainage curve, to give the upper limit of available water, and a field measured lower limit of available water.

To achieve the aims of the project it was attempted to measure as well as possible the water balance components P, ΔS, R and D in Equation 1 and use them to calculate ET. Climatic variables needed by the crop models were measured with automatic weather stations at all the ecotopes excepting for Setlagole/Clovelly where daily rainfall was measured by the farmer and the remaining values were obtained from the nearest suitably equipped weather station. ΔS was measured with neutron water meters. Specific calibration lines were compiled for each soil, and where necessary for each soil horizon. Runoff was measured with automatic tipping-bucket runoff meters, and D was estimated from drainage curves. Grain yields were measured at the end of each season. Since ET is closely related to yield (Bennie, *et al*, 1994) the procedure outlined provides a suitable means of testing crop model performance, identifying weaknesses, and therefore facilitating improvement of the models.

For testing model performance against measured values the statistical procedures proposed by Willmott (1981) were used. Risk assessment was by means of predicted cumulative yield probability functions (CDF's). These were obtained by running the models with long-term climate data for each ecotope.

3.2 Experimental details

Table 3.1 Descriptions of the experiments on each ecotope

Ecotope	Crop	Kind of experiment	Row width (m)	Approx. plant population (plants ha^{-1})
Setlagole /Clovelly	maize	farmer's field	2.3	14 000
Wolmaransstad /Hutton	maize	single plot	2.3	17 000
Kroonstad /Avalon	maize	randomised block	see detail below	see detail below
Bethal /Hutton	maize	randomised block	see detail below	see detail below
Bethal/Avalon	maize	single plot	0.9	35 000
Ermelo /Longlands	maize	farmer's field	0.9	35 000
Bultfontein /Clovelly	wheat	randomised block	see detail below	see detail below
Petrusburg /Bloemdal	wheat	randomised block	see detail below	see detail below

Water balance measurements on the Kroonstad/Avalon ecotope were made on selected treatments of a randomised blocks row width X plant population experiment of the Grain Crops Institute. The responsible researcher was Mr. M.A. Prinsloo. Treatments consisted of 3 populations (15 000, 30 000 and 45 000 plants per hectare), and 4 row-widths (1.0 m, 1.5 m, 2.0 m, and alternate rows of 1 and 2 m, or "tramlines"). There were 3 replications. The treatments selected for water balance measurements were all the combinations of the first two named populations and the first three named row widths. The water balance results presented are mean values for all the treatments studied.

On the Bethal/Hutton ecotope water balance measurements were made on a randomised block, plant population X N level experiment on the OTK experiment farm Wildebeesfontein. The responsible researcher was Mr. I.A. Koster.

The water balance measurements on the Bultfontein/Clovelly and Petrusburg/Bloemdal ecotopes were made on a cultivar/crop modelling experiment of the Small Grain Institute. The responsible researchers were Messrs. J. Purchase, W. Killian and W.H.O. du Toit. As the water extraction patterns for the different cultivars were very similar, mean values are presented.

3.3 Model testing and adaptation

Testing and adaptation of the DSSAT3 (MAIZE) model was done by Messrs. M. Prinsloo and A. du Toit of the Grain Crops Institute, and of the PUTU-MAIZE and the PUTU-WHEAT models by Prof. A. Singels of the Department of Agrometeorolgy, University of the Orange Free State. Mr. J.J. Anderson was the ISCW cooperator for these tasks. The necessary adaptions to the DSSAT3 wheat model still have to be made.

4. DESCRIPTION OF THE ECOTOPES STUDIED

The value of the ecotope concept lies in the fact that, because it incorporates all aspects of the APS system, it defines all the factors which influence the productivity of land, viz. climate, soil and topography. Because of the complexity of the system, and the interaction of the many processes involved, detailed definition of each ecotope is needed to facilitate the extrapolation of information to other similar ecotopes (i.e. pedotransfer activities) at which it has not been possible to monitor the water balance processes. To ensure maximum value from the expensive measurements made at each ecotope, it is therefore desirable that each one be characterized as well as possible. Effective characterization is the purpose of this chapter. The focus will be on those soil characteristics which influence the water balance.

Only a very brief written description will be given of each ecotope, as most of the supporting information is self explanatory. In each case there is a profile description and analytical data (Appendix 1), a table containing concise information (Tables 4.1. to 4.8) about important characteristics (note that PLEXW, potential extractable water, = DUL - LL) and figures in the text describing the drainage curve and soil water extraction pattern. Numbering in Appendix 1 and of the tables and figures in the text follow the order in which the ecotopes are presented below. Rainfall details for each ecotope are presented in Chapter 5.

4.1 Setlagole/Clovelly

This ecotope is situated in a semi-arid area with a mean annual precipitation (MAP) of 446 mm, close to the edge of the Kalahari desert. Approximately 500 000 ha of land is cultivated in this region, which is considered by many to be marginal for cropping. The main crops grown are maize, groundnuts and cotton. The Setlagole/Clovelly ecotope represents the better soils in the region.

The soil is yellow brown and sandy and with a potentially very deep root zone (2100 mm, Table 4.1). The DUL is a measured value but the drainage curve has been synthesised from measurements on a similar soil elsewhere.

4.2 Wolmaransstad/Hutton

This is a relatively shallow (900 mm, Table 4.2) red medium textured soil. The underlying material, consisting of colluvial stones and rocks mixed with a little soil, has a permeability which is probably moderate to slow. The climate is slightly less arid than that at Setlagole. The MAP is 541 mm.

4.3 Kroonstad/Avalon

In the present context the climate can be described as between semi-arid and sub-humid. The MAP is 575 mm. The Avalon soils are important for cropping in the summer rainfall areas of South Africa. The characteristic horizon is the soft plinthic which starts here at a depth of around 600 mm below a medium textured yellow brown B horizon (Table 4.3). The effective rooting depth for maize varies from season to season depending on rainfall. With continuous heavy rains early in the season the effective rooting depth for maize will probably only be about 600 mm. During a season with good rains very early, followed by dry months, the effective rooting depth will probably be around 1200 or 1400 mm.

4.4 Bethal/Hutton

This ecotope and the Bethal/Avalon are situated about 200 meters apart in one of the best maize growing areas in South Africa. The climate is sub-humid and the MAP 680 mm. The soil is deep, red, and medium to fine textured, with a high water holding capacity (Table 4.4).

4.5 Bethal/Avalon

The soil has similar characteristics (Table 4.5) to those already described for the Kroonstad/Avalon ecotope, although the soil water regime here is somewhat wetter. Details about the water regime are presented in Chapter 5.

4.6 Ermelo/Longlands

The climate is sub-humid, MAP is 680 mm, and the soil is hydromorphic, with an E horizon at 500 mm (Table 4.6). This horizon becomes waterlogged during wet years, which occur relatively frequently in the region. Waterlogging is the main limiting factor for maize production.

4.7 Bultfontein/Clovelly

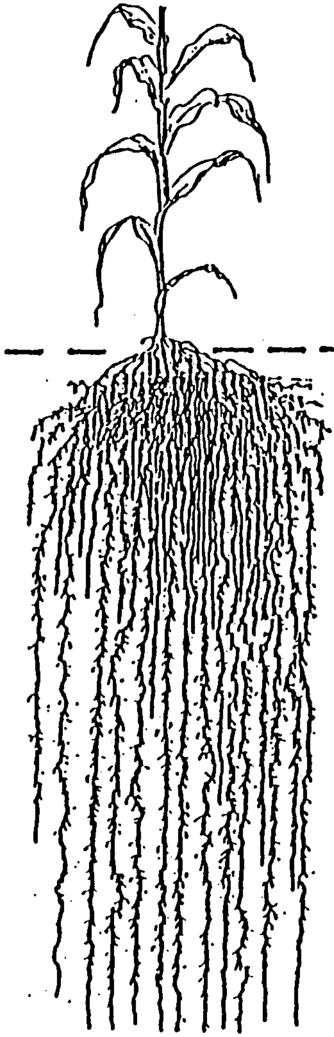
This is a deep, yellow brown, sandy soil (Table 4.7) in a semi-arid environment. MAP is 438 mm. Both wheat and maize are grown successfully in the region. Wheat was the crop for the present study.

4.8 Petrusburg/Bloemdal

The climate is semi-arid, MAP is 443 mm, and the soil deep, sandy, and red brown in colour (Table 4.8). The region is too dry for dryland maize production but wheat is grown with reasonable success, especially where the long-fallow strategy is used.

Profile detail

Diag. hor	Colour	Clay (%)	>2mm (%)	BD ($g.cm^{-3}$)	Depth (mm)
ot	YBr	6		1.5	200
ot	YBr	6		1.7	300
ye	YBr	8		1.7	600
ye	BrY	9		1.6	900
ye	BrY	10		1.6	1200
ye	BrY	10		1.6	1500
ye	BrY	10		1.6	2100



Water properties

DUL (mm)	LL (mm)	PLEXW (mm)	Ksat (mm/h)
20	7	13	
10	5	5	143
36	21	15	419
31	20	11	419
31	21	10	419
31	21	10	419
65	44	21	
224	139	85	

Table 4.1 The soil component of the Setlagole / Clovelly Ecotope.

Land type : Ah17
Terrain morphological unit : 4
Slope % : 1
Soil classification : Form : Clovelly
: Family : Setlagole

Fig.4.1.1 Drainage curve for the Setlagole / Clovelly ecotope

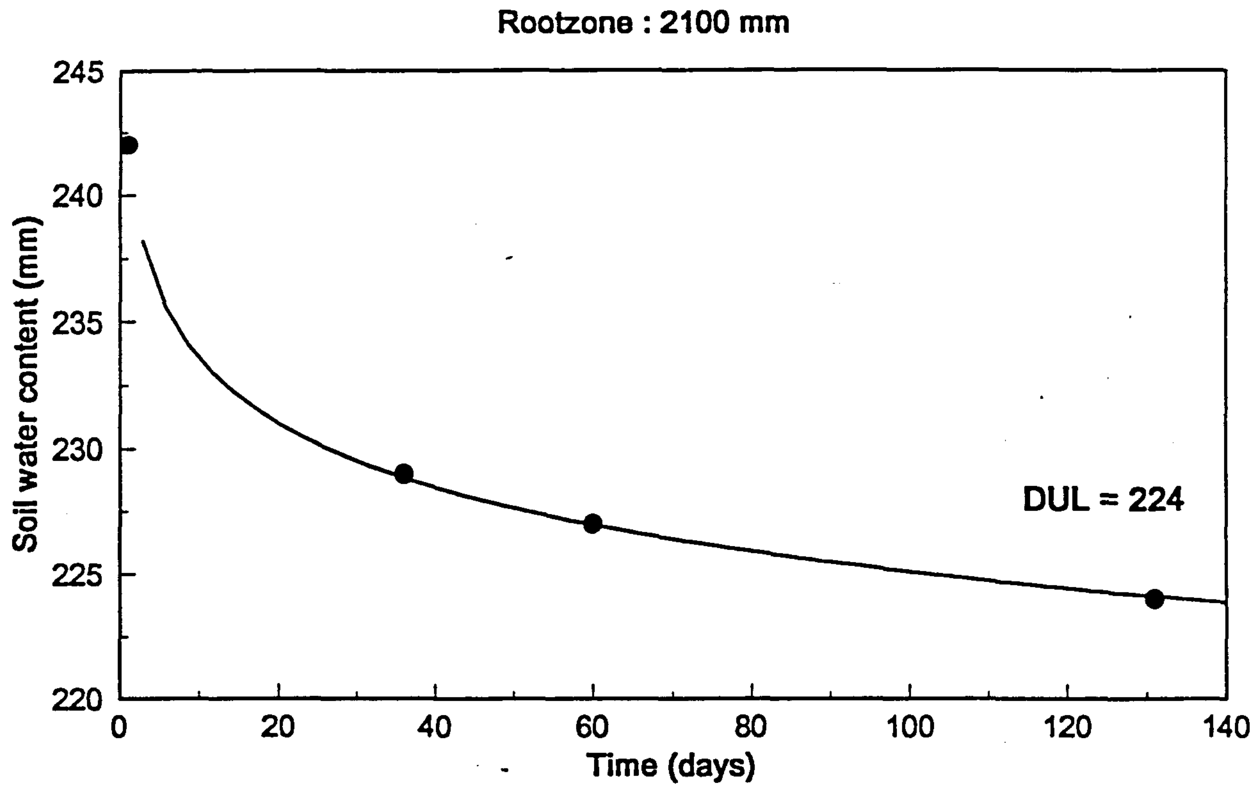
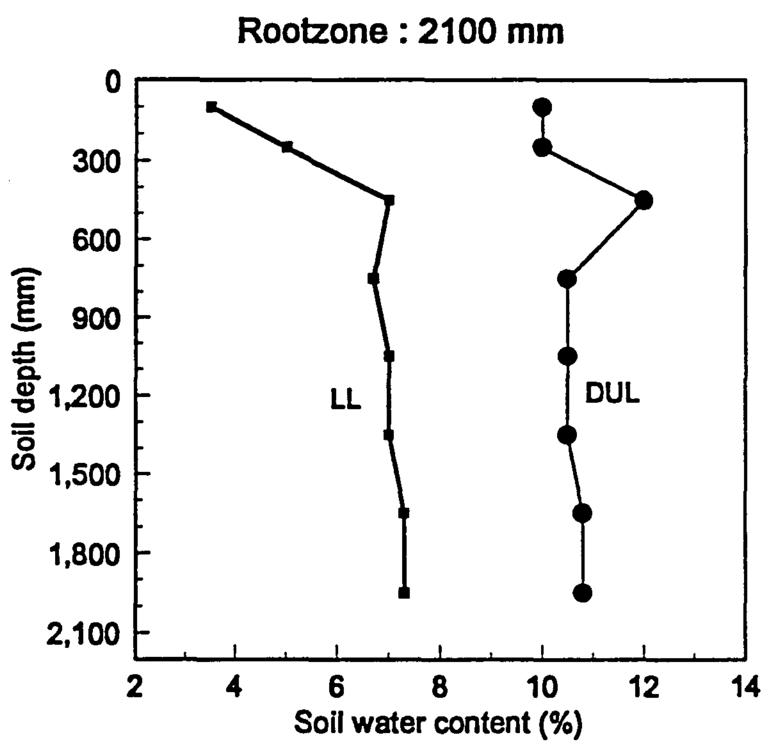
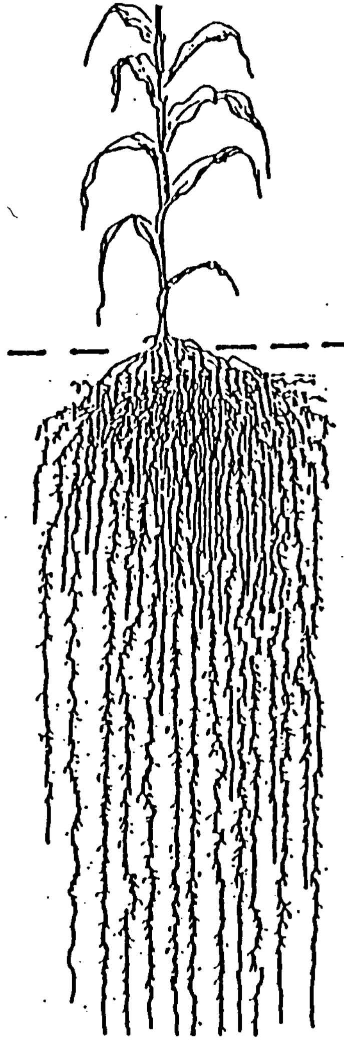


Fig.4.1.2 Soil water extraction diagram for wheat on the Bultfontein / Clovelly ecotope



Profile detail

Diag. hor	Colour	Clay (%)	>2mm (%)	BD ($g.cm^{-3}$)	Depth (mm)
ot	RBr	15		1.5	200
ot	RBr	15		1.5	300
re	RBr	22		1.5	600
re	RBr	24		1.5	900



Water properties

DUL (mm)	LL (mm)	PLEXW (mm)	Ksat (mm/h)
24	17	7	
15	9	6	
48	29	19	145
49	21	28	145
136	76	60	

Table 4.2 The soil component of the Wolmaranstad / Hutton Ecotope.

Land type : Bc19
Terrain morphological unit : 4
Slope % : 1
Soil classification : Form : Hutton
: Family : Ventersdorp

Fig.4.2.1 Drainage curve for the Wolmaransstad / Hutton ecotope

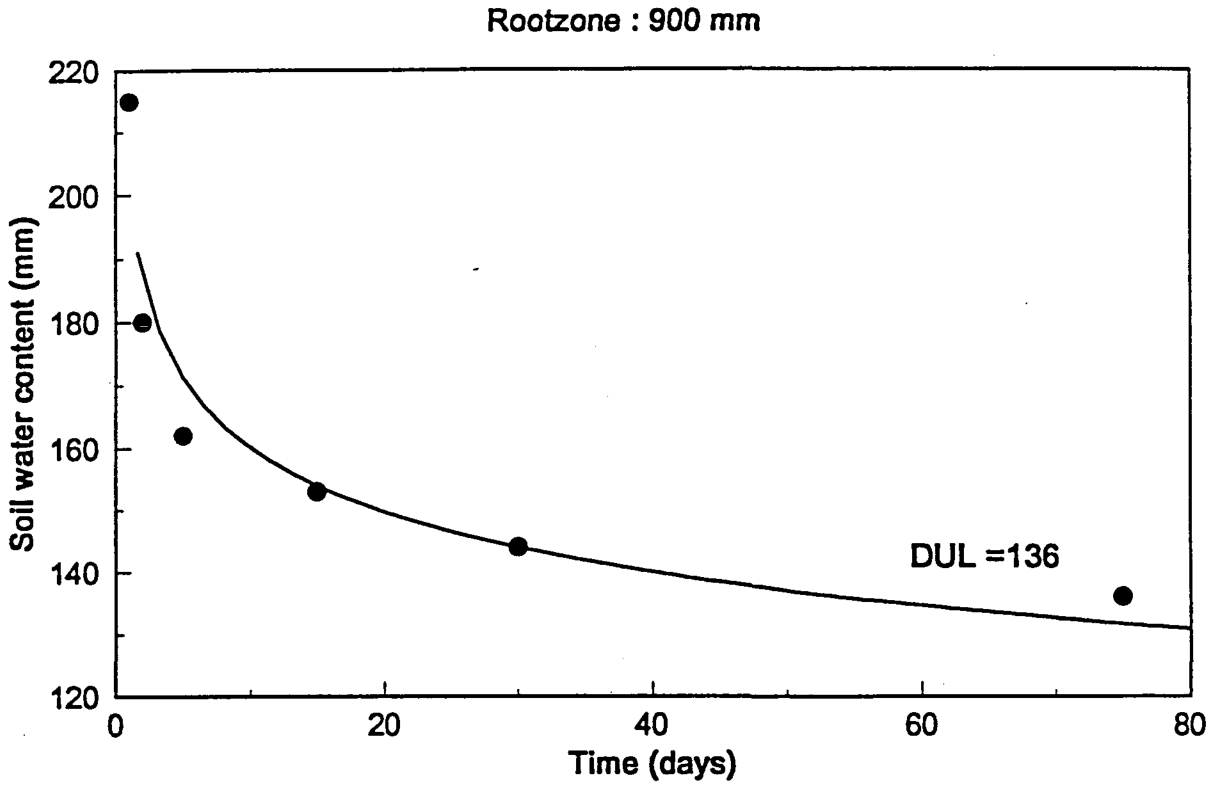
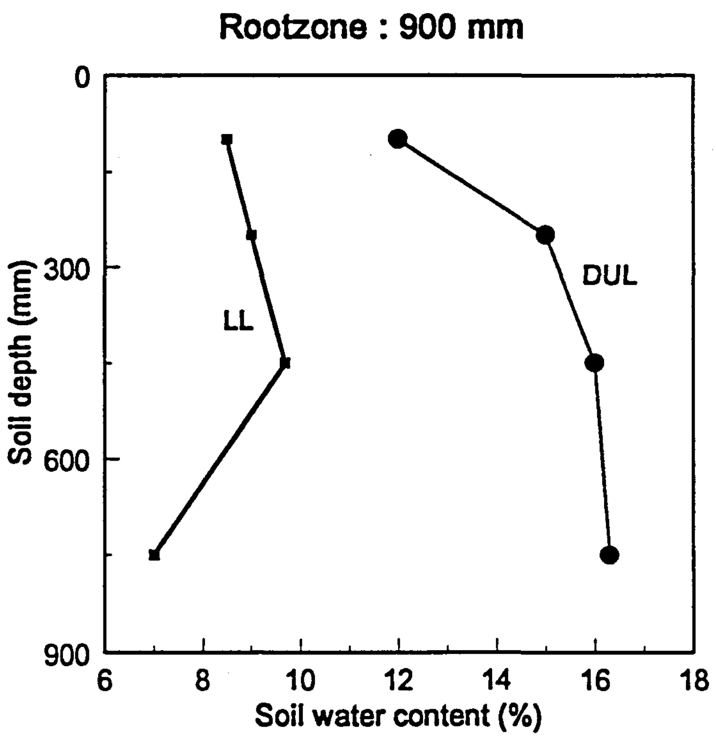
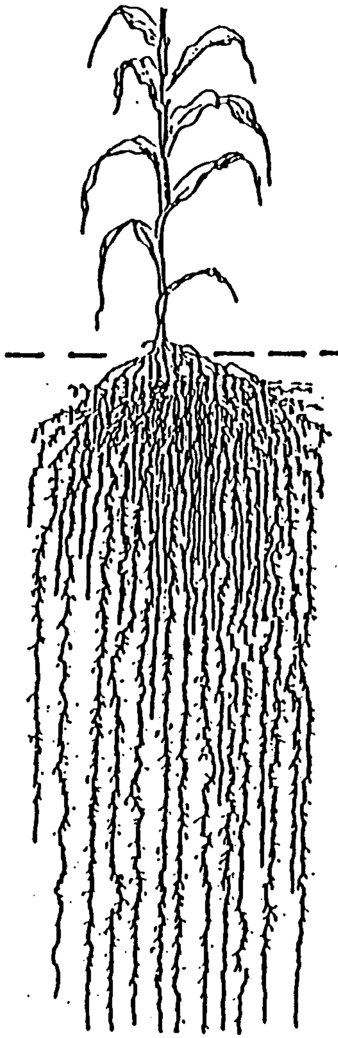


Fig.4.2.2 Soil water extraction diagram for maize on the Wolmaransstad / Hutton ecotope



Profile detail

Diag. hor	Colour	Clay (%)	>2mm (%)	BD (g.cm^{-3})	Depth (mm)
ot	Brown	8		1.5	200
ot	Brown	12		1.7	300
ye	DkYBr	16		1.6	600
Sp	DkYBr Mottled	32		1.6	800
Sp	Mottled	45		1.6	1000
Sp	Mottled	45		1.7	1400



Water properties

DUL (mm)	LL (mm)	PLEXW (mm)	Ksat (mm/h)
40	11	29	
17	9	8	
58	35	23	83
38	32	6	55
40	37	3	3
95	75	20	
288	199	89	

Table 4.3 The soil component of the Kroonstad / Avalon Ecotope

Land type : Bd21
Terrain morphological unit : 3
Slope % : 1.5
Soil classification : Form : Avalon
: Family : Kameelbos

Fig. 4.3.1 Drainage curve for the Kroonstad / Avalon ecotope

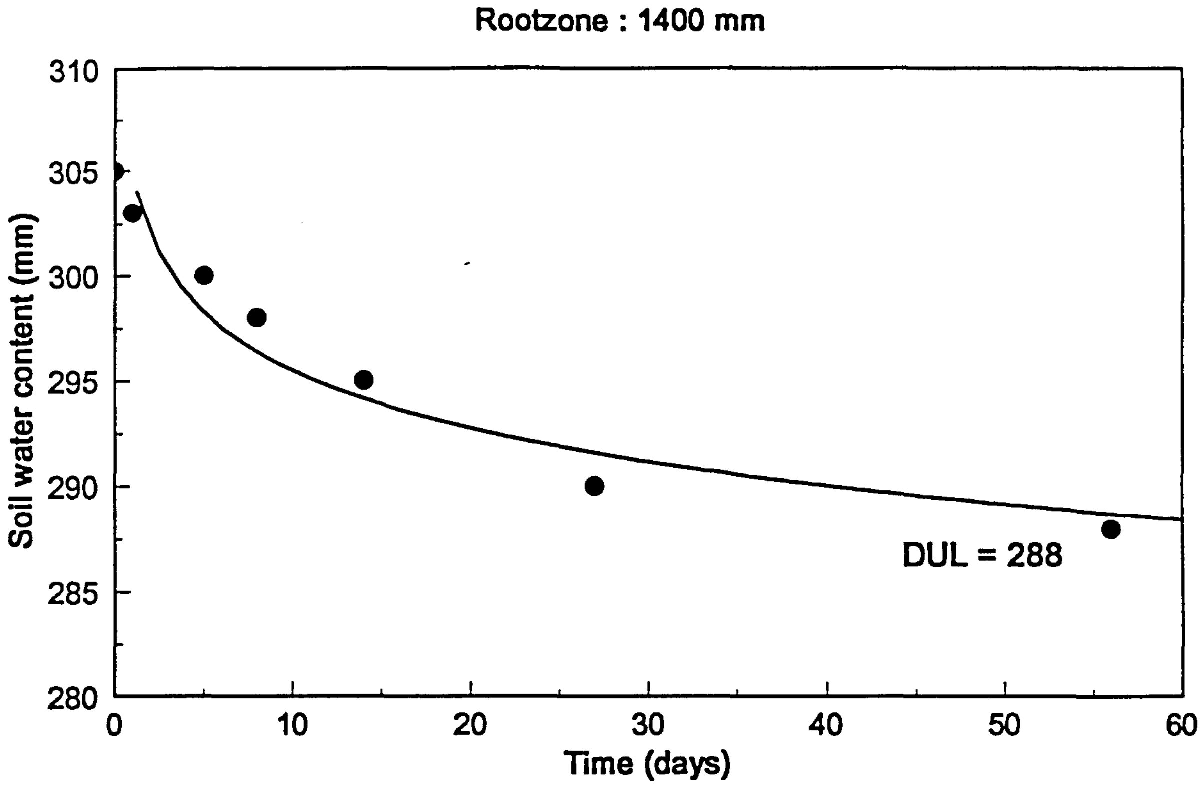
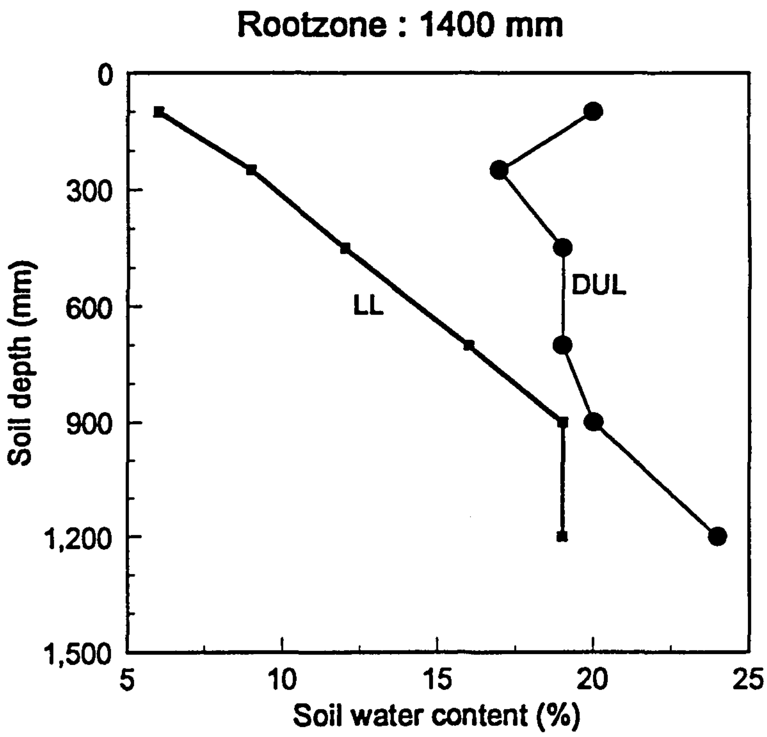
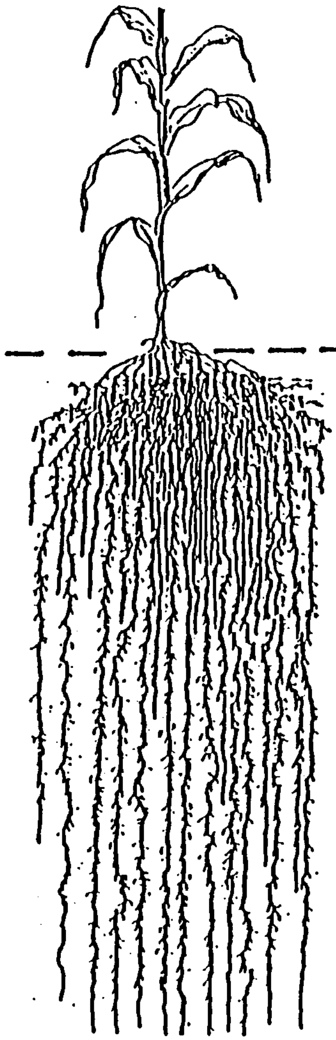


Fig. 4.3.2 Soil water extraction diagram for maize on the Kroonstad / Avalon ecotope



Profile detail

Diag. hor	Colour	Clay (%)	>2mm (%)	BD ($g.cm^{-3}$)	Depth (mm)
ot	DkRBr	18		1.3	200
ot	DkRBr	23		1.3	300
re	DkRBr	28		1.6	600
re	DkRBr	28		1.6	900
re	DkR	31		1.6	1200
re	DkR	31		1.6	1500
re	DkR	31		1.6	1800



Water properties

DUL (mm)	LL (mm)	PLEXW (mm)	Ksat (mm/h)
39	10	29	
17	5	12	
51	20	31	214
49	29	20	214
53	32	21	
55	38	17	
59	37	22	
323	171	152	

Table 4.4 The soil component of the Bethal / Hutton Ecotope.

Land type : Bb4
Terrain morphological unit : 4
Slope % : 1
Soil classification : Form : Hutton
: Family : Hayfield

Fig. 4.4.1 Drainage curve for the Bethal / Hutton ecotope

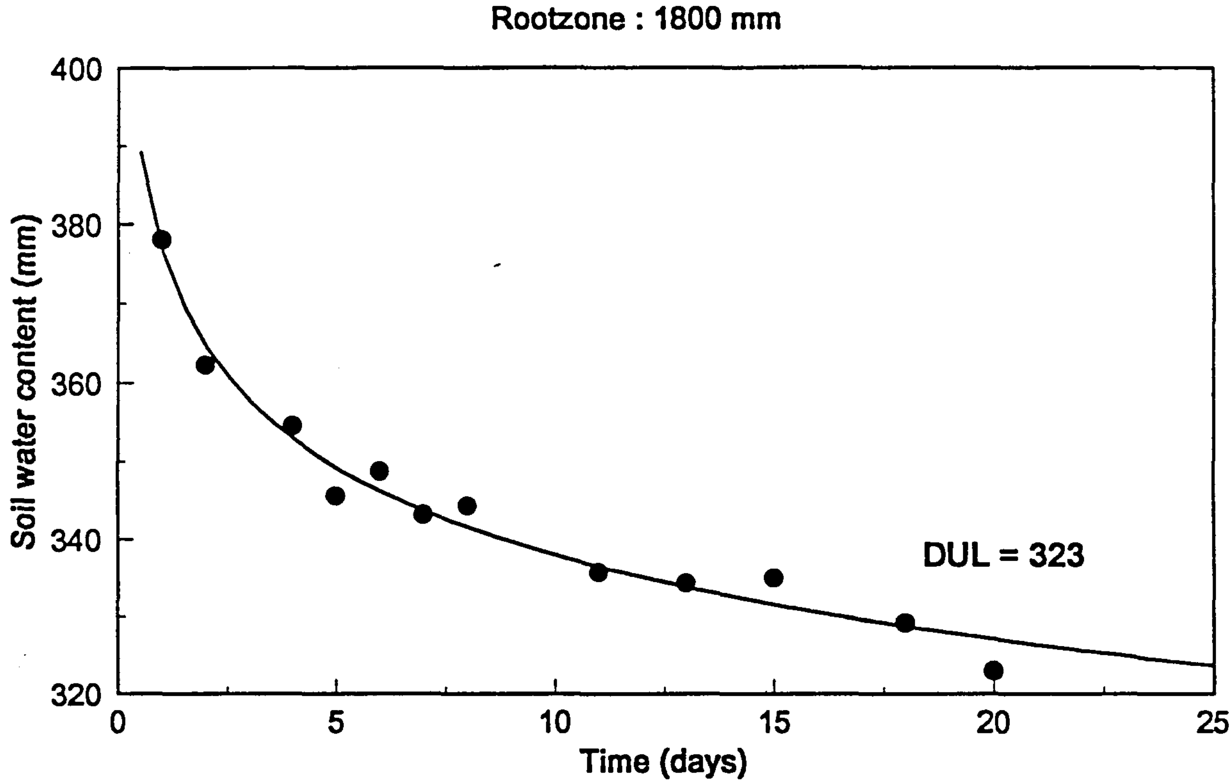
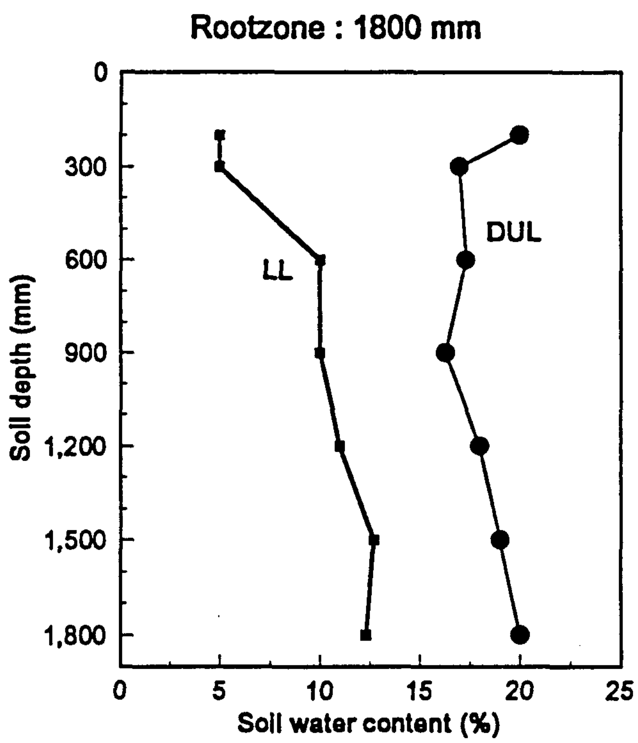
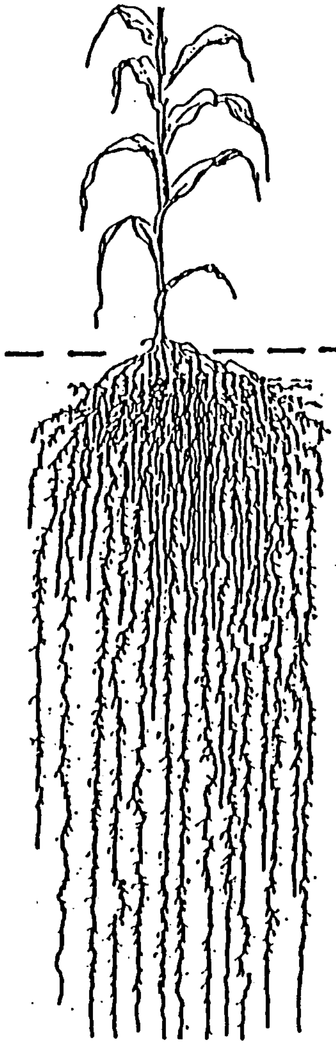


Fig 4.4.2 Soil water extraction diagram for maize on the Bethal / Hutton ecotope



Profile detail

Diag. hor	Colour	Clay (%)	>2mm (%)	BD ($g.cm^{-3}$)	Depth (mm)
ot	DkBr	9		1.7	200
ot	DkBr	16		1.7	400
ye	YBr	24		1.6	700
sp	Mottled	23		1.6	900
sp	Mottled	25		1.6	1200



Water properties

DUL (mm)	LL (mm)	PLEXW (mm)	Ksat (mm/h)
37	13	24	
34	14	20	
54	26	28	87
32	12	20	183
70	44	26	87
227	113	114	

Table 4.5 The soil component of the Bethal / Avalon Ecotope.

Land type : Bb4
Terrain morphological unit : 4
Slope % : 1
Soil classification : Form : Avalon
: Family : Mafikeng

Fig. 4.5.1 Drainage curve for the Bethal / Avalon ecotope

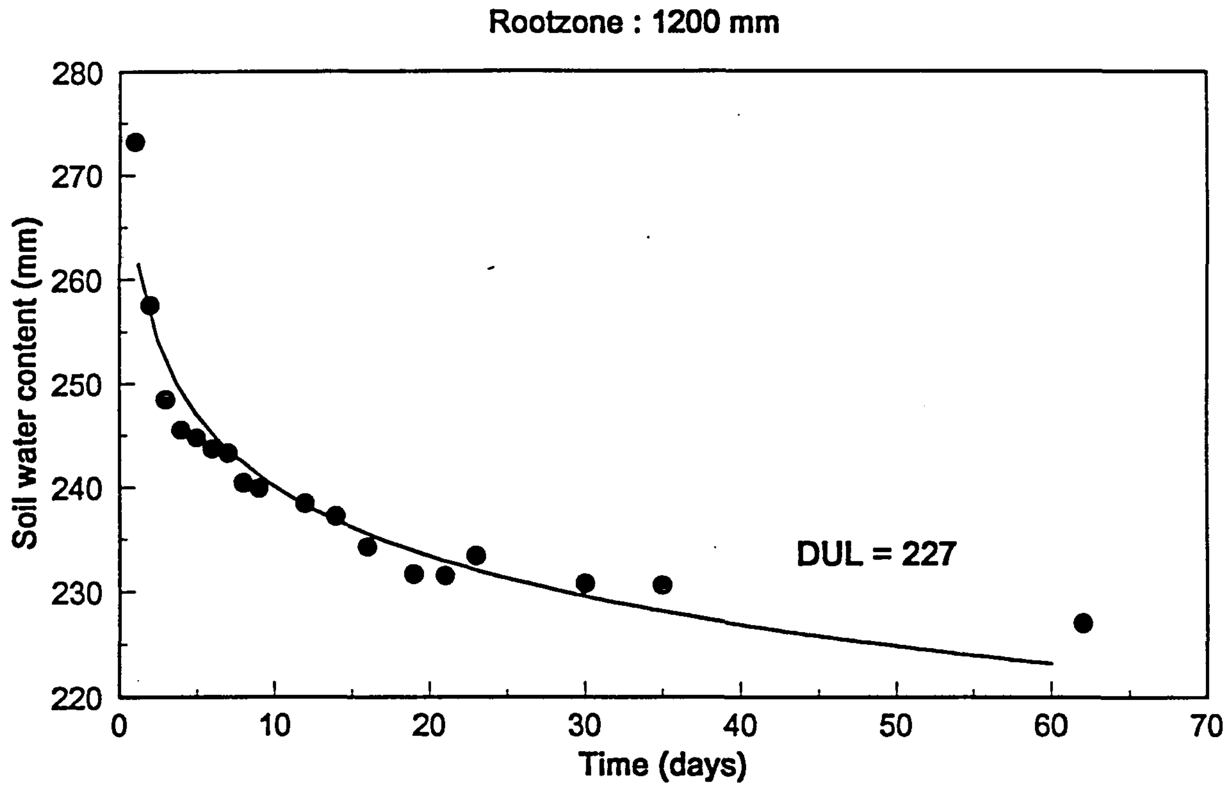
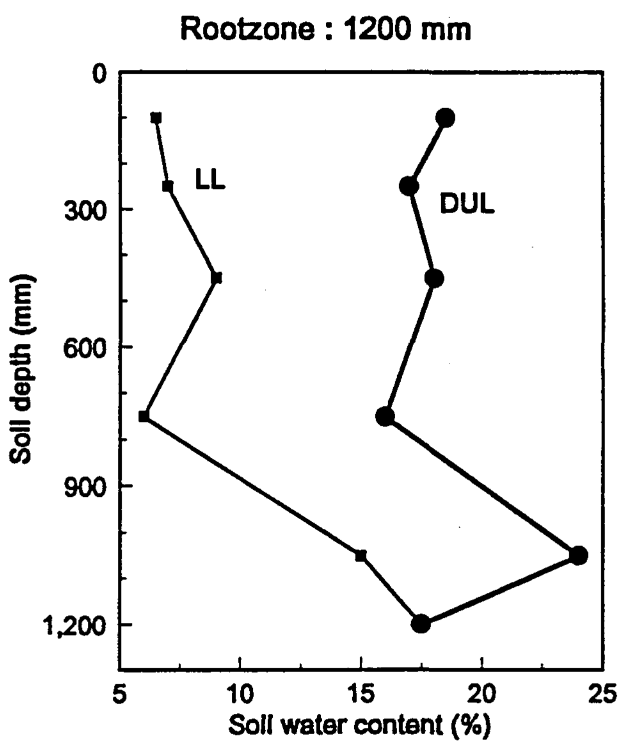
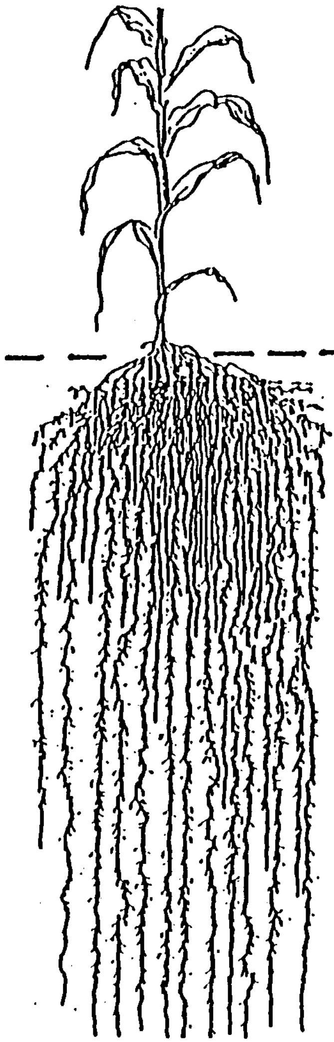


Fig. 4.5.2 Soil water extraction diagram for maize on the Bethal / Avalon ecotope



Profile detail

Diag. hor	Colour	Clay (%)	>2mm (%)	BD ($g.cm^{-3}$)	Depth (mm)
ot	Brown	8		1.4	200
ot	Brown	8		1.5	400
ot/E	LtYBr	4		1.5	500
E	LtYBr	4		1.9	700
Sp	LtGr Mottled	23		1.8	900
Sp	LtGr Mottled	23		1.8	1200



Water properties

DUL (mm)	LL (mm)	PLEXW (mm)	Ksat (mm/h)
29	14	15	
35	16	19	
20	10	10	
40	9	31	63
53	24	29	1
82	60	22	
259	113	126	

Table 4.6 The soil component of the Ermelo / Longlands Ecotope

Land type : Ca3
Terrain morphological unit : 3
Slope % : 3
Soil classification : Form : Longlands
: Family : Ermelo

Fig. 4.6.1 Drainage curve for the Ermelo / Longlands ecotope

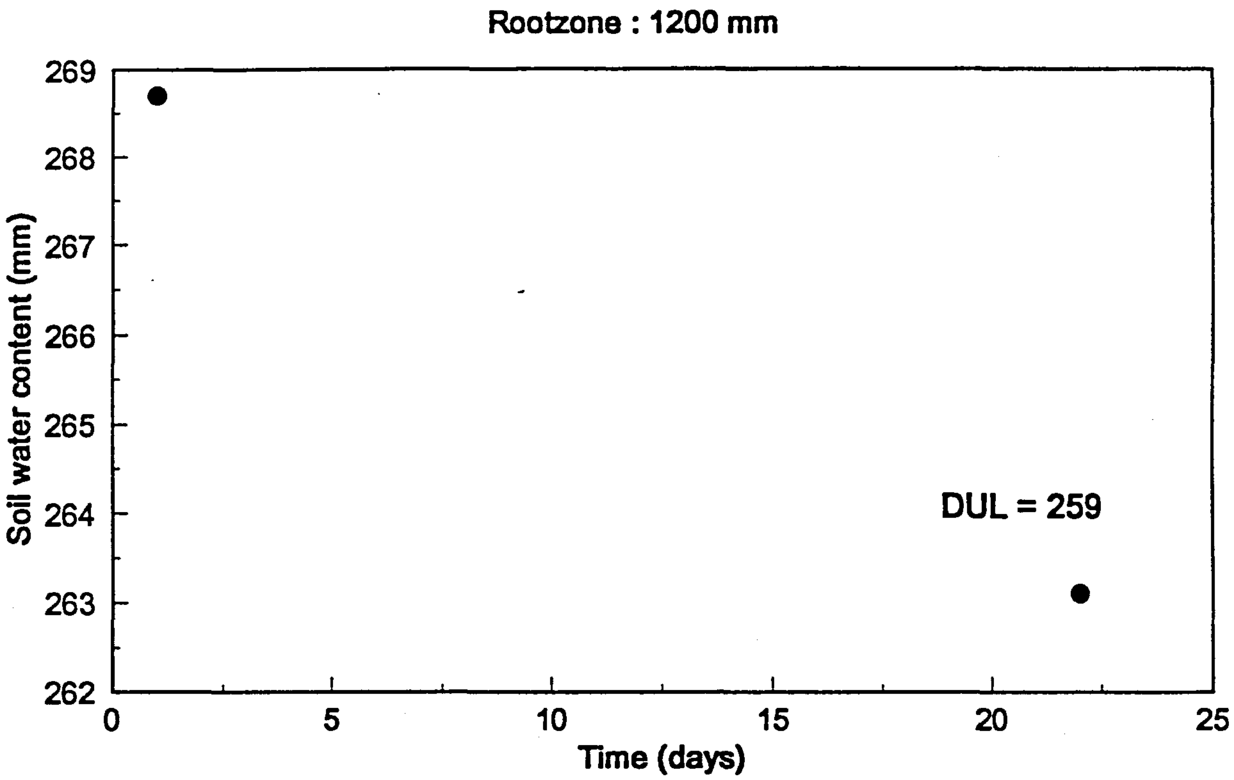
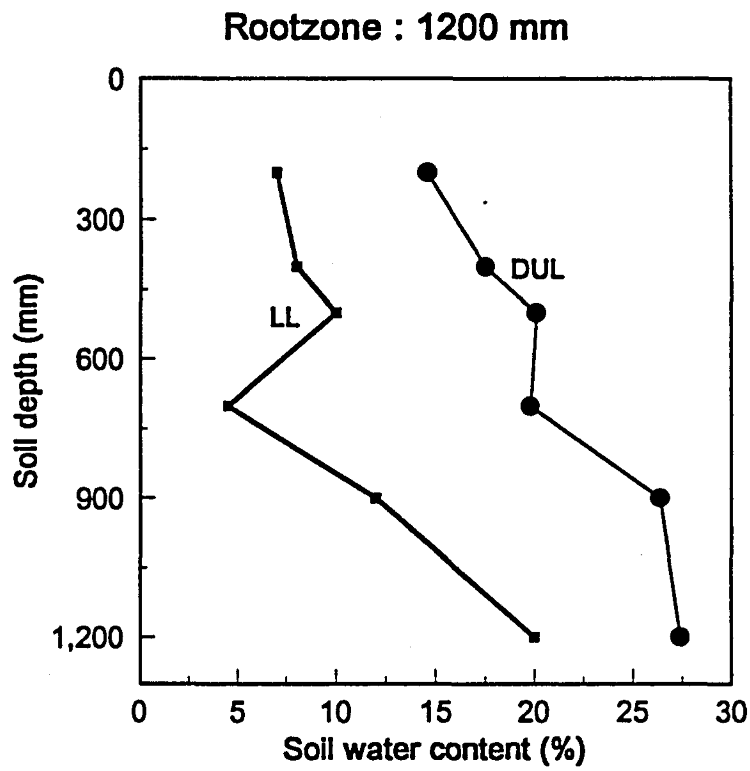
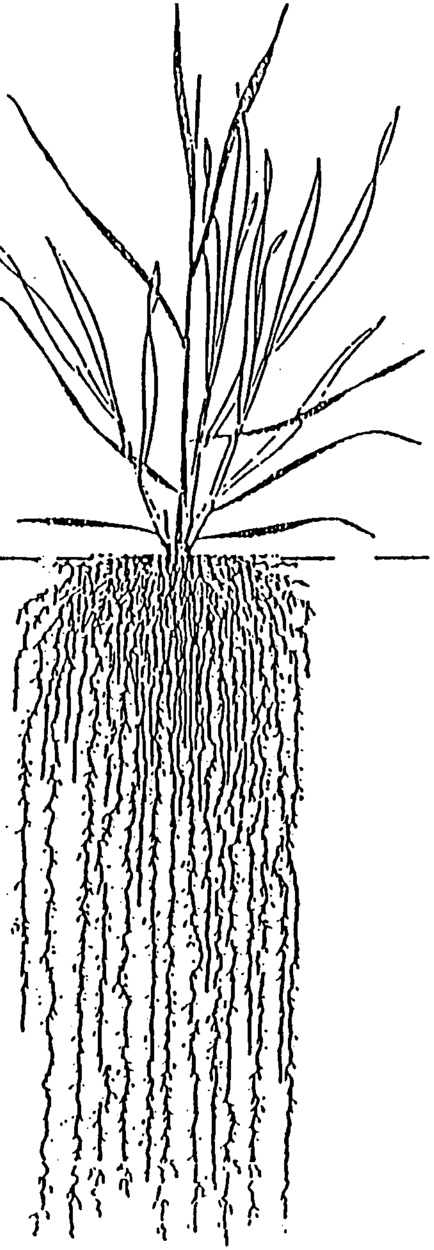


Fig 4.6.2 Soil water extraction diagram for maize on the Ermelo / Longlands ecotope



Profile detail

Diag. hor	Colour	Clay (%)	>2mm (%)	BD (g.cm^{-3})	Depth (mm)
ot	DkYBr	7		1.7	200
ot	DkYBr	11		1.7	600
ye	Br	18		1.5	900
ye	StrBr	17		1.5	1200
ye	YBr	20		1.5	1500



Water properties

DUL (mm)	LL (mm)	PLEXW (mm)	Ksat (mm/h)
24	6	18	57
55	33	22	57
44	31	13	189
50	33	17	261
52	45	7	110
225	148	77	

Table 4.7 The soil component of the Bultfontein / Clovelly Ecotope.

Land type : Ah20
Terrain morphological unit : 4
Slope % : 1
Soil classification : Form : Clovelly
: Family : Moollaagte

Fig.4.7.1 Drainage curve for the Bultfontein / Clovelly ecotope

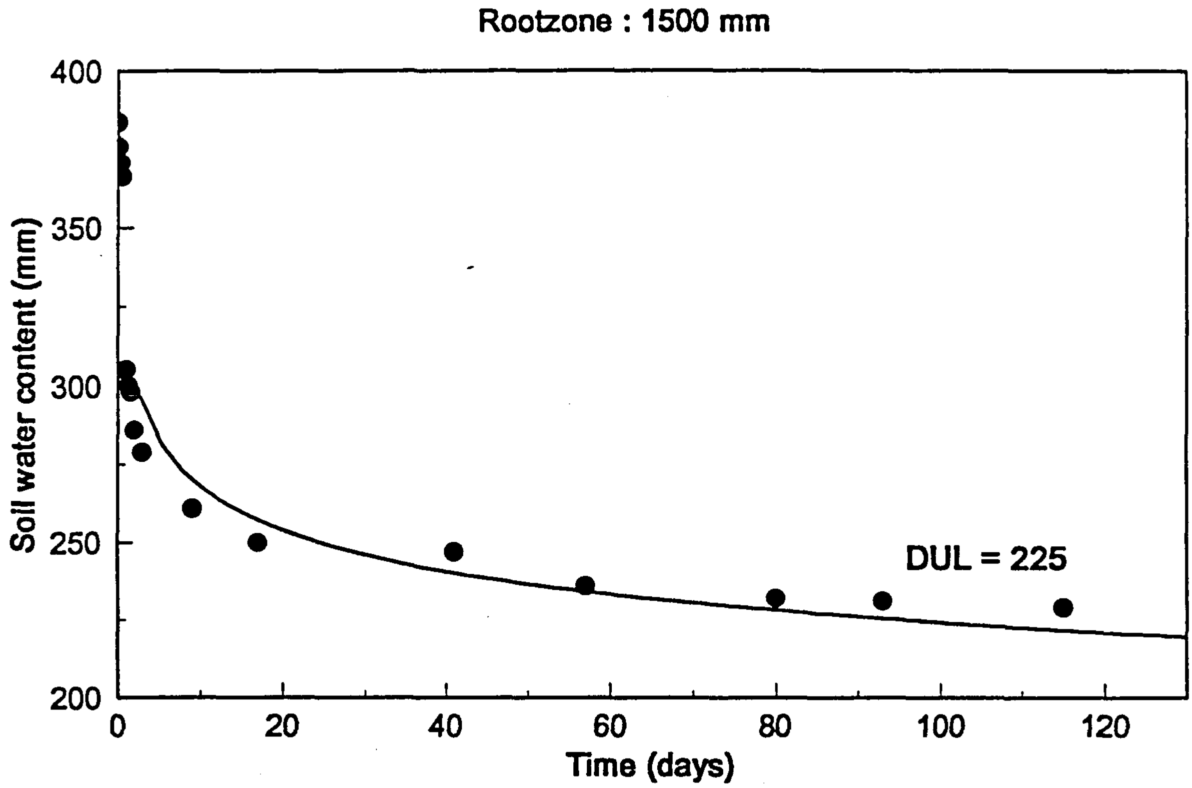
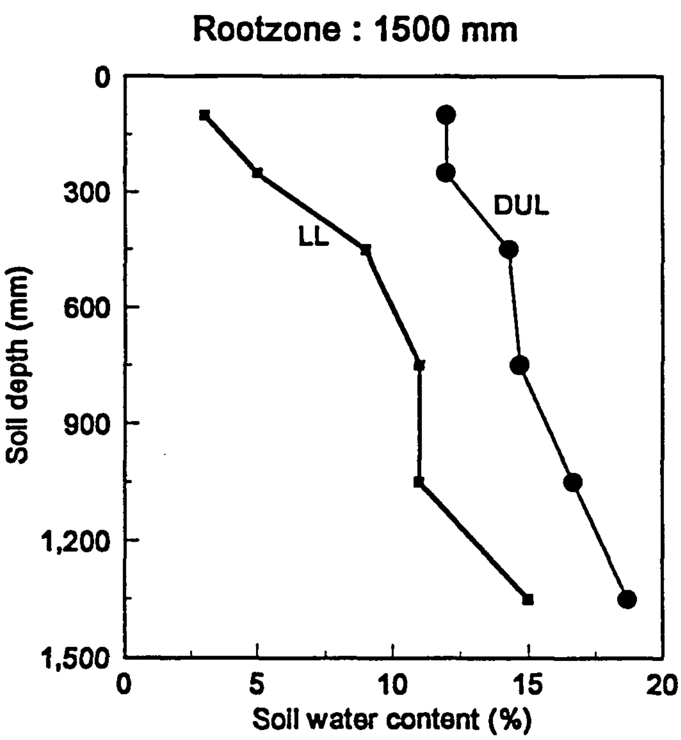
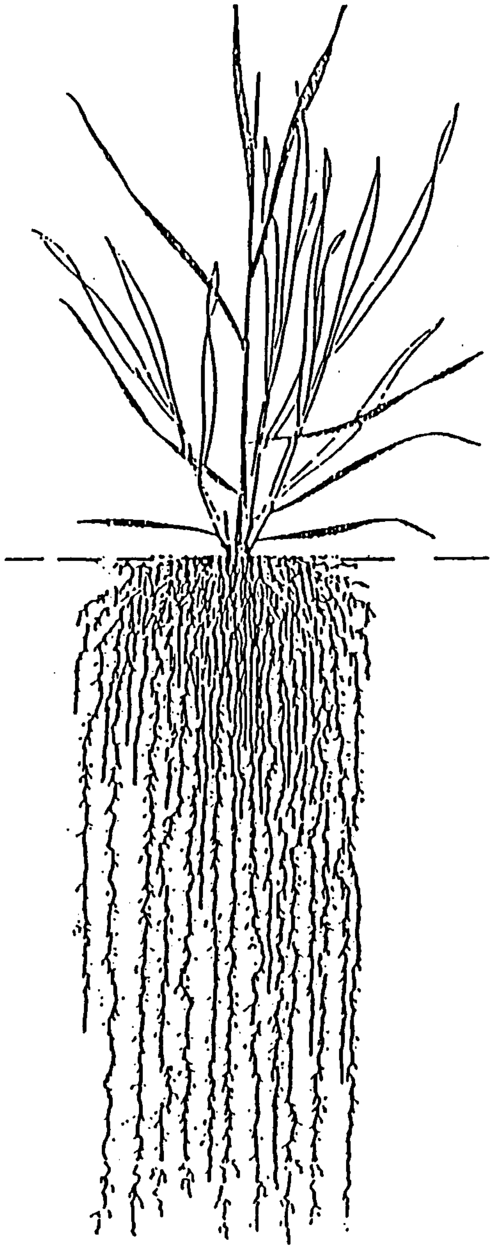


Fig.4.7.2 Soil water extraction diagram for wheat on the Bultfontein / Clovelly ecotope



Profile detail

Diag. hor	Colour	Clay (%)	>2mm (%)	BD (g.cm^{3})	Depth (mm)
ot	RBr	8		1.7	230
re	RBr	12		1.7	400
re	DkRed	22		1.6	770
re	Red	19		1.7	1500
on	Red + mottles	21		1.7	1800
on	Red + mottles	21		1.7	2100



Water properties

DUL (mm)	LL (mm)	PLEXW (mm)	Ksat (mm/h)
39	8	31	101
28	9	19	51
64	26	38	212
140	58	82	121
52	31	21	81
48	36	12	
371	168	203	

Table 4.8 The soil component of the Petrusburg/Bloemdal Ecotope.

Land type : Ae46
Terrain morphological unit : 4
Slope % : 1
Soil classification : Form : Bloemdal
: Family : Vrede

Fig. 4.8.1 Drainage curve for the Petrusburg / Bloemdal ecotope

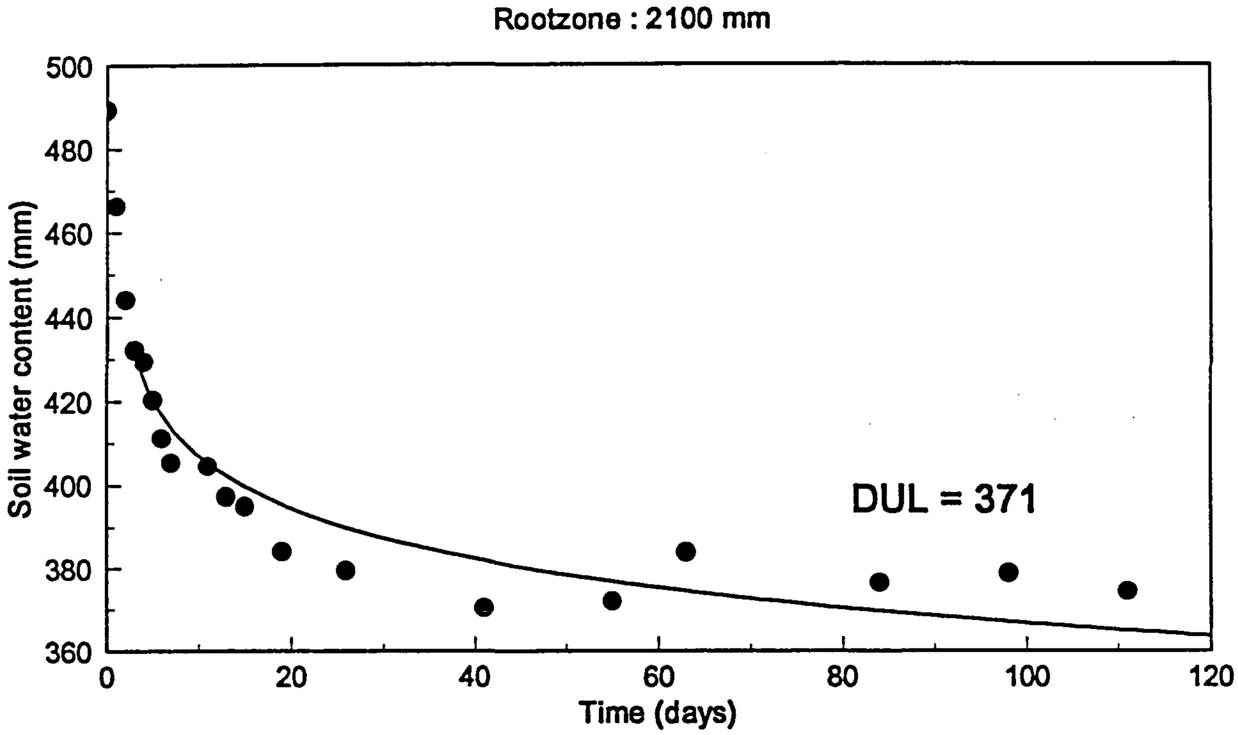
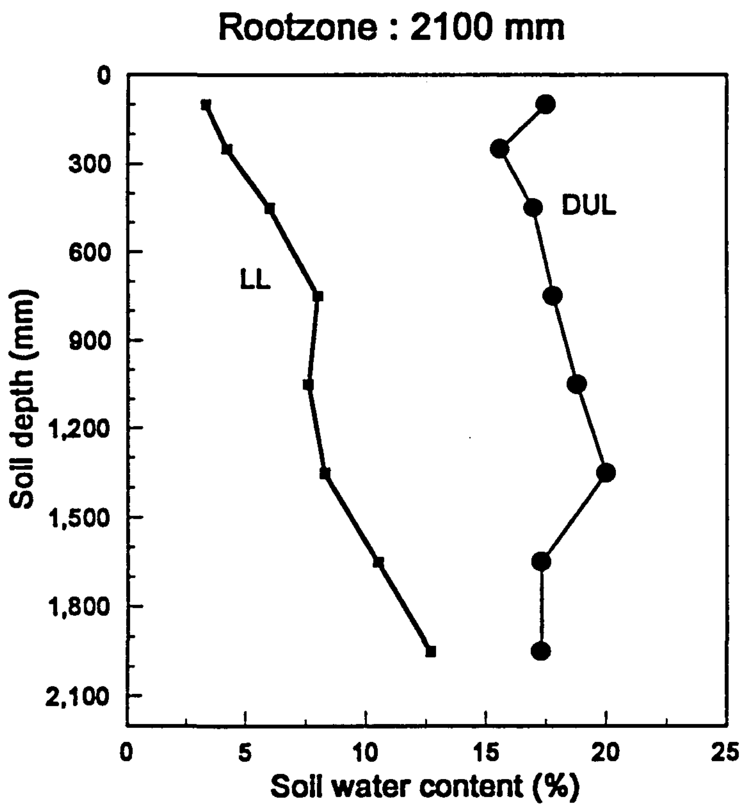


Fig. 4.8.2 Soil water extraction diagram for wheat on the Petrusburg / Bloemdal ecotope



5. COMPARING MEASUREMENTS AND SIMULATIONS OF SOIL WATER EXTRACTION AND YIELD

5.1 SETLAGOLE/CLOVELLY ECOTOPE

5.1.1 Seasonal Rainfall

The rainfall over the three seasons and the long-term mean monthly precipitation (MMP) is presented in Table 5.1.1.

Table 5.1.1 Setlagole/Clovelly ecotope: rainfall distribution for the 1993/94, 94/95 and 95/96 maize growing seasons and MMP for the growing season

Season	OCT.	NOV.	DEC.	JAN.	FEB.	MARCH	APRIL	TOTAL
1993/94	155	53	133	102	66	36	12	557
1994/95	3	50	39	99	14	98	14	317
1995/96	54	25	130	157	145	60	128	699
MMP*	29	47	62	81	72	76	40	407

* For the relevant Land Type climate zone (Soil and Irrigation Research Institute Staff, 1984)

5.1.2 Measured and predicted yields

These are presented in Table 5.1.2 and discussed in conjunction with the water extraction patterns presented in Section 5.1.3

Table 5.1.2 Measured and predicted maize yields (kg ha^{-1}) for the Setlagole /Clovelly ecotope

	Season		
	1993/94	1994/95	1995/96
Measured	3800	750	4570
DSSAT3	3151	285	5089
PUTU	3256	1659	4329

5.1.3 Measured and predicted soil water extraction

1993/94 Season

There was only about 35 mm of available water in the root zone at planting on 8/12/1993 (Figure 5.1.1). All this water was stored in the top 900 mm of the root zone (Figure 5.1.2). Good rains fell between days 13 and 20 after planting and again between days 32 and 35 after planting (Figure 5.1.1). As the plants were small at this stage the crop did not use much of this water, which then percolated into the deeper layers almost filling up the 900-2100 mm part of the root zone to DUL (Figure 5.1.2). To simulate the root zone water content accurately it was necessary that the models also be able to simulate this downward movement of the water accurately. DSSAT3 seems to have done quite well in this respect. The water content simulation diagrams show water reaching the last four layers on days 19, 27, 35 and 45 respectively. There were fairly good results, judging by the water content measurements for these layers on day 51, especially in the case of the 1500-2100 mm layer. It seems that the percolation rate for this water into the soil below 900 mm may have been over-estimated by PUTU - see for example the two peaks on the 1200-1500 mm diagram. Simulation of the water content of the 0-900 mm layer is well done by PUTU, as was also the final water content of the deeper layers. Added to the fact that there was sufficient water during the early season to produce large plants, the rain of 42 mm at flowering probably played an important role in determining the relatively good yield of 3800 kg ha^{-1}. The yield was slightly underestimated by both models but both estimates were nevertheless within the 20% error value considered to be reasonable.

1994/95 Season

There was only 20 mm of available water in the root zone at planting, all of it in the top 600 mm. It was also a dry season (Table 5.1.1) with only four storms of more than 20 mm, with th best fall of 71 mm on 6 and 7 March. This was unfortunately just after flowering (Figure 5.1.1). There was little rain after this and as expected the yield was very low.

Up to day 70 the water content of the 0-600 mm layers is very well simulated by both models. The plants suffered very severe stress during the period 70-85 days, with the remaining 10 mm of available water all situated below 1200 mm (Figure 5.1.3). This was an extreme test for the models. They responded excellently - see for example the simulation lines on the diagrams for the 1200-1500, 1500-1800 and 1800-2100 mm layers in Figure 5.1.3. The PUTU simulation kept on long enough to respond to the good rain around day 88. It seems however that the damage to the crop had already been done resulting in the low yield of 750 kg ha^{-1}. The DSSAT3 and PUTU simulations yielded 285 and 1659 kg ha^{-1} respectively. Considering the very severe circumstances, these can be considered as reasonable results.

1995/96 Season

This was not only a very wet season (72% above average) but the distribution was also favourable (Table 5.1.1 and Figure 5.1.1). The result was a good yield for this ecotope ie. 4570 kg ha^{-1}. It is clear from the measurements of the water content of the deepest part of the root zone (1800-2100 mm) - see Figure 5.1.4, that considerable deep drainage occurred between days 20 and 128 after planting. Using data from the drainage curve the amount is estimated to be 33 mm. Yield was well simulated by DSSAT3 and PUTU giving 4239 and 5089 kg ha^{-1} respectively. Both models simulate the water content of the 0-300 mm layers very well, the 300-600 mm layer fairly well, with less satisfactory results in the lower parts of the root zone. The problem here is probably the unknown percolation rate of water through the root zone above DUL, while root water-extraction is occurring. The measured relationship between hydraulic conductivity and water content for this soil is a basic need in order to solve this problem.

Fig. 5.1.1 Setlagole / Clovelly ecotope : Measured and predicted changes in the water content of the whole rootzone (2100 mm) ; 1993 / 94, 1994 /95 and 1995 / 96 seasons

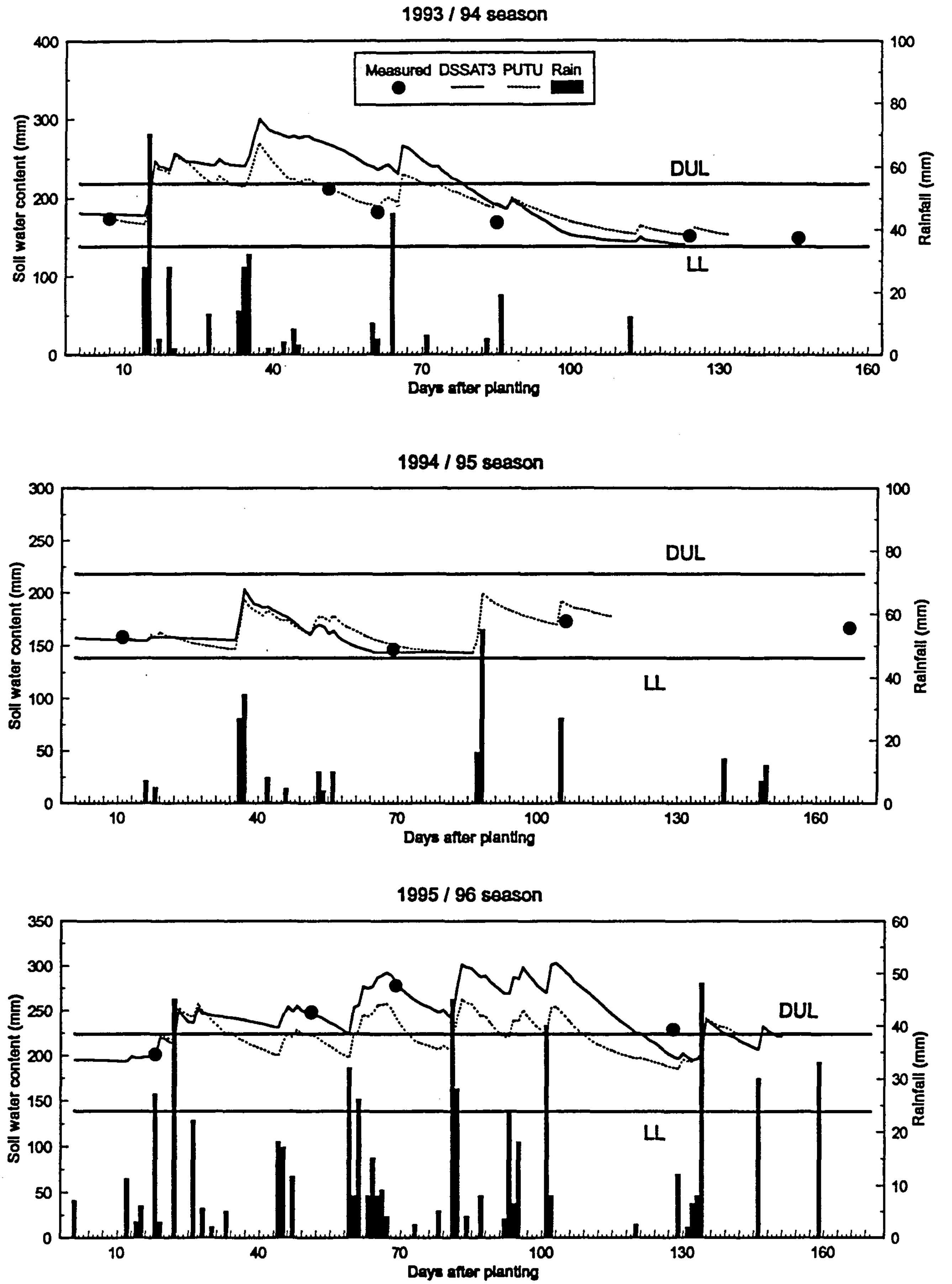


Fig. 5.1.2 Setlagole / Clovelly ecotope : Measured and predicted changes in the soil water content of the individual layers during the 1993 / 94 season

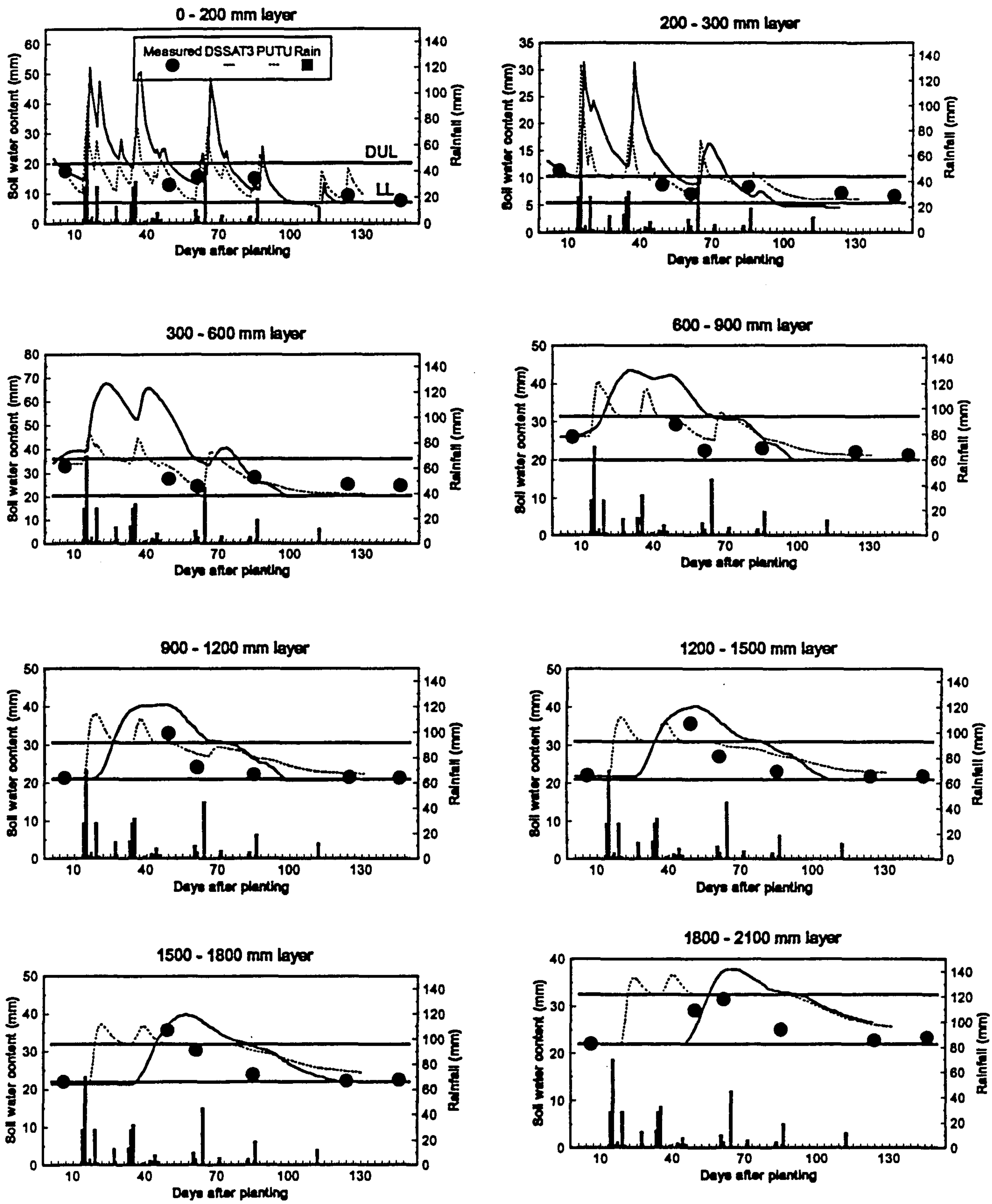


Fig. 5.1.3 Setlagole / Clovelly ecotope : Measured and predicted changes in the soil water content of the individual layers during the 1994 / 95 season

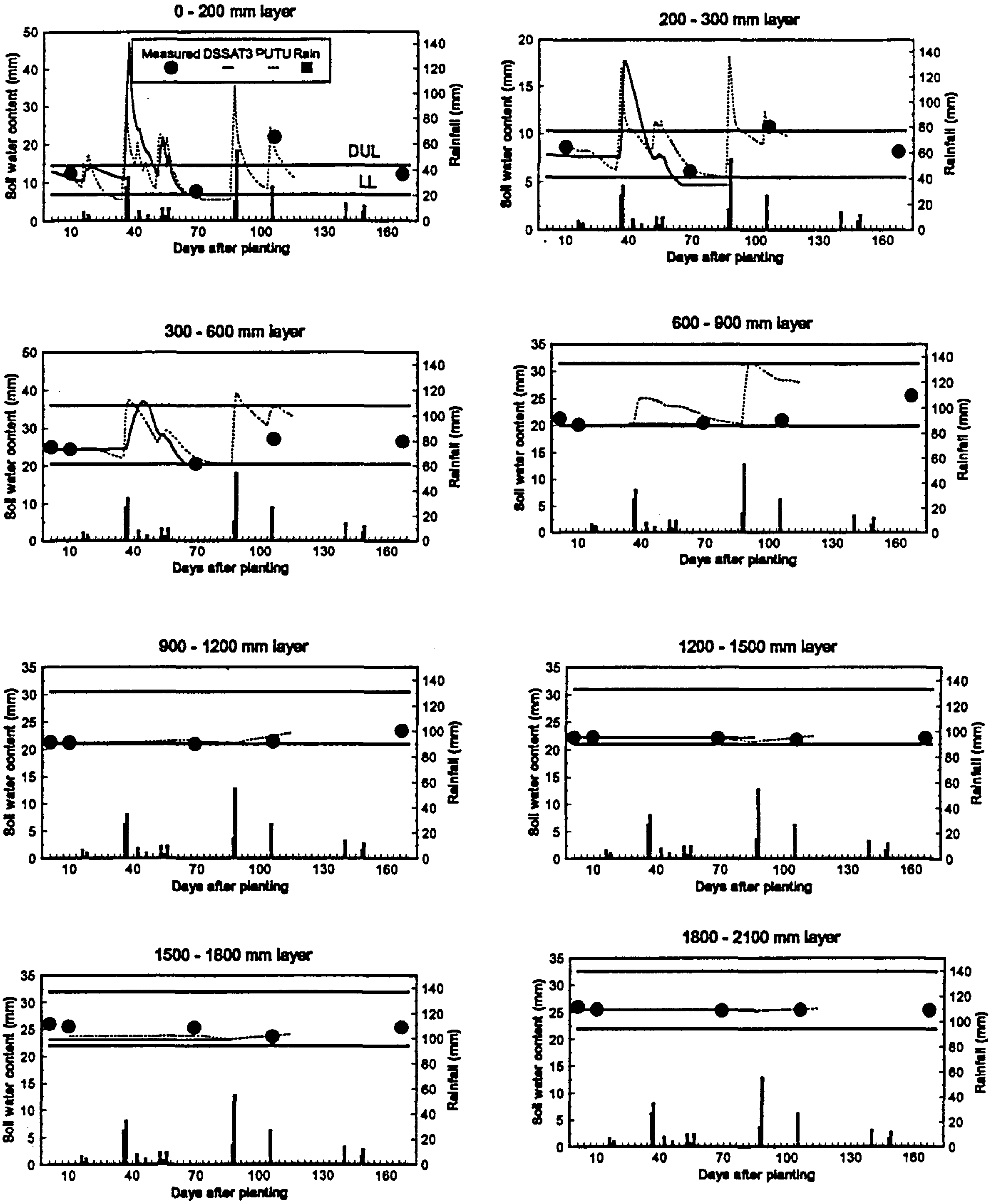
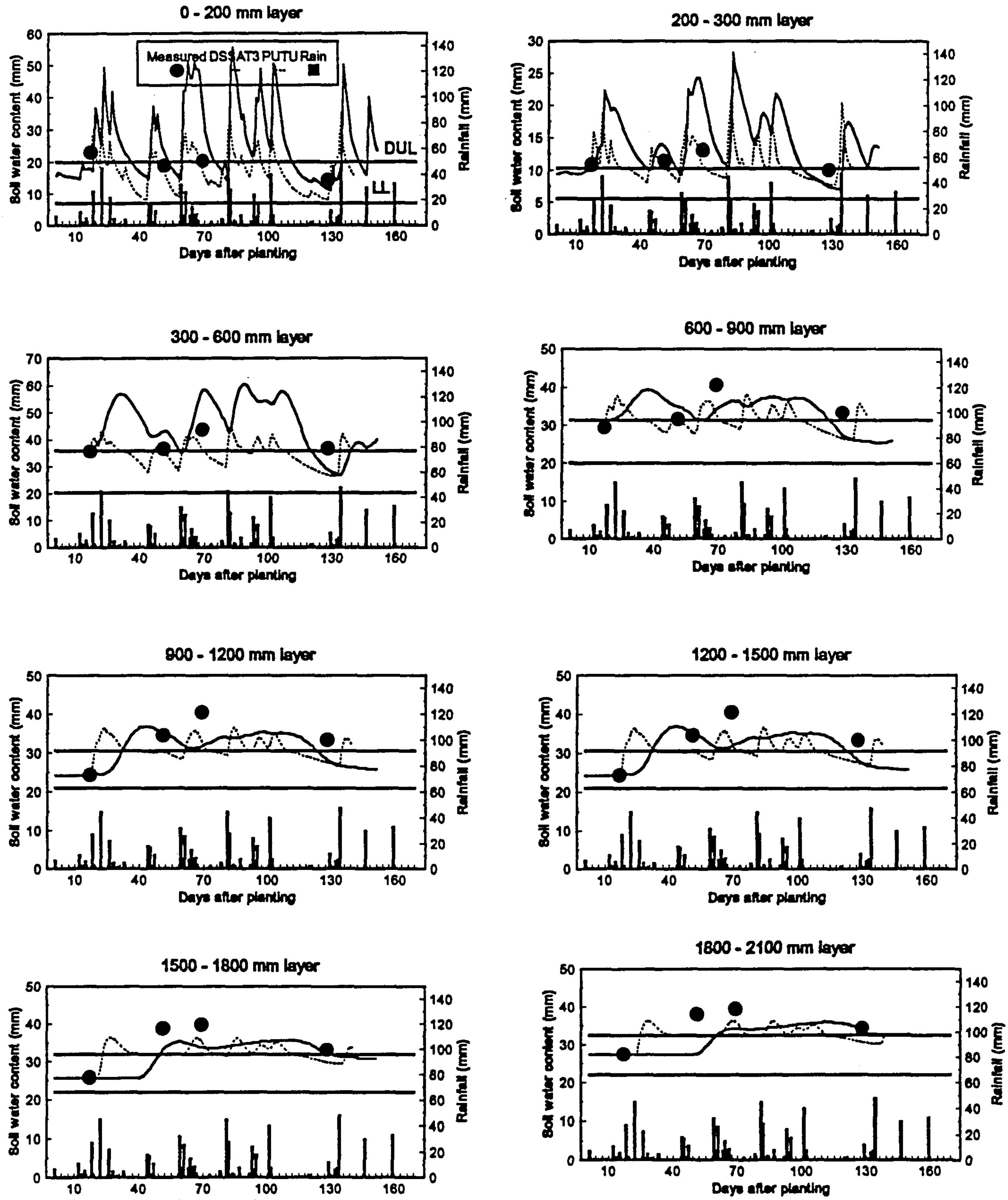


Fig. 5.1.4 Setlagole / Clovelly ecotope : Measured and predicted changes in the soil water content of the individual layers during the 1995 / 96 season



5.2 WOLMARANSSTAD/HUTTON ECOTOPE

5.2.1 Rainfall

The rainfall over the three seasons and the long-term mean monthly precipitation (MMP) is presented in Table 5.2.1.

Table 5.2.1 Wolmaranstad/Hutton ecotope: rainfall distribution for the 1993/94, 94/95 and 95/96 maize growing seasons and MMP

SEASON	OCT	NOV	DEC	JAN	FEB	MARCH	APRIL	TOTAL
1993/94	180	104	120	139	170	40	16	769
1994/95	8	58	79	122	29	100	31	427
1995/96	62	96	211	152	84	58	88	751
MMP*	38	66	80	98	82	83	47	494

*For the relevant Land Type climate zone (Soil and Irrigation Research Institute, 1986)

5.2.2 Measured and predicted yields

These are presented in Table 5.2.2. and discussed in conjunction with the water extraction patterns presented in section 5.2.3.

Table 5.2.2 Measured and predicted maize grain yields (kg ha^{-1}) for the Wolmaransstad/Hutton ecotope

	Season		
	1993/94	1994/95	1995/96
Measured	1140	1720	1520
DSSAT3	1601	654	1560
PUTU	3118	1989	3104

Fig. 5.2.1 Wolmaransstad / Hutton ecotope : Measured and predicted changes in the water content of the whole rootzone (900 mm) ; 1993 / 94, 1994 /95 and 1995 / 96 seasons

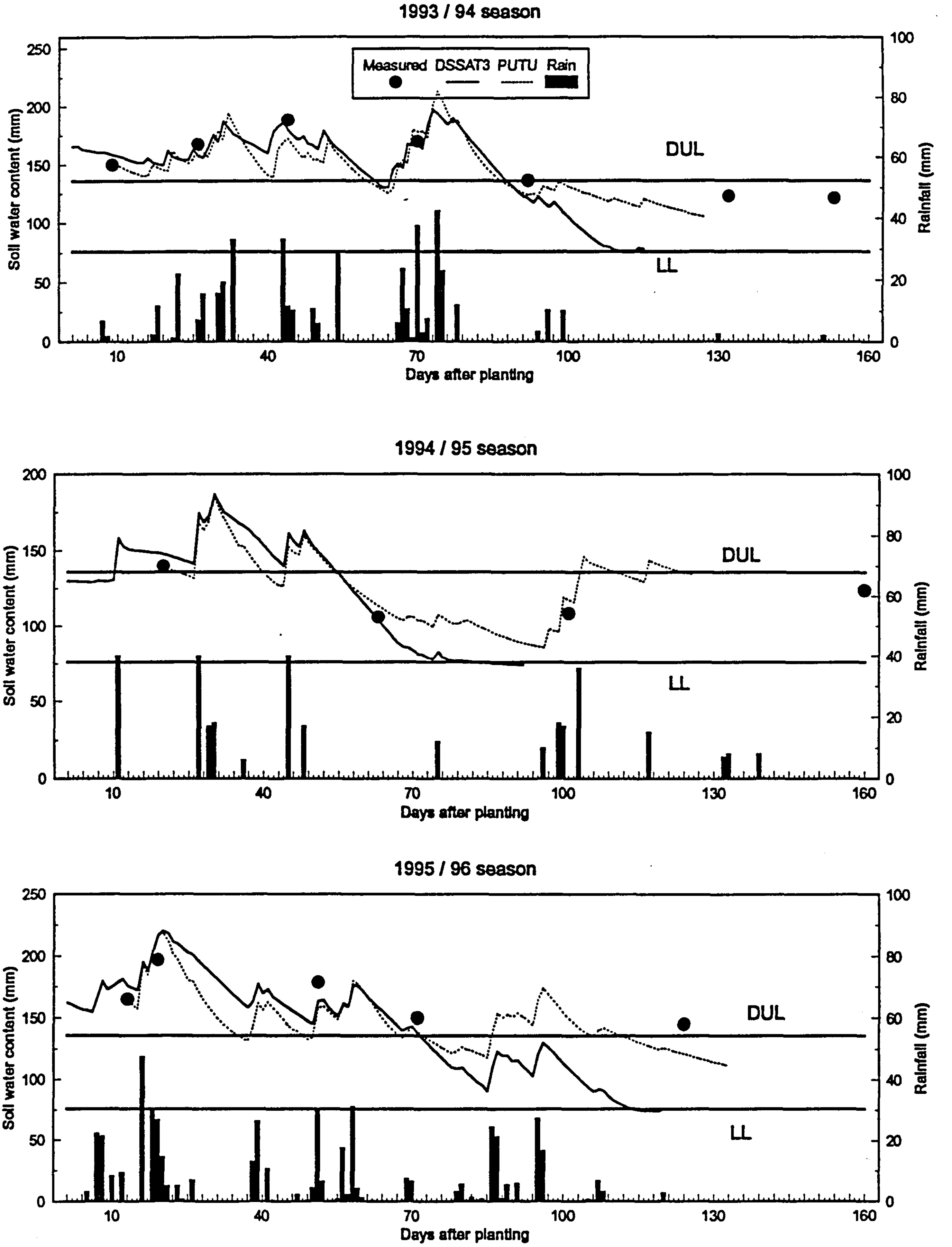


Fig. 5.2.2 Wolmaransstad / Hutton ecotope : Measured and predicted changes in the soil water content of the individual layers during the 1993 / 94 season

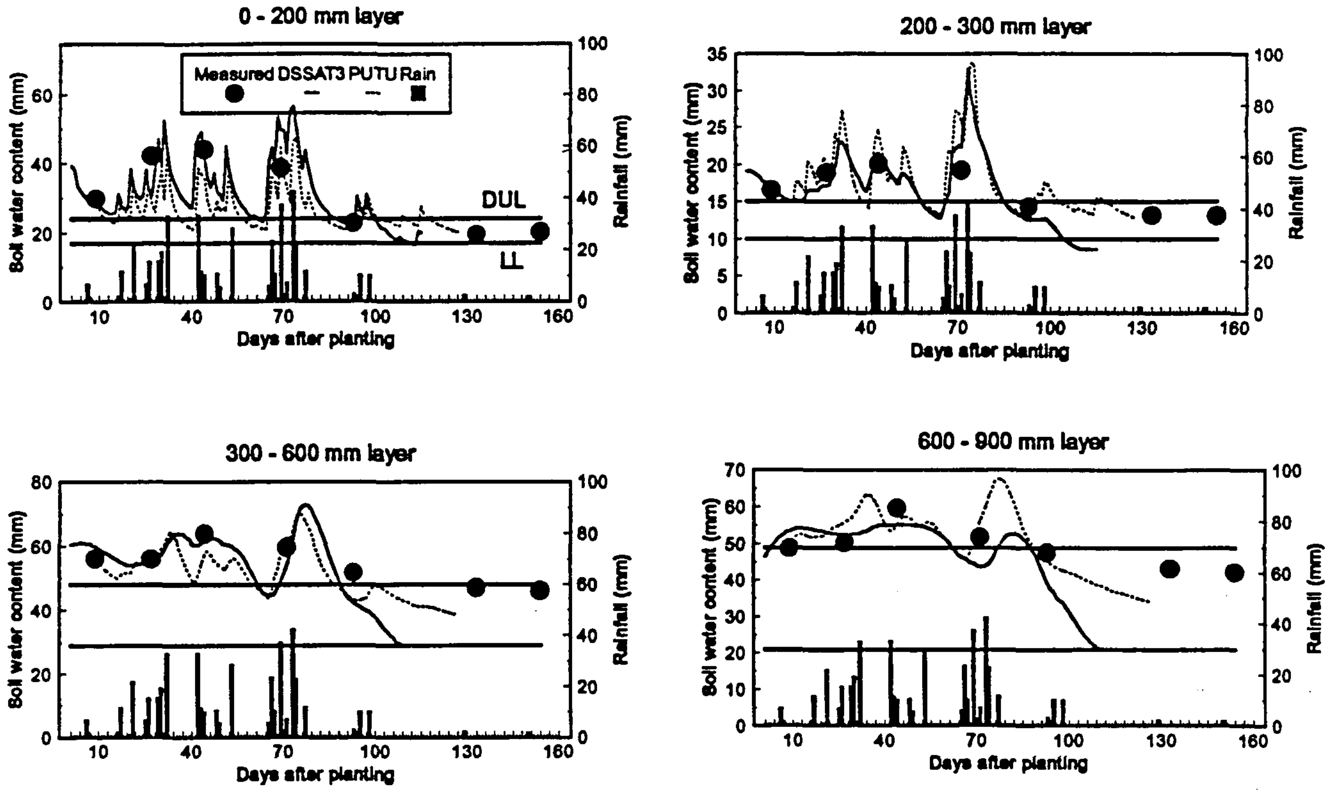


Fig. 5.2.3 Wolmaransstad / Hutton ecotope : Measured and predicted changes in the soil water content of the individual layers during the 1994 / 95 season

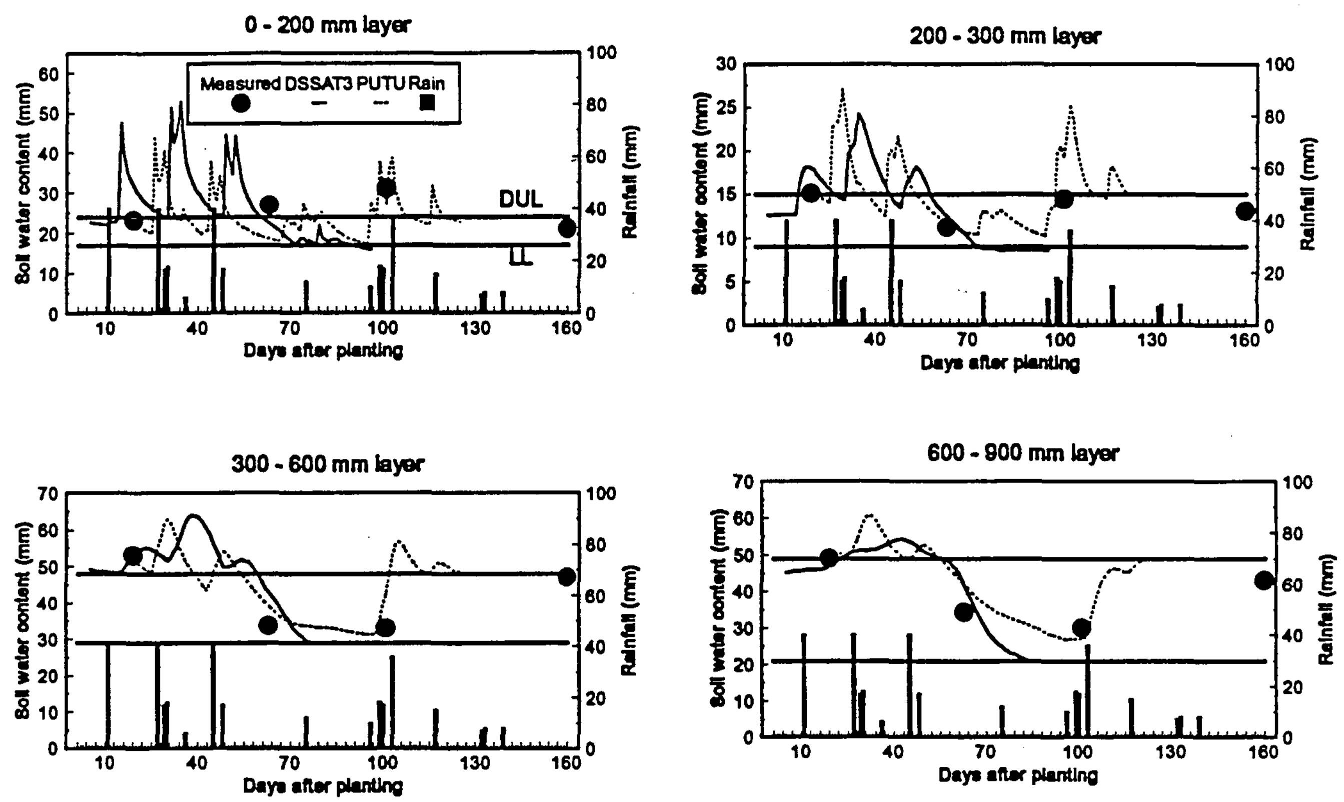
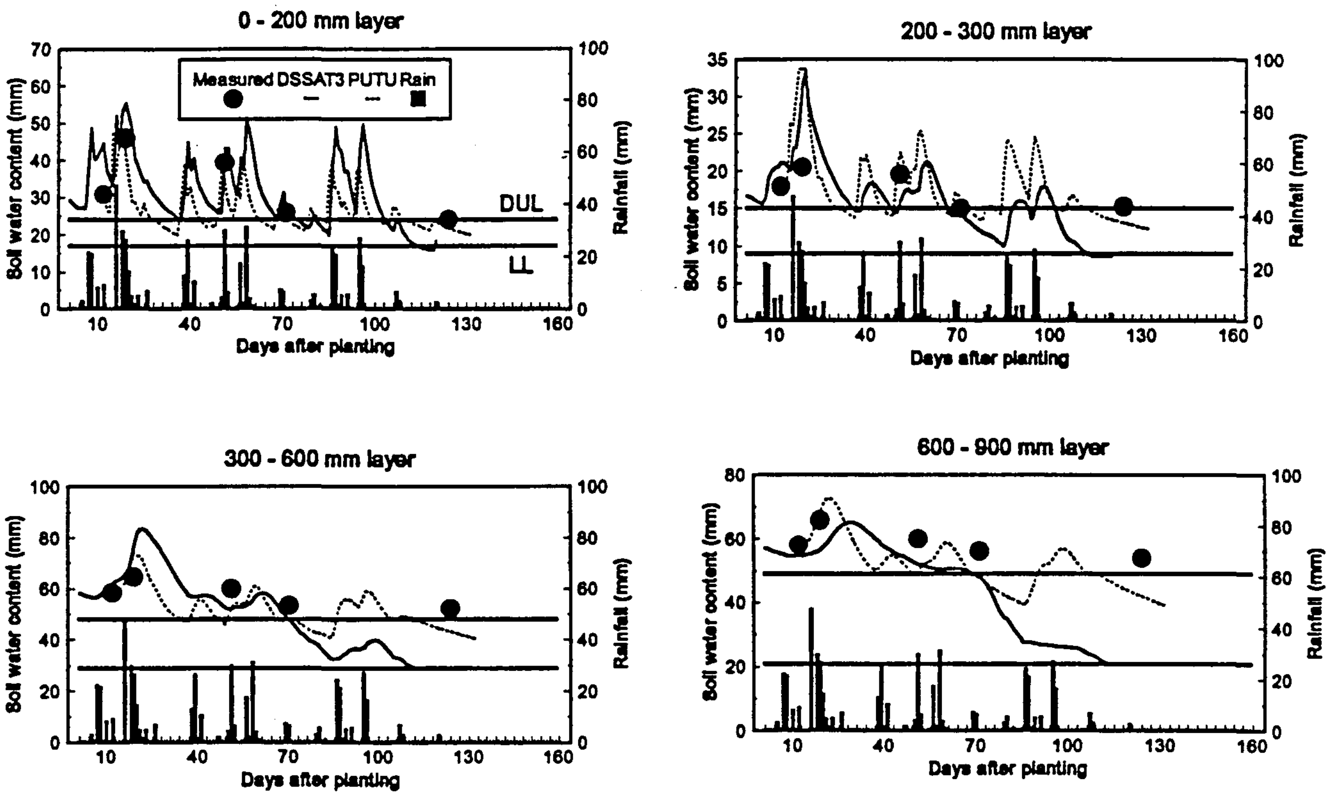


Fig. 5.2.4 Wolmaransstad / Hutton ecotope : Measured and predicted changes in the soil water content of the individual layers during the 1995 / 96 season



5.2.3 Measured and predicted soil water extraction

1993/94 Season

This was a very wet season up to the end of February, and then dry for the later part (Table 5.2.1 and Figure 5.2.1). At planting (2/12/1993), the root zone water content was slightly above DUL, and remained above DUL for approximately the first three months (Figure 5.2.1). This is a shallow soil with an underlying stony layer of unknown permeability, which also varies spatially. The latter conclusion is drawn from the observation that during measurements after heavy rains, water-tables were found at some places and not at others. The Ksat determinations made at 900 mm just above the stony layer, yielding 145 mm hr^{-1} (Table 4.2.1), are of little value since they only reflect the hydraulic conductivity of the thin soil layer above the stones. Very reliable simulations cannot be expected under these conditions. Water content simulations of all four layers by both models (Figure 5.2.2) were surprisingly good. The soil water-extraction rate simulated by DSSAT3 from all the layers, approximately from day 100 onwards, is excessively high. This probably indicates the prediction of too high a root density and therefore too high a value for total root water uptake rate.

The measured yield of 1140 kg ha^{-1} is not a true reflection of the growth potential for this season. In spite of very good rains early in the season, plant growth was unsatisfactory. Possible reasons were a lack of nitrogen due to excessive leaching, or some degree of waterlogging early in the season. A considerably higher yield should have been achieved had soil water been the only variable. It is therefore not possible to make a very reliable comment regarding the 3118 and 1601 kg ha^{-1} yields predicted by PUTU and DSSAT3 respectively. Judging by the premature cessation of growth predicted by DSSAT3 at day 115, due presumably to excessively rapid water-extraction from just before day 100, it may well be that the predicted yield of 1601 kg ha^{-1} is somewhat low.

1994/95 Season

The total rainfall for the season was slightly below average (Table 5.2.1) with a harmful trough around flowering, between 49 and 75 days after planting (Figure 5.2.1). At planting (17/12/94) the water content was at DUL in all the soil layers (Figure 5.2.1).

The post rainfall soil water content peaks simulated by the two models in the 0-200 and 200-300 mm soil layers are similar in shape but different in height and position. PUTU reacts before DSSAT3, giving peaks to the left of those of DSSAT3. Since there were no measurements just after a heavy rain, it is not possible to decide which simulation is the most accurate. Soil water content simulations appear to have been reasonably well done by both models up to day 63. Over the next 10 days the predicted water extraction rate by DSSAT3 appears to be excessively rapid resulting in premature cessation of growth and a yield prediction (654 kg ha^{-1}) that is 62% lower than the measured value of 1989 kg ha^{-1}. This is a repetition of the observation on the Setlagole/Clovelly ecotope. PUTU seems to predict soil water content accurately from day 62 to day 126 when the simulation ended. This is supported by a good yield prediction of 1720 kg ha^{-1} which is within 14% of the measured value.

1995/96 Season

The rainfall from October to January was 85% above average and thereafter approximately average (Table 5.2.1). At planting (29/11/1995), the water content of the root zone was above DUL and no measurements below DUL were recorded during the growing season (Figure 5.2.1). The earlier remarks about the underlying layer which restricts deep drainage are therefore particularly relevant here.

In spite of the difficulty described above, both models simulate the soil water content of all the layers (Figure 5.2.4) surprisingly well until day 70. Thereafter DSSAT3 exhibits the same weakness as before, which is that of an excessively rapid extraction rate resulting in LL being reached on day 113, whereas the measured value on day 124 showed a water content slightly above DUL for all the layers. The simulation of water extraction by PUTU in the period between day 70 and day 124 seems to be reasonably reliable.

As for the 1993/94 season, the maize growth was very poor, probably due to waterlogging and excessive nitrogen leaching. The measured yield was 1520 kg ha^{-1} and those simulated by PUTU and DSSAT3 were 3104 and 1560 kg ha^{-1} respectively.

5.3 KROONSTAD/AVALON ECOTOPE

5.3.1 Seasonal rainfall

Relevant data is presented in Table 5.3.1. It was not possible for the farmer to plant during the 1994/95 season due to drought. A small area for research purposes was eventually planted on 16 January 1995. It was unfortunately destroyed by cattle.

Table 5.3.1 Rainfall distribution for the Kroonstad/Avalon ecotope for the 1993/94, 1994/95 and 1995/96 maize seasons, and MMP

SEASON	OCT.	NOV.	DEC.	JAN.	FEB.	MARCH	APRIL	TOTAL
1993/94	183	56	143	73	122	32	28	637
1994/95	47	35	41	53	66	93	29	364
1995/96	130	86	53	91	195	50	37	642
MMP*	55	76	83	94	76	76	44	504

*For the relevant Land Type climate zone (Soil and Irrigation Research Institute, 1984)

5.3.2 Measured and predicted yields

These are present in Table 5.3.2 and discussed in conjunction with the water extraction patterns presented in section 5.3.3

Table 5.3.2 Measured and predicted maize grain yields (kg ha^{-1}) for the Kroonstad/Avalon ecotope

	Season	
	1993/94	1995/96
Measured	5763	2970
DSSAT3	*	4396
PUTU	4854	2051

* not determined

5.3.3. Measured and predicted soil water extraction

1993/94 season

The planting date was 10/11/1993. October was very wet with approximately three times the average rainfall. Total rainfall for the growing season was above average (Table 5.3.1), with favourable distribution up to around day 100 and very little significant rain after that (Figure 5.3.1.).

The morphology of this Avalon form soil is similar to that of the Bethal/Avalon, and therefore their water regimes are also similar. The soft plinthic horizon (sp) here occurs at a depth of between about 600 and 800 mm (Appendix 1.3). It is therefore in this horizon that lateral water movement in the landscape is expected to occur, causing the soil in the lower positions to be wetter than expected for extended periods after heavy rain. The situation occurred to a marked degree during the 1995/96 season (Figure 5.3.1), but evidently to a limited extent during the 1993/94 season due to the rainfall amounts and distribution (Figure 5.3.1). Due evidently to the heavy rain in October the sp horizon (600-800 mm) was above DUL at planting and remained at that level for most of the season (Figure 5.3.2), and probably fed the overlying yellow brown apedal B1 horizon (300-600 mm) by capillary action so that its water content also remained fairly high (Figure 5.3.2).

The root zone was at DUL at planting (Figure 5.3.1) and remained close to that level in all the layers approximately until day 60 (around flowering) due to favourable rainfall. Results for DSSAT3 for this season are not available. PUTU simulated the soil water content fairly well in the main part of the root zone up to around day 120. After that the predicted extraction rate was too rapid in the 3rd, 4th, and 5th layers. The measured yield was 5763 kg ha^{-1}. The PUTU prediction was slightly low (4854 kg ha^{-1}), possible due to the simulation of slightly too much stress caused by the excessive root water extraction rate after day 120.

1995/96 Season

October was again wet, followed by average rainfall until February when almost three times the normal rainfall was recorded. This included a few very heavy storms close together around day 42 (Figure 5.3.1). Much runoff occurred during these storms and the whole landscape became saturated. After day 74 there was relatively little rain.

Planting (2/01/1996) was late because of low rainfall in December. The root zone was approximately at DUL in the most important part of the root zone (200 - 900 mm). Experience gained up to this stage led to the decision that 1200 mm was a more appropriate root zone depth here than the previous value of 1400 mm. Measurements in deep layers where there is little significant root extraction not only wastes time but can also introduce unnecessary errors.

Prolonged lateral water movement in the sp horizon seems to have resulted in erroneous water content prediction by the models during the second half of the season, as in the case of the Bethal/Avalon ecotope. Between days 41 and 55 there was a water table at a depth of between 400 and 700 mm at the experimental site. Subsequent depth measurements gave the following results: 885 mm on day 66; 900 mm on days 77, 84, 98 and 114. The shallow water table immediately after the heavy rain seems to have been sufficiently shallow, and sufficiently prolonged, to damage the crop significantly. Growth was unsatisfactory after this.

The measured yield was 2970 kg ha^{-1}, and predictions by DSSAT3 and PUTU 4396 and 2051 kg ha^{-1} respectively.

Fig. 5.3.1 Kroonstad / Avalon ecotope : Measured and predicted changes in the water content of the whole rootzone ; 1993 / 94 and 1995 / 96 seasons

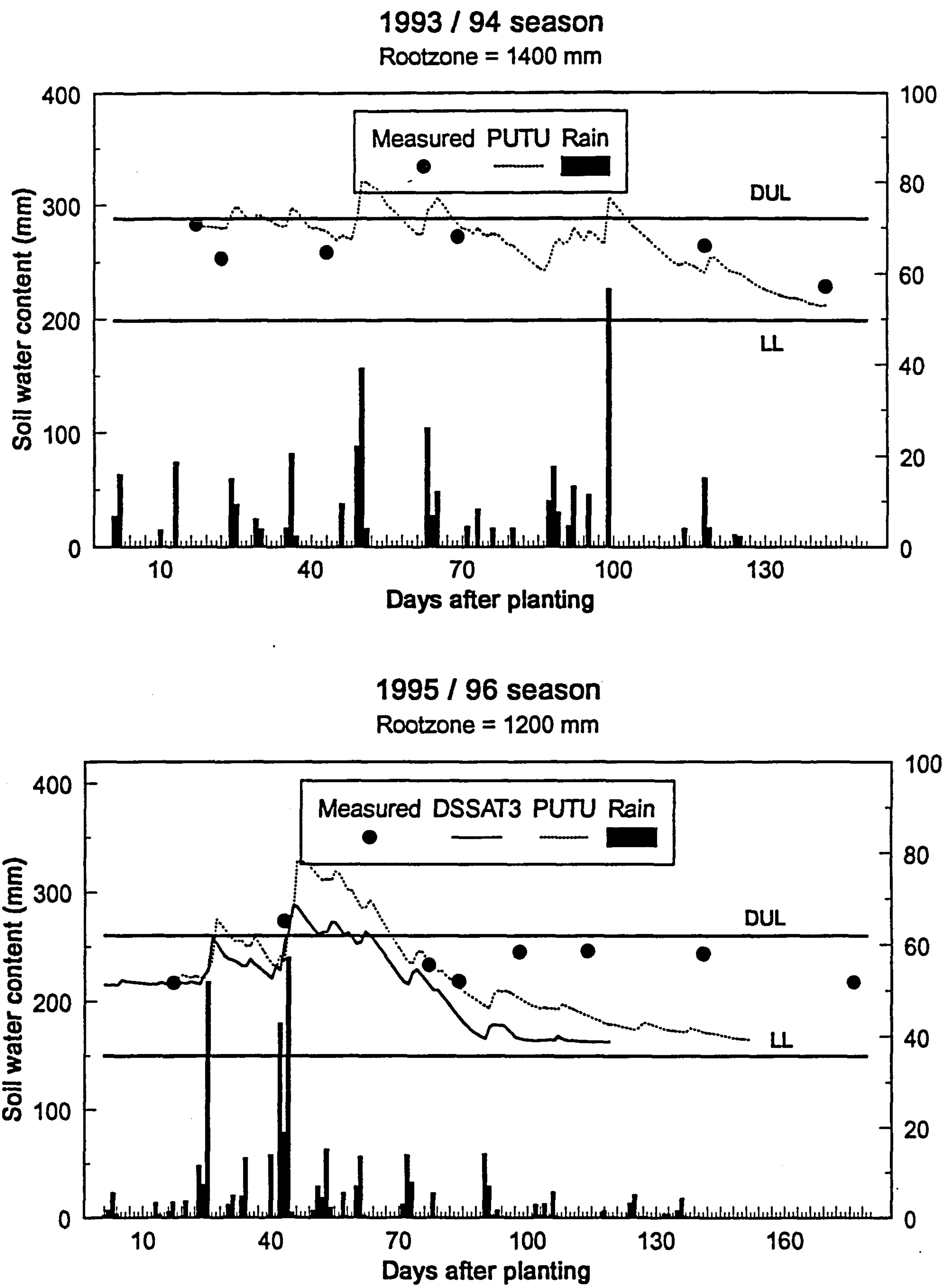


Fig. 5.3.2 Kroonstad / Avalon ecotope : Measured and predicted changes in the soil water content of the individual layers during the 1993 / 94 season

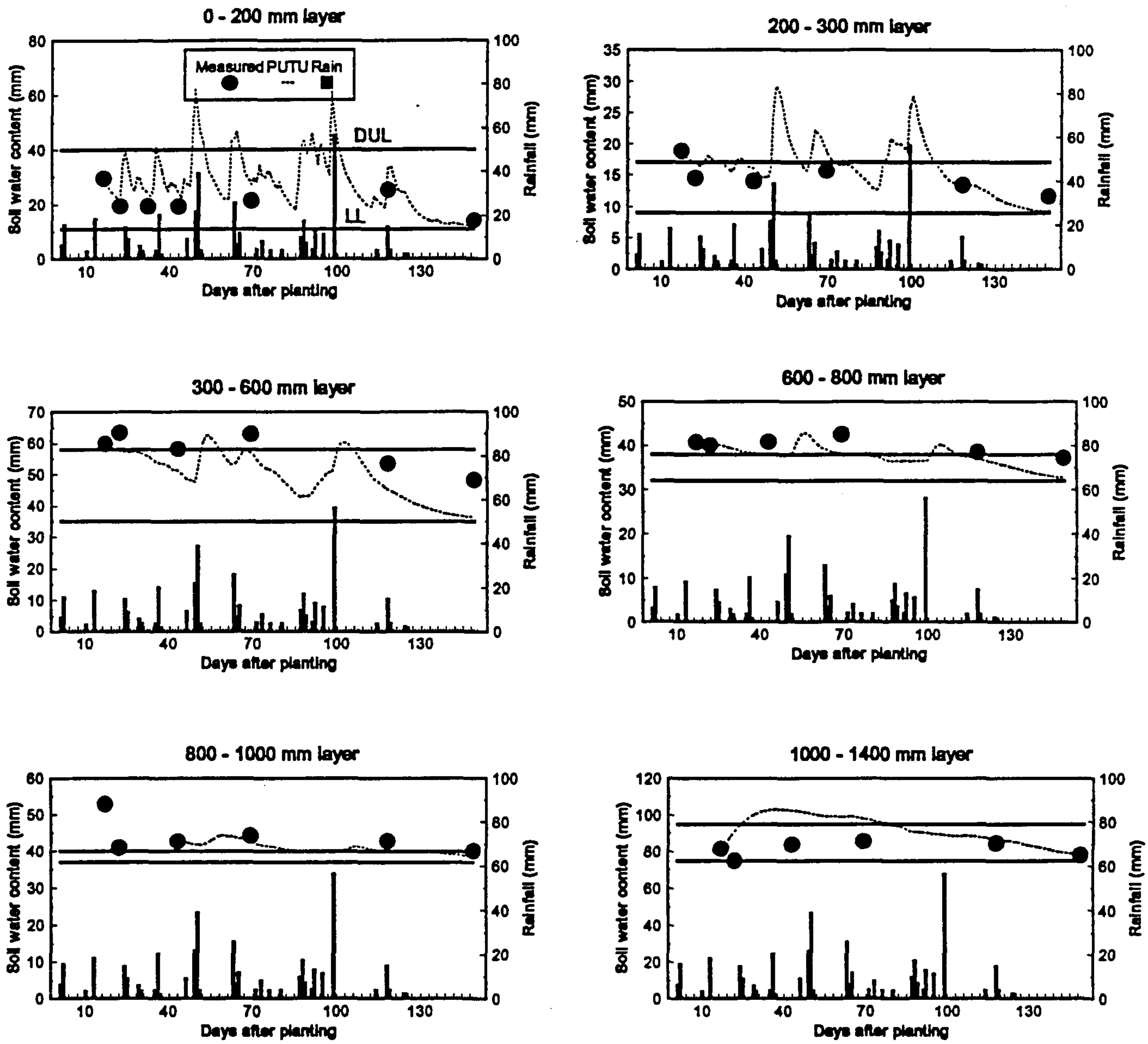
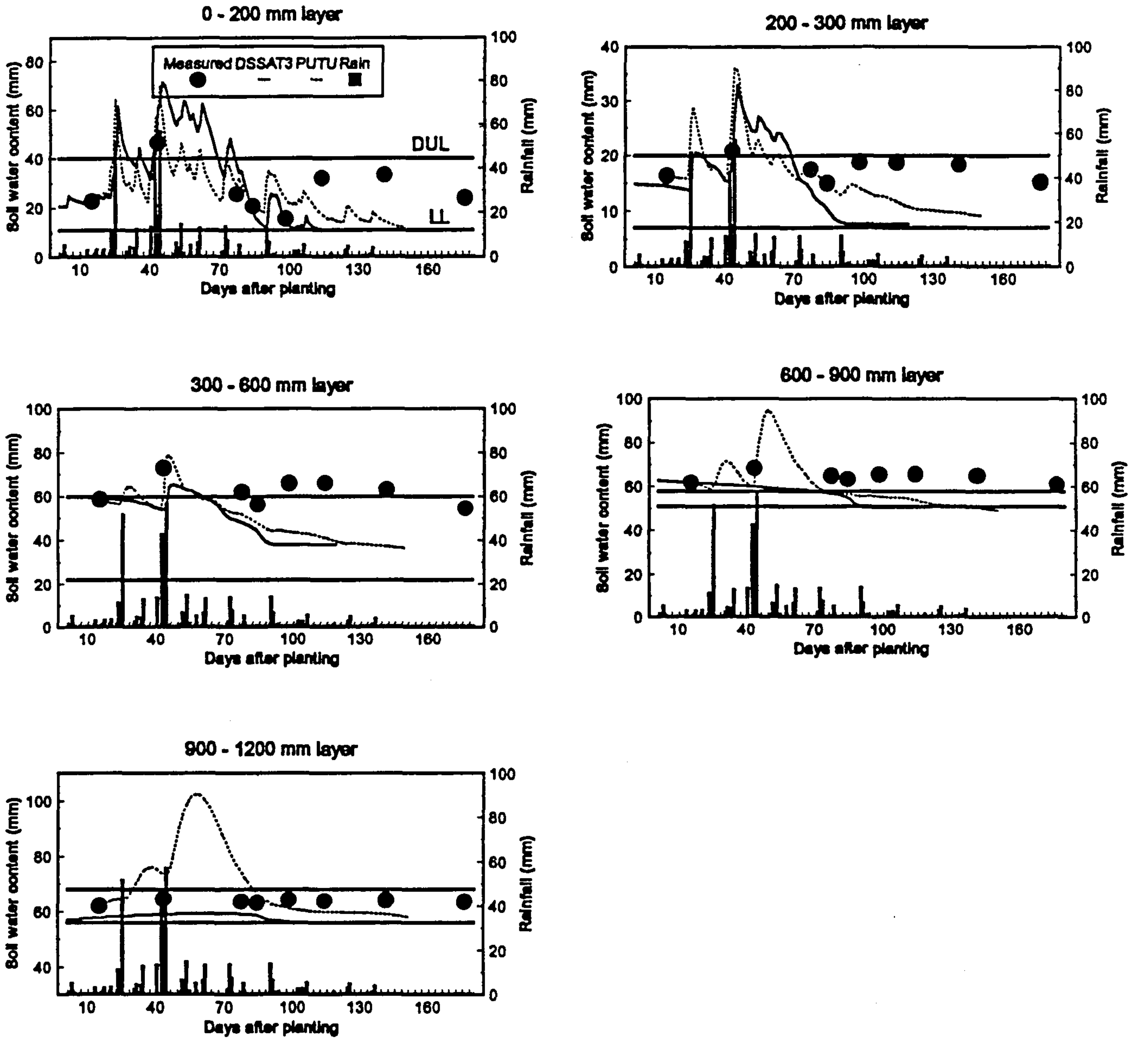


Fig. 5.3.3 Kroonstad / Avalon ecotope : Measured and predicted changes in the soil water content of the individual layers during the 1995 / 96 season



5.4 BETHAL/HUTTON ECOTOPE

5.4.1 Seasonal rainfall

The relevant data are presented in Table 5.4.1

Table 5.4.1. Rainfall distribution for the Bethal/Hutton ecotope for the 1993/94, 1994/95 and 1995/96 maize seasons and MMP for the growing season

SEASON	OCT.	NOV.	DEC.	JAN.	FEB.	MARCH	APRIL	TOTAL
1993/94	151	157	147	141	126	95	10	827
1994/95	74	56	90	172	45	82	51	570
1995/96	123	127	69	44	265	125	52	805
MMP*	64	109	110	119	93	79	40	614

*For the relevant Land Type climate zone (Soil and Irrigation Research Institute, 1985)

5.4.2. Measured and predicted yields. These are presented in Table 5.4.2 and discussed in conjunction with the water extraction patterns presented in section 5.4.3

Table 5.4.2 Measured and predicted maize yields (kg ha^{-1}) for the Bethal/Hutton ecotope

	Season		
	1993/94	1994/95	1995/96
Measured	9756	2275	9600
DSSAT3	9741	4398	8504
PUTU	4279	2791	5101

5.4.3 Measured and predicted soil water extraction

1993/94 season

This was a very wet season (Table 5.4.1), with the rainfall also favourably distributed (Figure 5.4.1). The root zone was at DUL at planting on 01/11/1993 and the frequent rains up to around day 100 kept the water content of all the layers close to DUL until then. The available water was then slowly extracted, the root zone ending up at about 50% full at the end of the season. There was therefore virtually no drought stress, and because the soil is well drained (high KSat. values throughout see Table 4.3.1), also no stress due to waterlogging. Water extraction from the different layers was well simulated by the models, and prediction of the measured yield of 9756 kg ha^{-1} by DSSAT3 (9741 kg ha^{-1}) was excellent. A low yield was predicted by PUTU (4279 kg ha^{-1}). This failure is probably due to a faulty lower temperature threshold value during the grain filling stage in PUTU. The temperatures during this stage on this (and the Bethal/Avalon) ecotope, are frequently rather low. This weakness shows up again in the results for the 1994/95 and 1995/96 seasons, and is repeated for all three seasons on the nearby Bethal/Avalon ecotope.

1994/95 season

Rainfall for most of the season was fairly normal, with a considerably higher than normal amount in January. The root zone water content at planting (1/11/1993) was approximately at DUL. The crop grew very well but suffered severe hail damage during flowering, resulting in a relatively low yield of 2275 kg ha^{-1}. Due to this problem it is not meaningful to compare measured and predicted soil water extraction patterns for the last and most important part of the season. Both models seemed to have simulated water extraction in a reasonable way during the first part of the season. Maize yields on nearby lands, unaffected or slightly affected by hail, were around 4000 kg ha^{-1}. The DSSAT3 predicton of 4398 kg ha^{-1} was therefore again very good.

1995/96 season

The rainfall pattern was unusual (Table 5.4.1). October's rainfall was approximately twice the long-term mean, followed by a fairly normal November, then a trough in December and

January with only 50% of the average amount, then torrential rains during February and the first half of March amounting to 375 mm, compared to the long-term mean for the same period of around 100 mm. The planting date was 1/11/1993. The root zone was at DUL at this stage. Water extraction was fairly well predicted by both models to a depth of 900 mm. In the last three layers (900-1800 mm) DSSAT3 seems to have underpredicted water additions after the heavy rains in February, resulting in inaccurate extraction patterns. The PUTU simulation of the water content of three layers is reasonably good.

The measured and predicted yields by PUTU and DSSAT3 were 9600, 5101 and 8504 kg ha^{-1} respectively.

Fig. 5.4.1 Bethal / Hutton ecotope : Measured and predicted changes in the water content of the whole rootzone (1800 mm) ; 1993 / 94, 1994 /95 and 1995 / 96 seasons

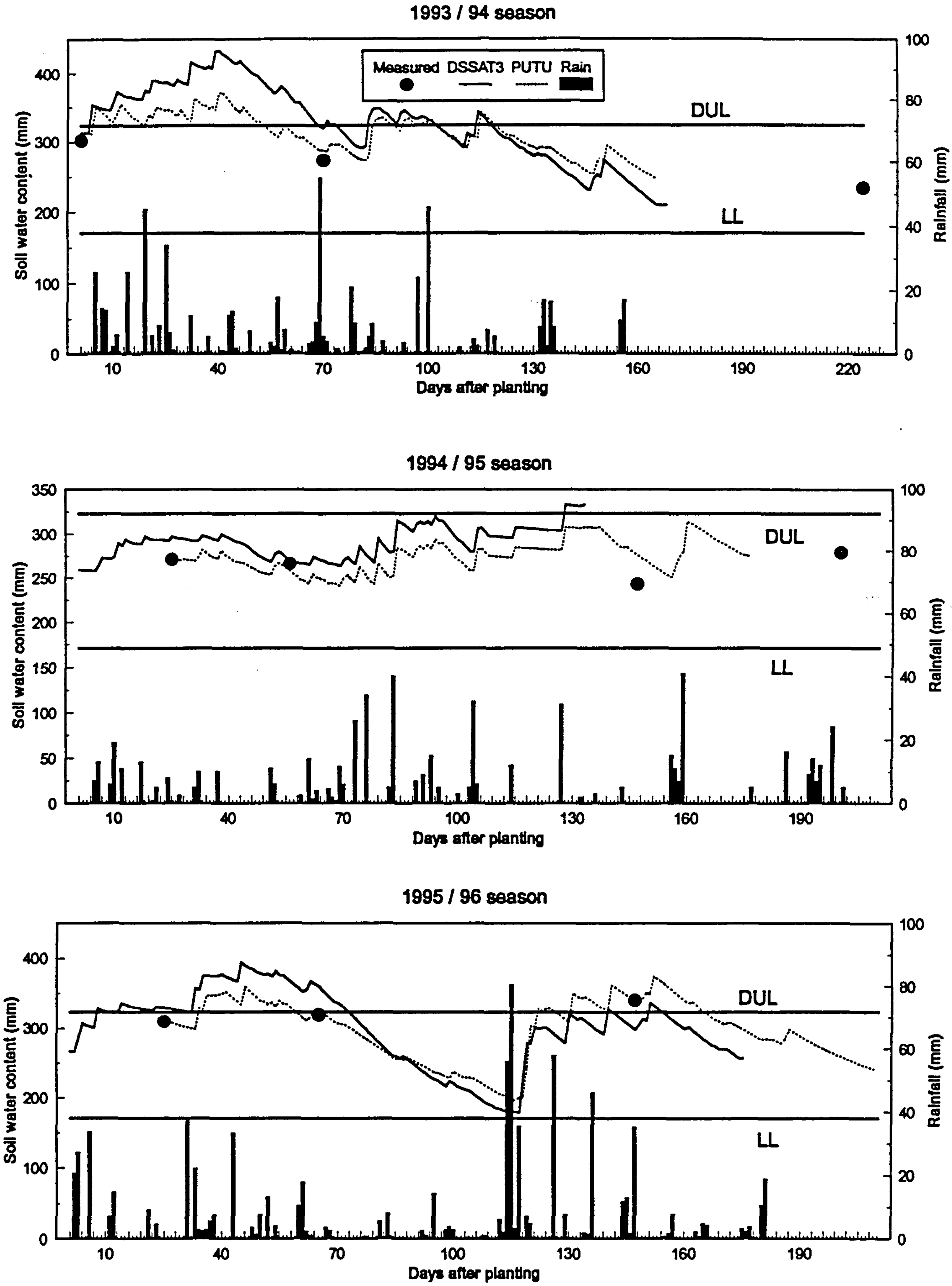


Fig. 5.4.2 Bethal / Hutton ecotope : Measured and predicted changes in the soil water content of the individual layers during the 1993 / 94 season

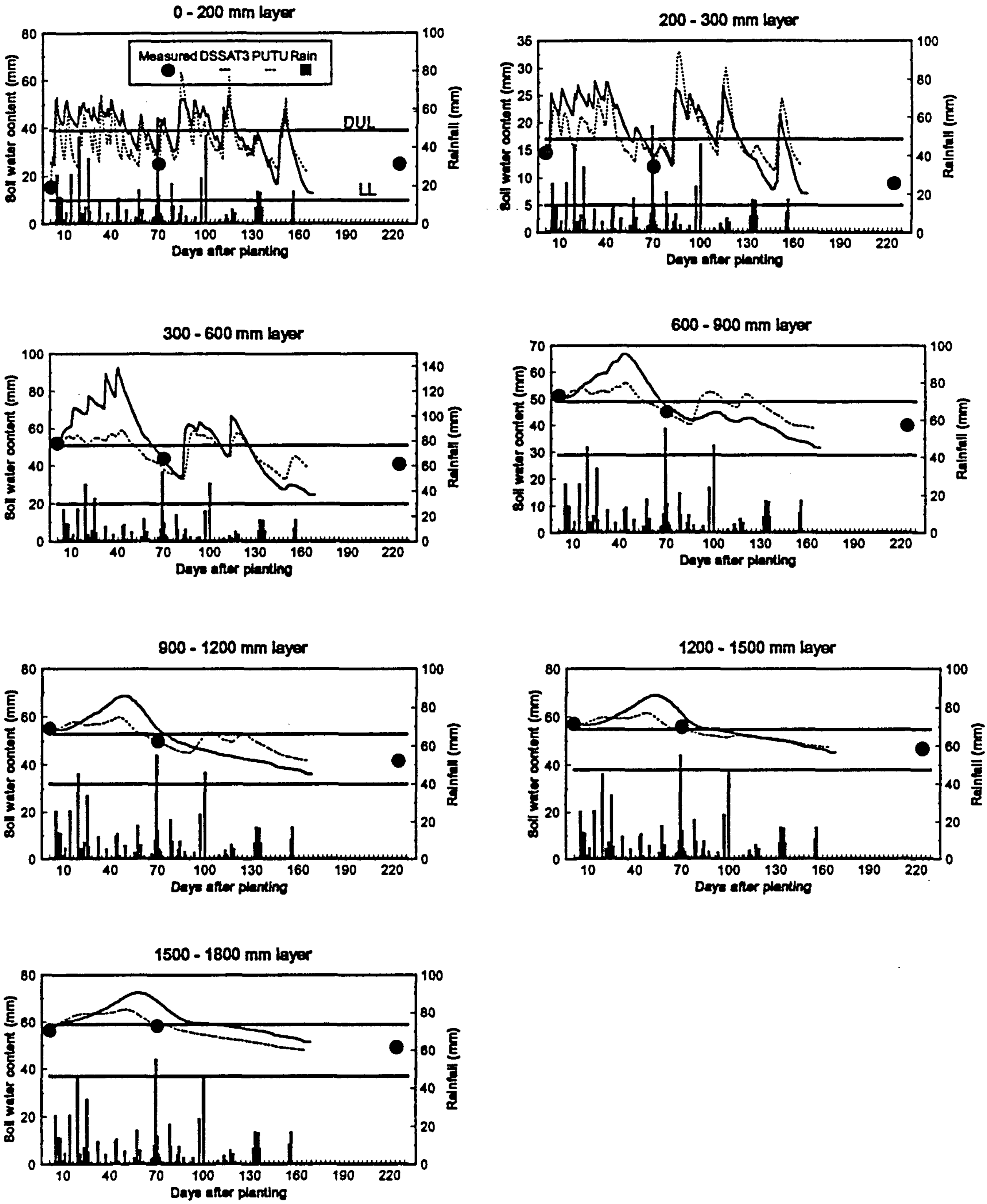


Fig. 5.4.3 Bethal / Hutton ecotope : Measured and predicted changes in the soil water content of the individual layers during the 1994 / 95 season

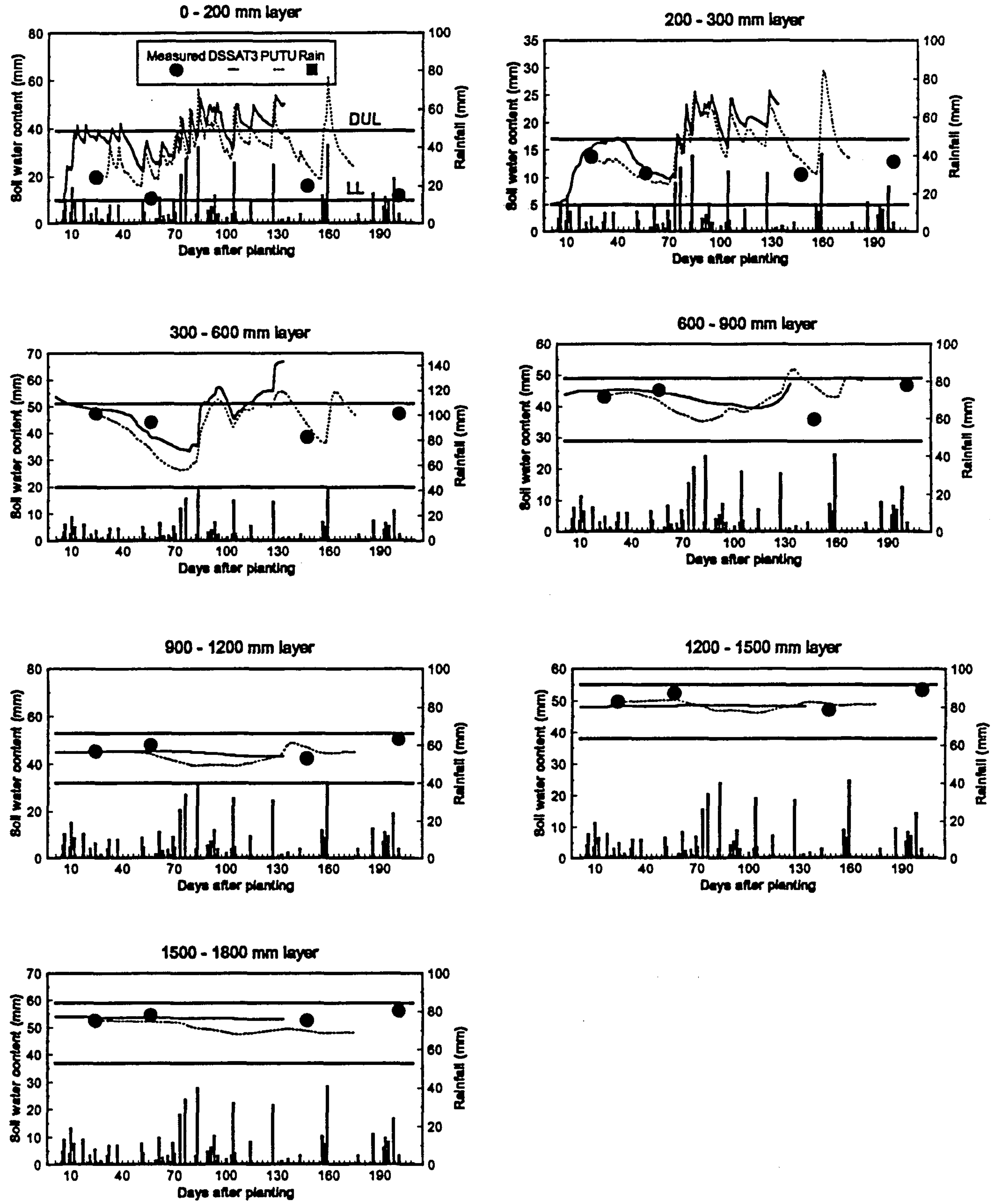
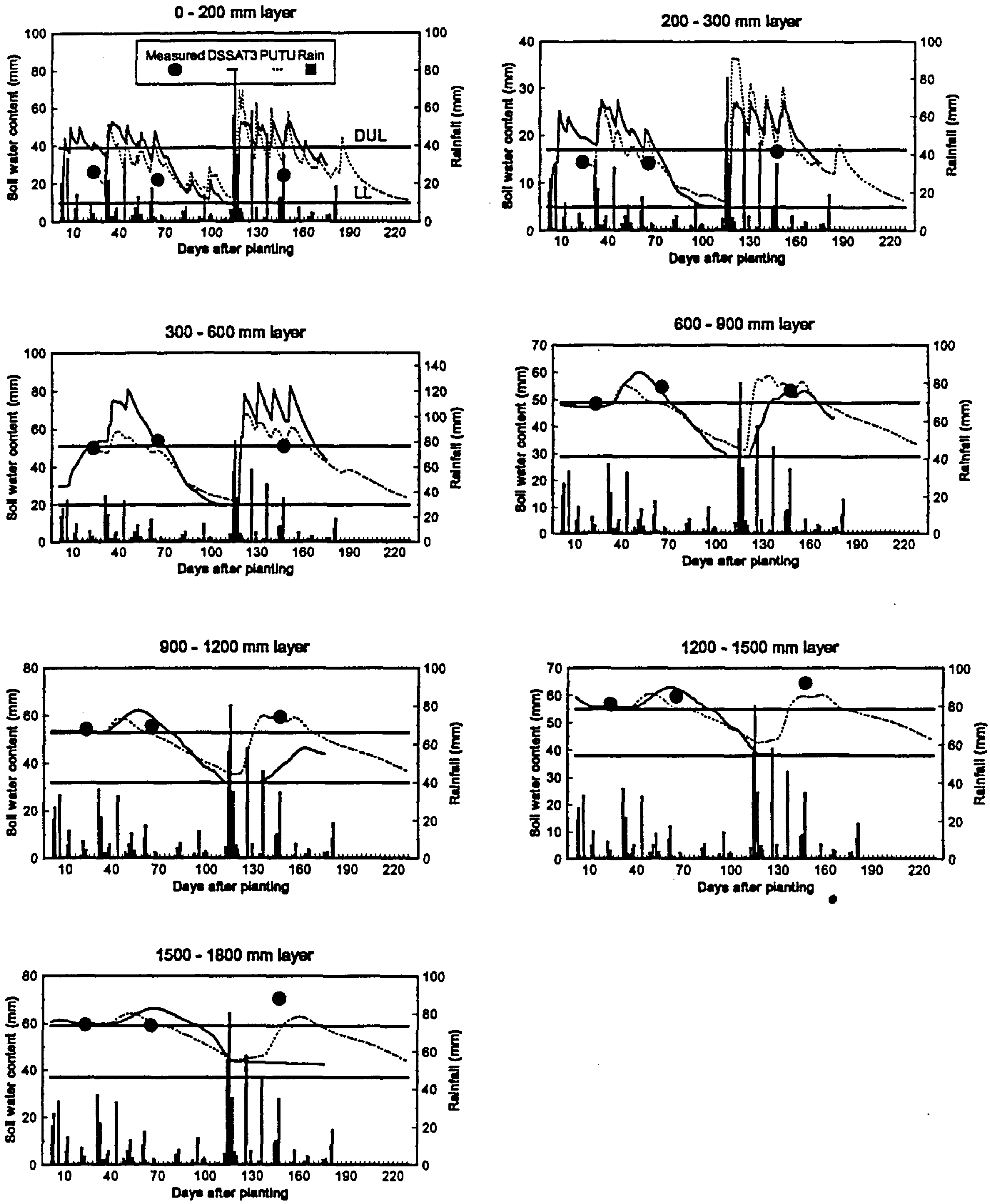


Fig. 5.4.4 Bethal / Hutton ecotope : Measured and predicted changes in the soil water content of the individual layers during the 1995 / 96 season



5.5 BETHAL/AVALON ECOTOPE

5.5.1 Rainfall

Since this ecotope is within a few hundred meters of the Bethal/Hutton ecotope the rainfall is the same as that given in Table 5.4.1.

5.5.2 Measured and predicted yields.

These are presented in Table 5.5.1 and discussed in conjunction with the water extraction patterns presented in section 5.5.3.

Table 5.5.1 Measured and predicted maize yields (kg ha^{-1}) for the Bethal/Avalon ecotope

	Season		
	1993/94	1994/95	1995/96
Measured	10575	2326	6700
DSSAT3	9741	4398	9698
PUTU	4272	2826	4903

5.5.3 Measured and predicted soil water extraction

1993/94 Season

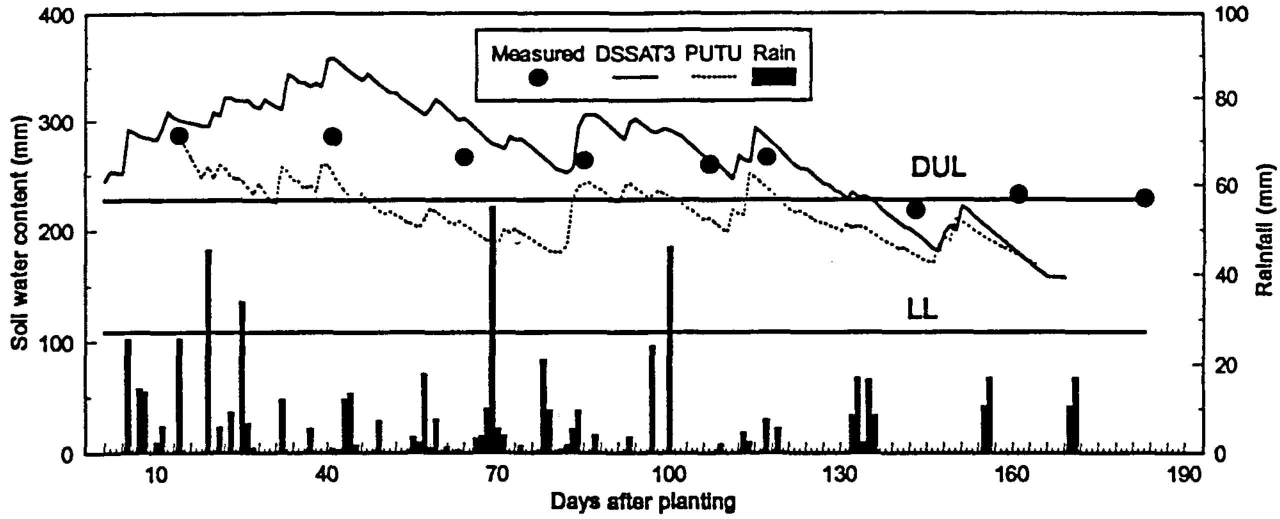
This was a very wet season, with the October to March rainfall (817 mm) 42% above average (574 mm) for that climate zone. The rainfall was also favourably distributed.

At planting (1/11/1993) the root zone water content was about 60 mm above DUL (Figure 5.5.1) due to the high rainfall in October (Table 5.4.1).

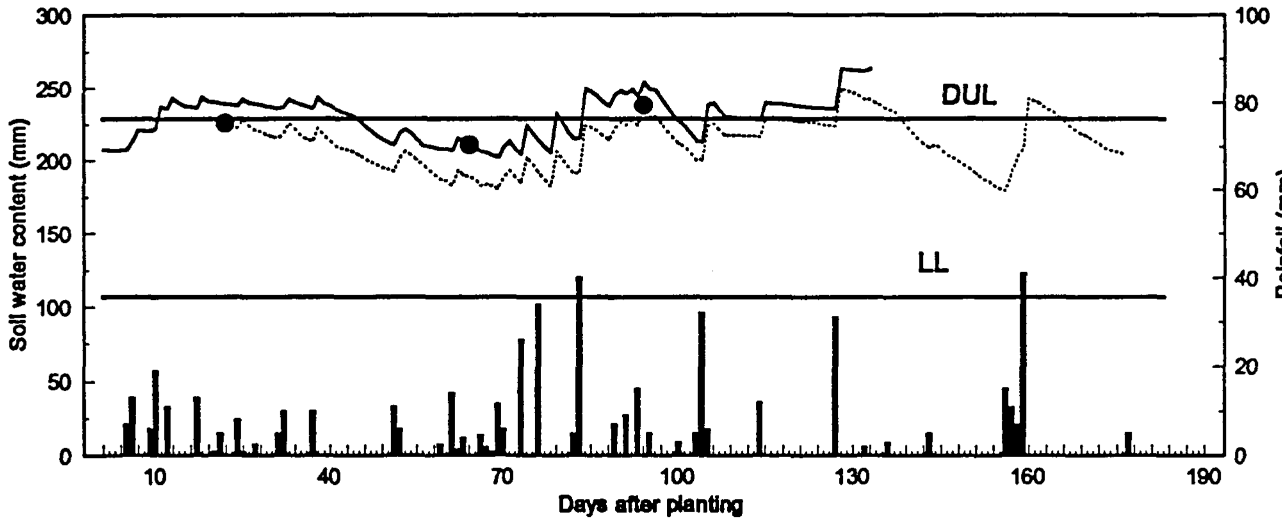
To understand soil water content fluctuations in this soil it is necessary to consider the morphology of the soil profile as described in Appendix 1.5. The soft plinthic horizon (sp) between 650 and 1170 mm reflects the results of centuries of intermittent waterlogging. Three observations are relevant. Firstly, the prominent mottles, including coarse grey areas in both the first portion (650-850 mm), the sp1, and in the second portion (850-1170 mm), the sp2. They indicate relatively frequent and prolonged periods of hydromorphy. The grey areas have a relatively high sand content, the result of hydromorphy which promotes the process of ferrolysis causing clay disintegration, leaving a sand rich material. It is thought that preferential movement of water in the sp horizons will take place in these grey sandy areas (Le Roux, Van Staden, Hensley & Botha, 1996). The localization and hardening of iron and manganese concretions is considerably more marked in the sp1 than in the sp2. This indicates that a greater degree of drying out of the sp1 has occurred through the centuries than

Fig. 5.5.1 Bethal / Avalon ecotope : Measured and predicted changes in the water content of the whole rootzone (1200 mm) ; 1993 / 94, 1994 /95 and 1995 / 96 seasons

1993 / 94 season



1994 / 95 season



1995 / 96 season

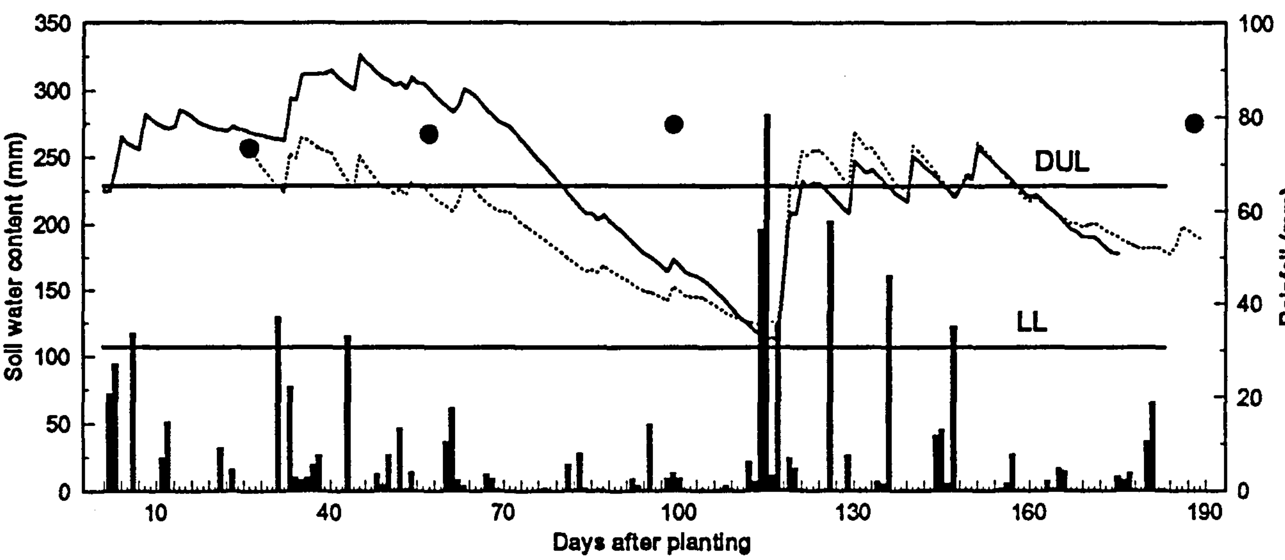


Fig. 5.5.2 Bethal / Avalon ecotope : Measured and predicted changes in the soil water content of the individual layers during the 1993 / 94 season

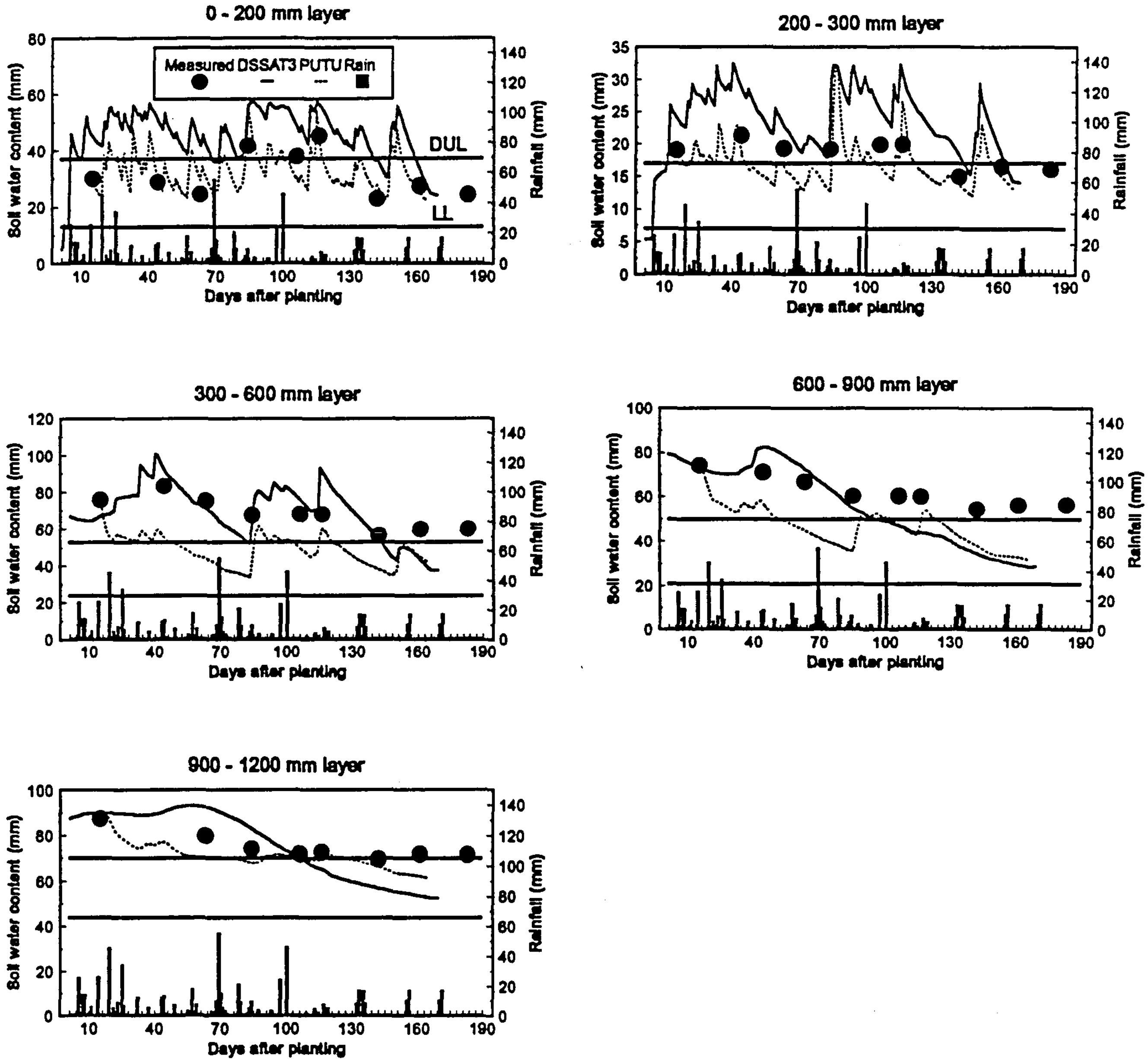


Fig. 5.5.3 Bethal / Avalon ecotope : Measured and predicted changes in the soil water content of the individual layers during the 1994 / 95 season

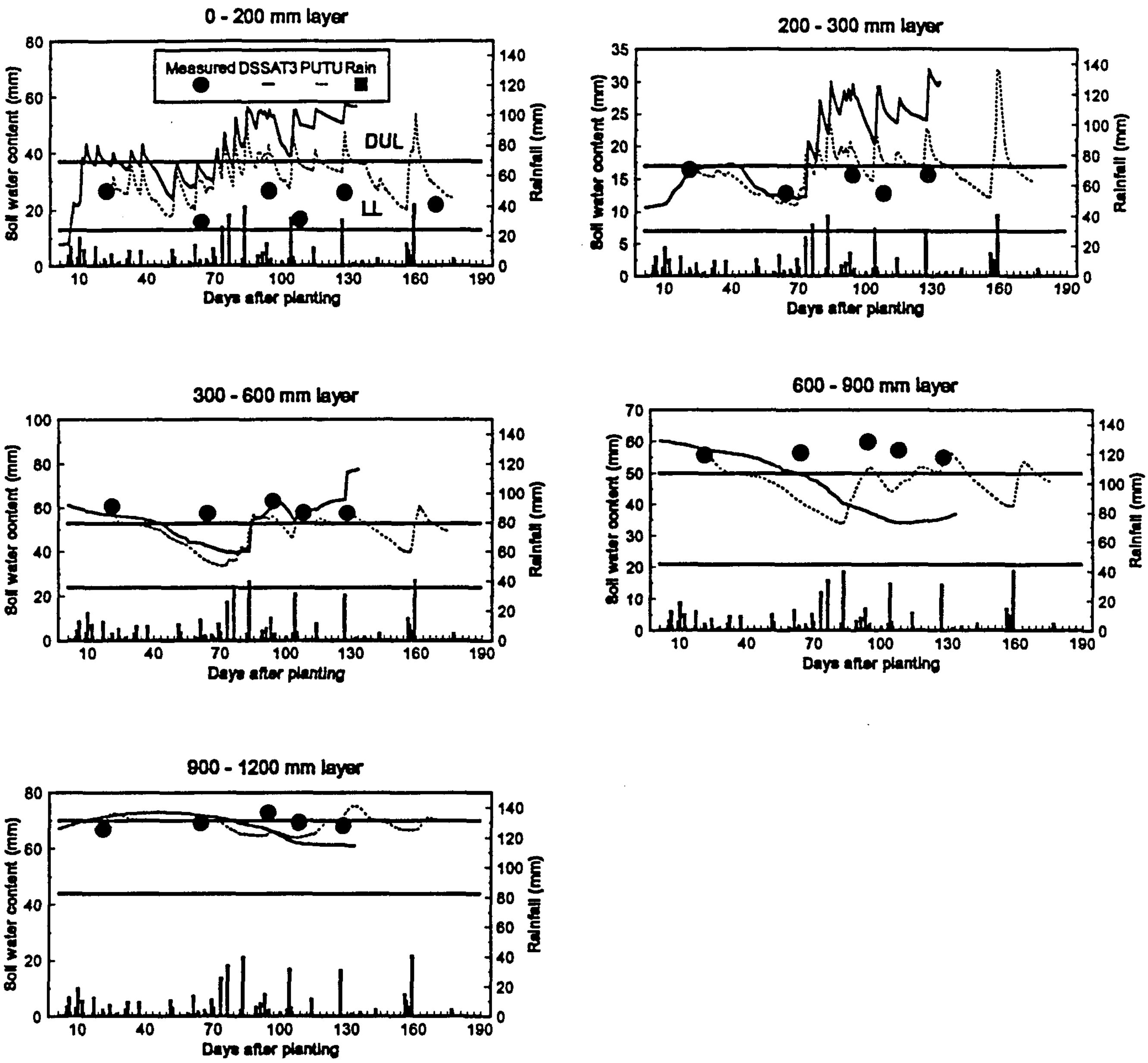
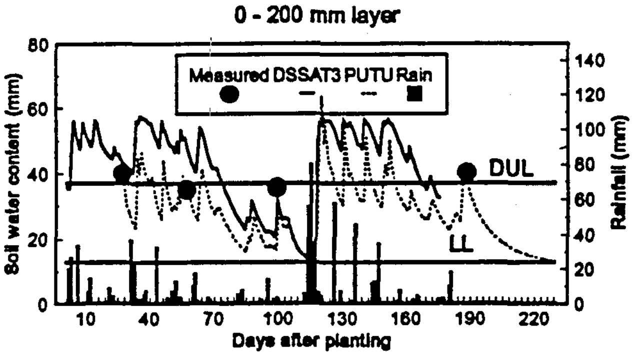
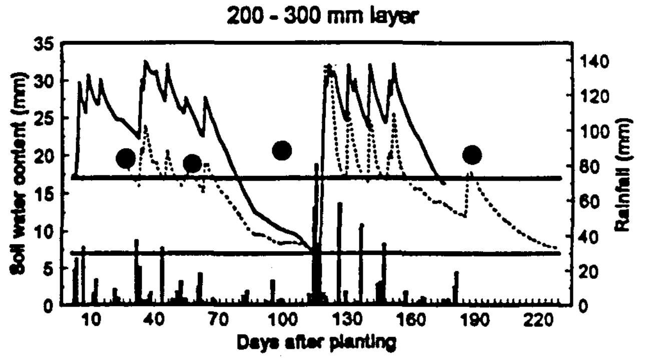
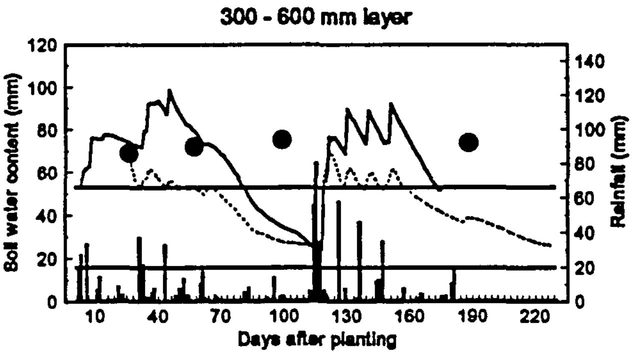
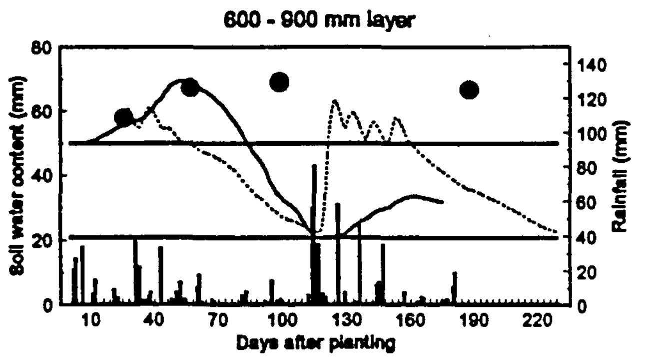


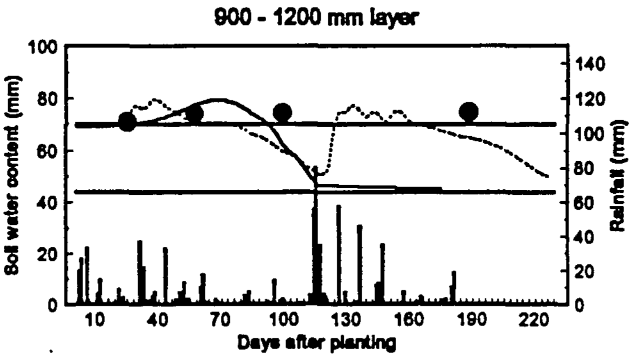
Fig. 5.5.4 Bethal / Avalon ecotope : Measured and predicted changes in the soil water content of the individual layers during the 1995 / 96 season











in the case of the sp2. This is confirmed by the overall colour of the sp2 compared to the sp1. In the sp2 yellow and grey predominate whereas in the sp1 a slightly more reddish brown colour is visible.. Secondly, measurements of the saturated hydraulic conductivity (Ksat) of these two horizons presented in Table 5.1, show values of 183 and 87 mm hr^{-1} respectively. Thirdly, water content measurements during the very wet early part of this season revealed a water table for long periods at about 700 mm. Based on these observations, and others on this and other Avalon soils, it is suggested that vertical water movement is restricted below the sp1 horizons, and that considerable lateral movement occurs, probably especially in the sp1 (Le Roux, et.al., 1996). If this is correct, growth simulations at a particular point on this type of soil, ie. which exclude landscape drainage considerations, are likely to be inaccurate during very wet seasons. There are probably two main reasons for this. Firstly, the prediction of the soil water content of the different soil layers is likely to be faulty due to lateral water movement "feeding" the soil, via the sp1, from higher-lying areas. Secondly, depending on the extent of this "feeding", and on the depth of the sp1 and sp2, there is the possibility of growth depression due to waterlogging. The latter is not yet catered for by either of the models tested here. Valuable information in this connection has however been obtained in the present project to assist with the development of an appropriate sub-routine. For this ecotope a water table for approximately the first 75 days at about 700 mm had virtually no harmful effect on yield (10 575 kg ha^{-1}), whereas on the Ermelo/Longlands ecotope where the water table remained at about 500 mm for most of the season, growth was poor and irregular, giving a yield which varied from zero to about 2 500 kg ha^{-1} depending on where the sampling was done. A provisional threshold water table depth for maize can therefore be set at about 600 mm. A similar value (500 mm) was chosen by Singels (1995) for a related study in the Viljoenskroon district.

The sustained high water content of the root zone, and of the individual soil layers, is clearly shown in Figures 5.5.1 and 5.5.2. The important layer here is the 600-900 mm one which represents the sp1. This layer was saturated or close to saturation until approximately day 75. Physiological maturity was reached around day 166. During this 91 day period there was 255 mm of rain with only one large event of 46 mm. The measured decrease in the soil water content of the root zone was 35 mm over this period. Estimating evapotranspiration from these figures yields a maximum value of 290 mm. This assumes negligible runoff and deep drainage. An independant estimate of evapotranspiration (ET), based on mean monthly A-pan values for this area and appropriate crop factors, and keeping in mind that the measured grain yield was 10 575 kg ha mm, yields 356 mm The difference between these two estimates of ET (356-290) gives a first approximation value of 66 mm for the amount of water which flowed into the root zone from higher up in the landscape, presumably mainly via the sp1 horizon during the 91 day period. This estimate of 66 mm is probably a minimum value, since the first ET estimate of 290 mm is a maximum value. The fact that the water content of the 900-1200 mm layer reached DUL approximately at day 100, while the water content of the sp1 layer never decreased as low as DUL, supports the hypothesis that the sp1 is the horizon in which most lateral flow occurs. The capillary rise distance above a water table in this soil is probably about 800 mm. A very wet sp1 horizon would therefore tend to keep the soil above it moist, at least to the top of the 200-300 mm layer, but with greatest influence on the 300-600 mm yellow brown apedal B horizon. This provides an explanation for why the water content of that horizon remained above DUL throughout the season.

PUTU simulates the water content of the first two layers very well, and then underestimates the water content of the 300-600 mm layer. This may be due either to capillary rise from the sp1 keeping the water content of this layer higher than expected, or to an over estimate of the permeability of the restricting layers below the sp1. The latter view is supported by the shape of the PUTU simulation for the sp1 horizon. DSSAT3 generally overestimates the water content of the soil down to 300 mm and then correctly simulates the 300-600 mm layer. Important here is that both models simulate a sharp decrease in the water content of the sp1 from approximately day 90 until the end, when they approach LL, whereas measured values remain above DUL. This is further supporting evidence for lateral inflow via the sp1 which, as expected, would not be catered for by the models.

The measured and predicted grain yields by DSSAT3 and PUTU were 10 575, 9 741 and 4272 kg ha^{-1} respectively. The low yield simulated by PUTU was evidently due to low temperatures during the last part of the season, for which the model was over sensitive. This weakness showed up again during the two following seasons. The DSSAT3 prediction is very good.

1994/95 Season

Rainfall was close to the long-term mean for most months, but 44% above average in January and approximately 50% below average in November and February (Table 5.4.1). The rainfall was favourably distributed, which resulted in the water content of the soil below 300 mm being maintained just above DUL. Rain percolating mainly into the 0-300 mm soil layer seems to have provided the water required for ET.

At planting (19/10/94) the water content of the root zone was slightly below DUL, and approximately at DUL for all the layers below 200 mm. The water content of these deeper layers was approximately at the same level as at the end of the 93/94 season. This observation is evidence for the reliability of the DUL values allotted to these layers. The crop grew well but was unfortunately severely damaged (73% loss of leaves) by hail during flowering. Since this would have had a significant influence on the later soil water extraction pattern, it needs to be kept in mind when assessing these patterns for the post flowering period. Both models seriously over-estimate the water content of the two surface layers, particularly after flowering; both also predict excessive extraction between days 40 and 80 from the 300-600 and the 600-900 mm layers. It is of interest to estimate the extent of lateral flow in the 600-900 mm layer (sp1 horizon approximately) during this drier year. Using the generalized equation of Nielsen, Reichardt & Wierenga (1983) (with an estimated β value) the hydraulic conductivity of the layer, at its prevailing water content throughout most of the growing season (55 mm), is estimated to be 0,1 mm day^{-1}. It is therefore concluded that although lateral flow probably did occur it was extremely slow. The almost negligible change in water content in the 900-1200 mm layer is well simulated by both models.

The measured yield of the hail damaged maize was 2326 kg ha^{-1}, and predicted yields by PUTU and DSSAT3 were 2826 and 4398 kg ha^{-1} respectively.

1995/96 Season

The unusual rainfall pattern has already been described in detail for the nearby Bethal/Hutton ecotope.

At planting (16/10/95) the water content of the root zone and all the layers (Figures 5.5.1 and 5.5.4) was slightly above DUL, a condition inherited from the end of the previous season. This was augmented by good rains during the rest of October, which probably filled the whole surrounding landscape with water. This water appears then to have moved laterally downslope in the sp1 keeping this horizon at the test site well above DUL throughout the December/January rainfall trough, and also contributing to the elevated water content of the yellow brown apedal B horizon (300-600 mm). The similar, yet spurious, water extraction pattern predicted by both models from all the layers during this period, approximately from day 60 to day 115, is therefore not surprising. Had it not been for the lateral feeding of the sp1, it is probable that the predicted extraction pattern during this period would have been correct.

The measured yield was 6700 kg ha^{-1} and predictions by PUTU and DSSAT3 were 4903 and 9698 kg ha^{-1} respectively. Judging by the water content measurements for the 300 to 600 mm layer, some field observations, and the 600 mm water table threshold value already described, it seems likely that the crop suffered a certain amount of damage due to waterlogging.

5.6 ERMELO/LONGLANDS ECOTOPE

5.6.1 Seasonal rainfall

The relevant data are presented in Table 5.6.1.

Table 5.6.1. Rainfall distribution on the Ermelo/Longlands ecotope for the 1993/94, 1994/95 and 1995/96 maize growing seasons and MMP

Season	OCT.	NOV.	DEC.	JAN.	FEB.	MARCH	APR.	TOTAL
1993/94	135	138	113	215	95	88	13	797
1994/95	37	77	123	94	15	101	71	518
1995/96	96	113	280	174	200	94	41	998
MMP*	64	109	110	119	93	79	40	614

* For the relevant Land Type climate zone (Soil and Irrigation Research Institute Staff, 1985)

5.6.2. Measured and predicted yields. These are presented in Table 5.6.2 and discussed in conjunction with the water extraction patterns presented in section 5.6.3

Table 5.6.2 Measured and predicted maize yields (kg ha^{-1}) for the Ermelo/Longlands ecotope

	Season	
	1993/94	1994/95
Measured	0 - 2512	2000
DSSAT3	9375	3318
PUTU	3821	463

5.6.3. Measured and predicted soil water extraction

1993/94 season

Rainfall during October, November and January was considerably above average (Table 5.6.1.). The planting date was 13/10/1993. The root zone was at DUL at this stage (Figure 5.6.1). Frequent rain kept the soil very wet throughout the season causing the crop to be damaged by waterlogging. There was a water table at a depth of approximately 500 mm for a period of at least 100 days during the season. The cause of this is evidently the very low hydraulic conductivity (Ksat) of 1 mm hr^{-1} (Table 4.6) of the soft plinthic horizon at a depth of around 800 mm.

The models simulated the water content fairly well up to around day 120. Thereafter they both predicted an excessively high extraction rate below a depth of 400 mm. The problem here is probably the same as that described for the Bethal/Avalon ecotope. Although the rainfall after day 100 was not excessive, the water content of all the soil layers remained very high. It seems that "feeding" of water by lateral movement from upslope areas also occurred here. Supporting evidence is provided by the results of hydraulic conductivity determinations in the E horizon, below the water table, by the "pump out" method. Results showed high values of between 14 and 15 m day^{-1}. Similar tests on the Vaalhartz irrigation scheme (sandy soil with about 8% clay) gave values around 7 m day^{-1}. (A. Streutker, Personal communication, 1989).

The measured yield varied from zero to 2554 kg ha^{-1} depending on where sampling was done. Since neither models have a waterlogging subroutine the predicted yields were too high, 9375 and 3821 kg ha^{-1} for DSSAT3 and PUTU respectively.

1994/95 season

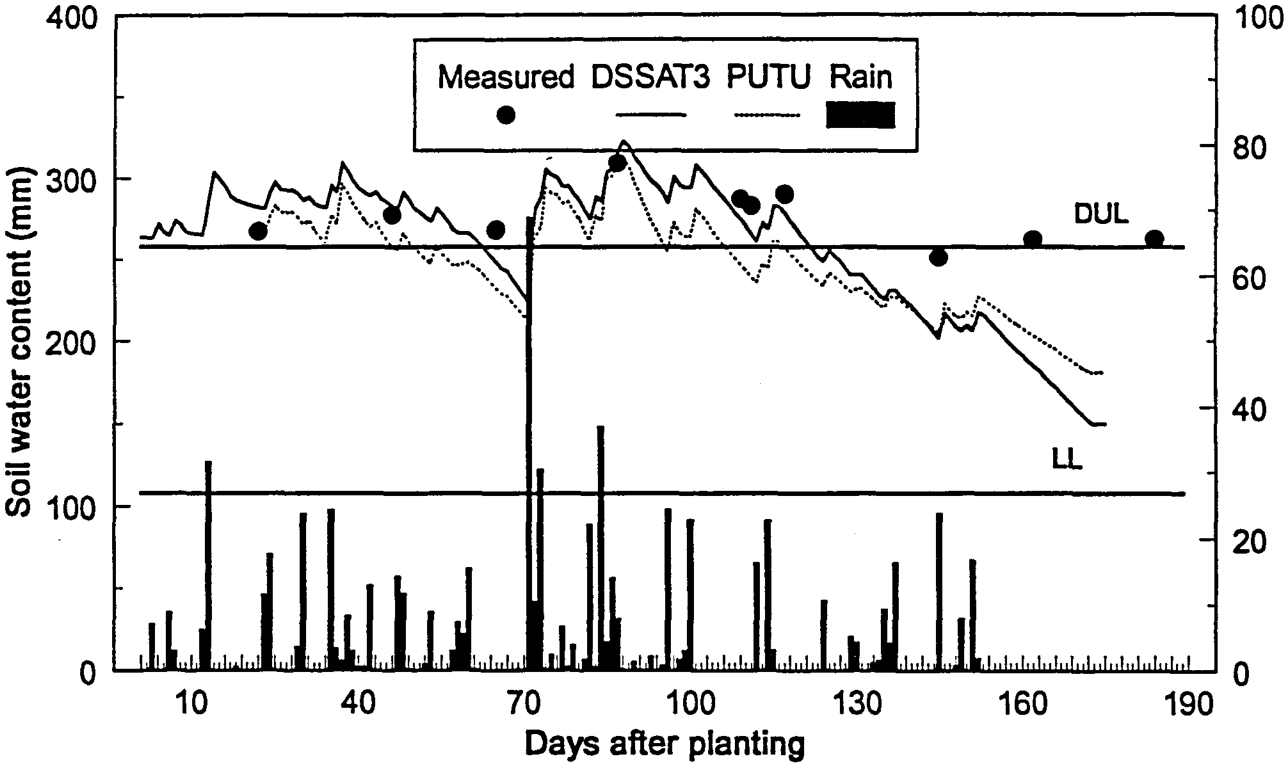
This was a relatively dry year with the rainfall below average for most months during the growing season. As far as having any influence on yield is concerned, the heavy rain between day 152 and 160 (Figure 5.6.1) can be ignored as it was too late in the season.

At planting on 20/10/94 the whole root zone was at DUL, just where it was at the end of the 93/94 season. Since there was very little rain in the intervening period, this confirms the reliability of the value used for this parameter. From planting until around day 88 there were frequent, relatively small amounts of rain which seem to have been sufficient to meet the crop's requirements. There seems to have been little water extraction from the soil below 200 mm. From around day 88 up to day 152 there was insufficient rain (55 mm) to meet the crop's requirements, and water started being extracted from the soil layers below 200 mm. Model predictions and measurements differ considerably during this period, the models, especially DSSAT3 (as in many other cases observed during these studies), predict far more rapid water extraction than what was measured. Since the water content of these layers was below DUL, the discrepancy cannot here be attributed to lateral water movement. The considerable extraction measured from the 900-1200 mm layer confirms that this actually forms part of the root zone in dry years.

The measured yield was 2000 kg ha^{-1} and those predicted by PUTU and DSSAT3 were 463 and 5341 kg ha^{-1} respectively. PUTU predicted a low yield because of very low temperature experienced between days 80 and 105.

Fig. 5.6.1 Ermelo / Longlands ecotope : Measured and predicted changes in the water content of the whole rootzone (1200 mm) ; 1993 / 94 and 1994 / 95 seasons

1993 / 94 season



1994 / 95 season

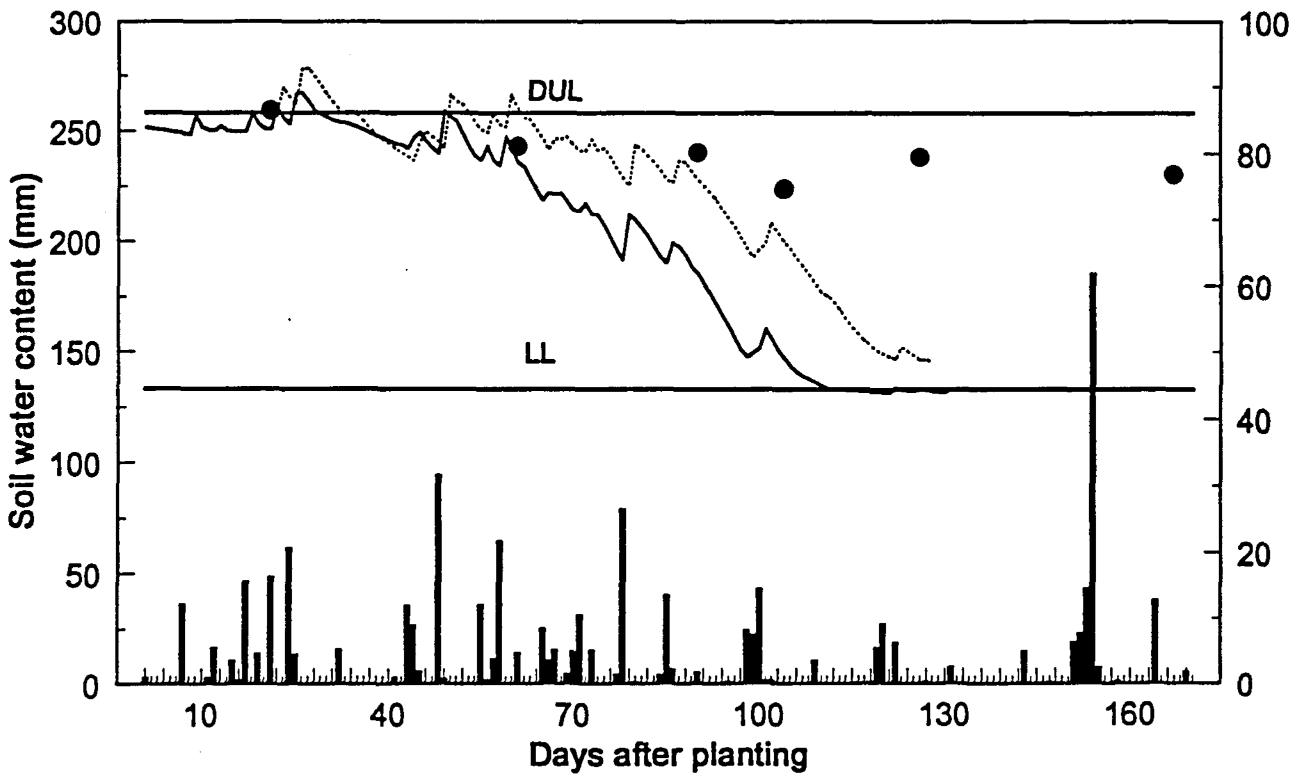


Fig. 5.6.2 Ermelo / Longlands ecotope : Measured and predicted changes in the soil water content of the individual layers during the 1993 / 94 season

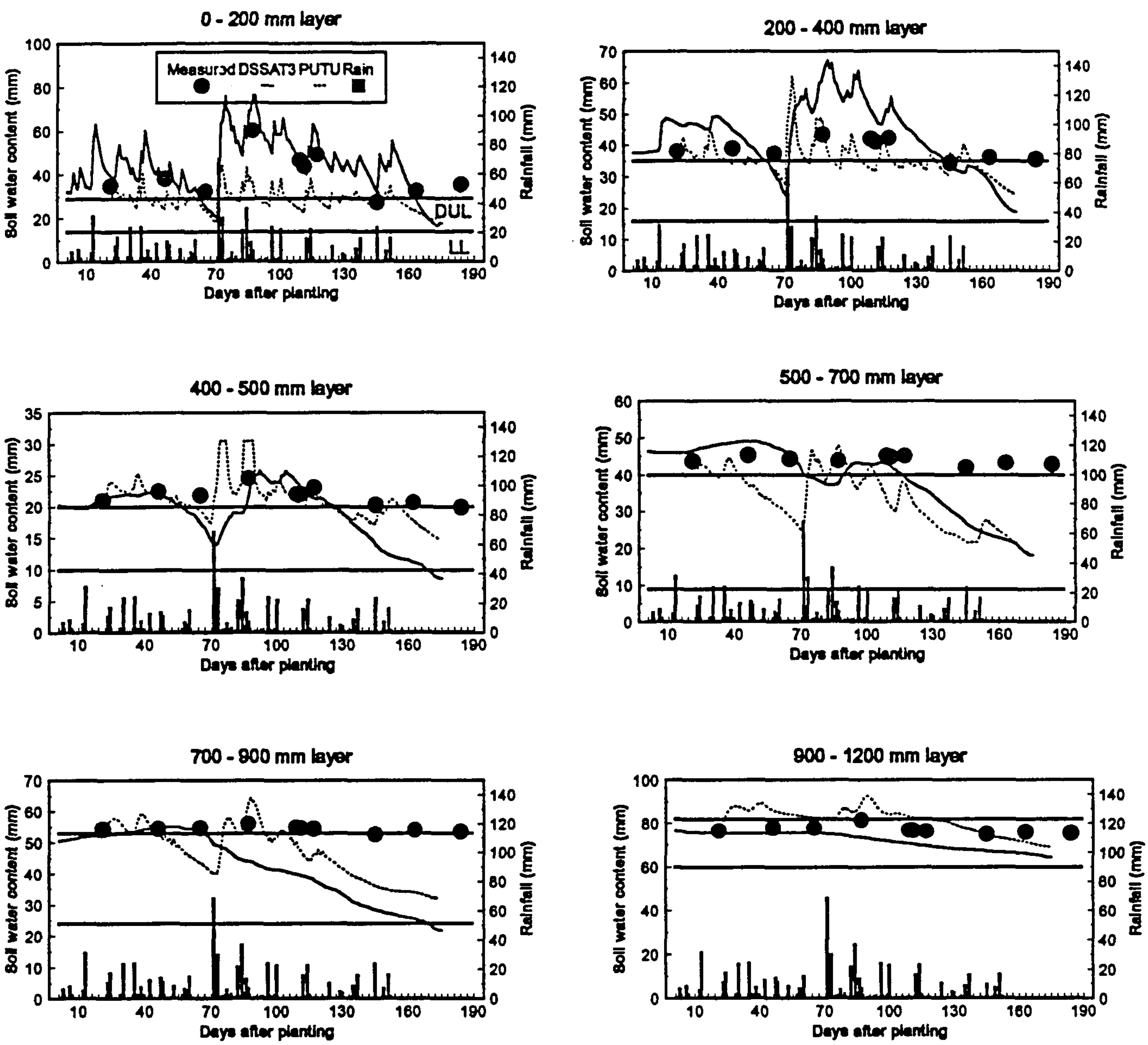
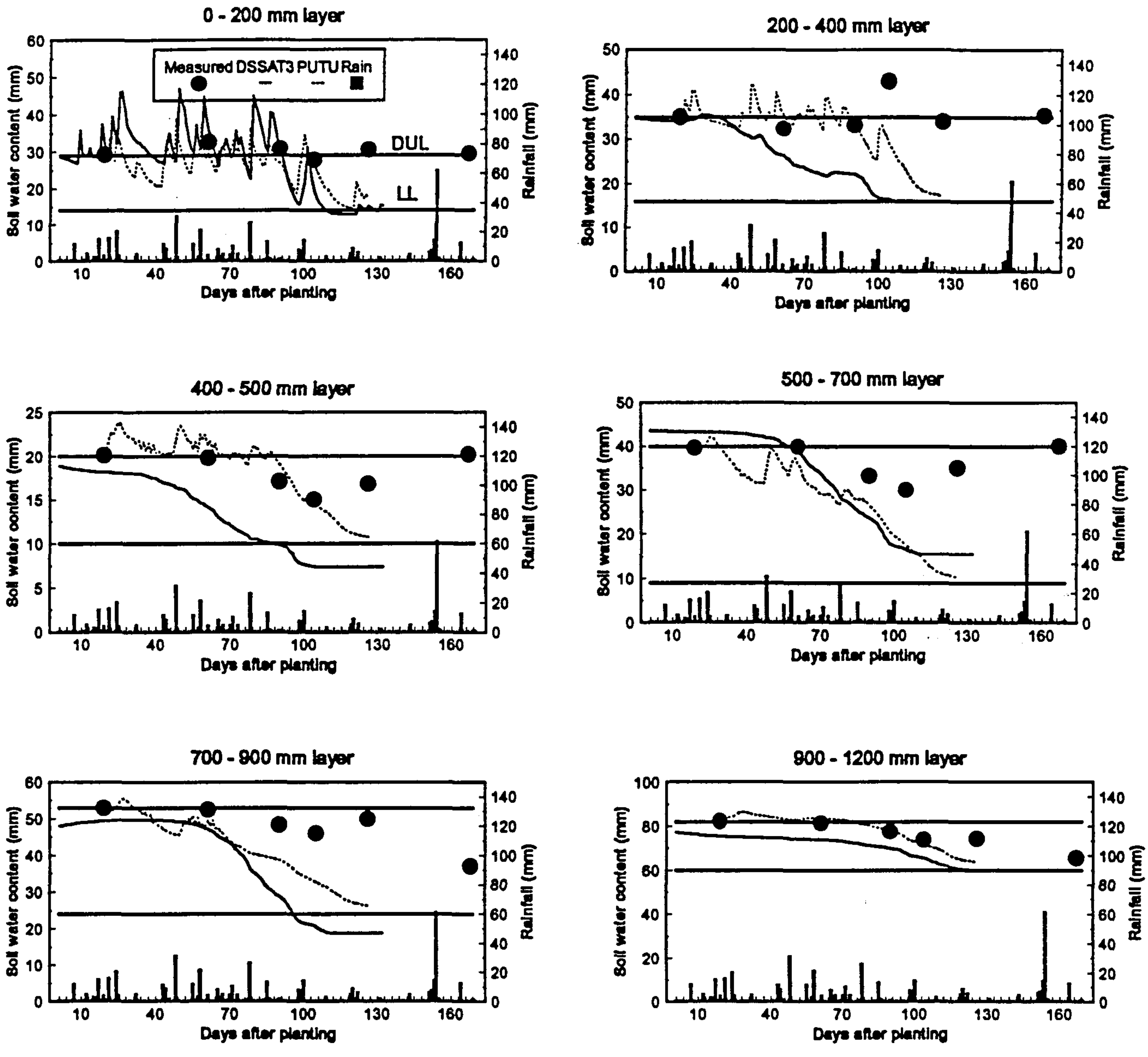


Fig. 5.6.3 Ermelo / Longlands ecotope : Measured and predicted changes in the soil water content of the individual layers during the 1994 / 95 season



5.7 BULTFONTEIN/CLOVELLY ECOTOPE

5.7.1 Seasonal Rainfall

The relevant rainfall data is presented in Table 5.7.1.

TABLE 5.7.1 Bultfontein/Clovelly ecotope rainfall distribution for the wheat growing seasons 1993, 1994, 1995, and MMP

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOT
1992	10	25	8	42	0	0	0	31	0	35	238	63	452
1993	23	65	20	13	20	0	0	2	1	97	36	49	326
1994	43	99	20	13	0	1	0	1	45	76	22	36	356
1995	77	69	61	28	116	6	0	14	0	47	73	145	636
MMP*	74	69	76	39	16	6	5	8	11	29	49	58	440

* For the relevant Land Type climate zone (Soil and Irrigation Research Institute, 1991)

5.7.2 Measured and predicted yields.

These are presented in Table 5.7.2 and discussed in conjunction with the water extraction patterns presented in section 5.7.3

Table 5.7.2 Measured and predicted wheat yields (kg ha^{-1}) for the Bultfontein/Clovelly ecotope

	Season		
	1993	1994	1995
Measured	2174	2660	1400
DSSAT3	124	79	195
PUTU	1709	662	1598

Fig. 5.7.1 Bultfontein / Clovelly ecotope : Measured and predicted changes in the water content of the whole rootzone (1500 mm) ; 1993 , 1994 and 1995 seasons

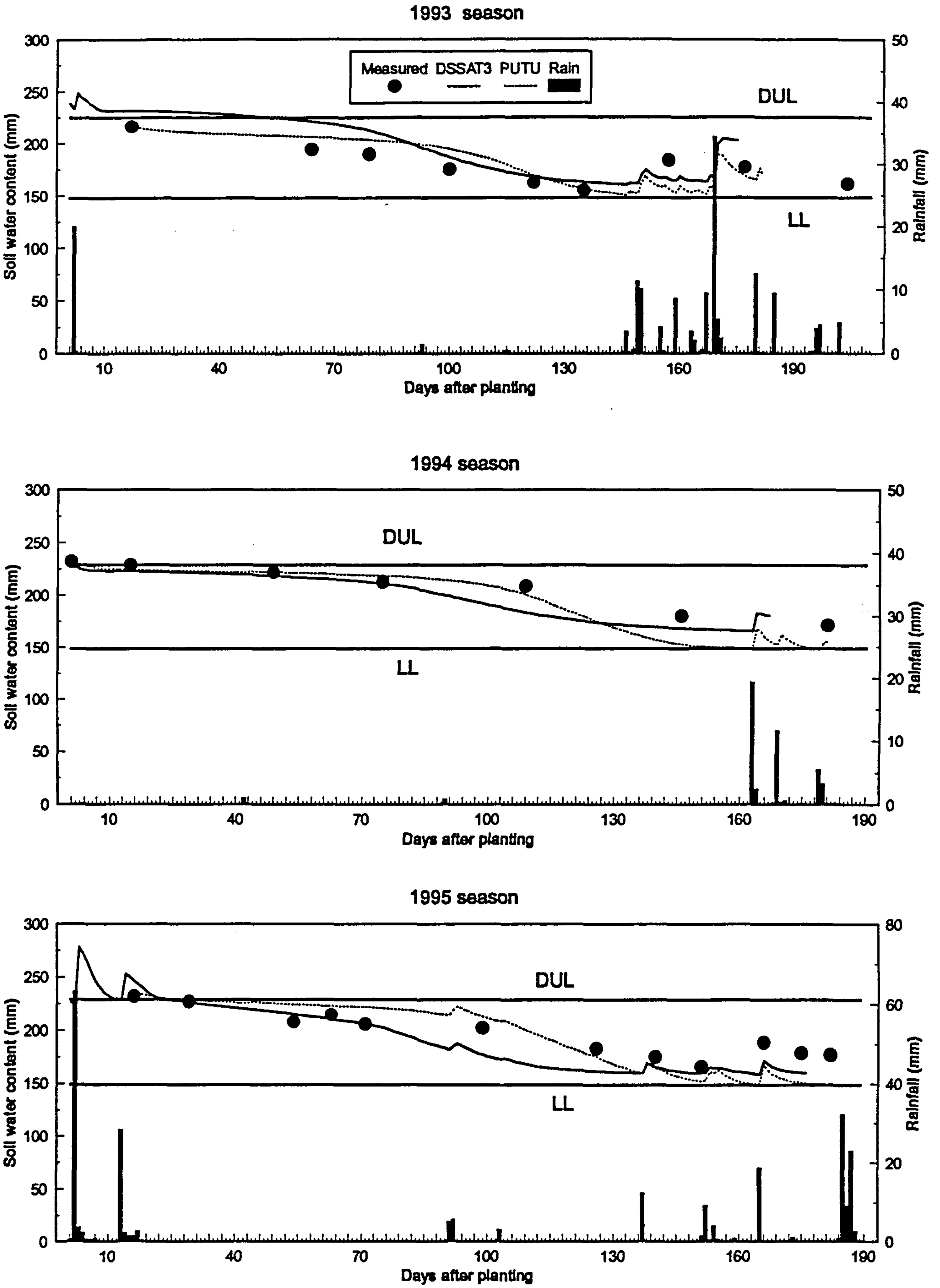


Fig. 5.7.2 Bultfontein / Clovelly ecotope : Measured and predicted changes in the soil water content of the individual layers during the 1993 season

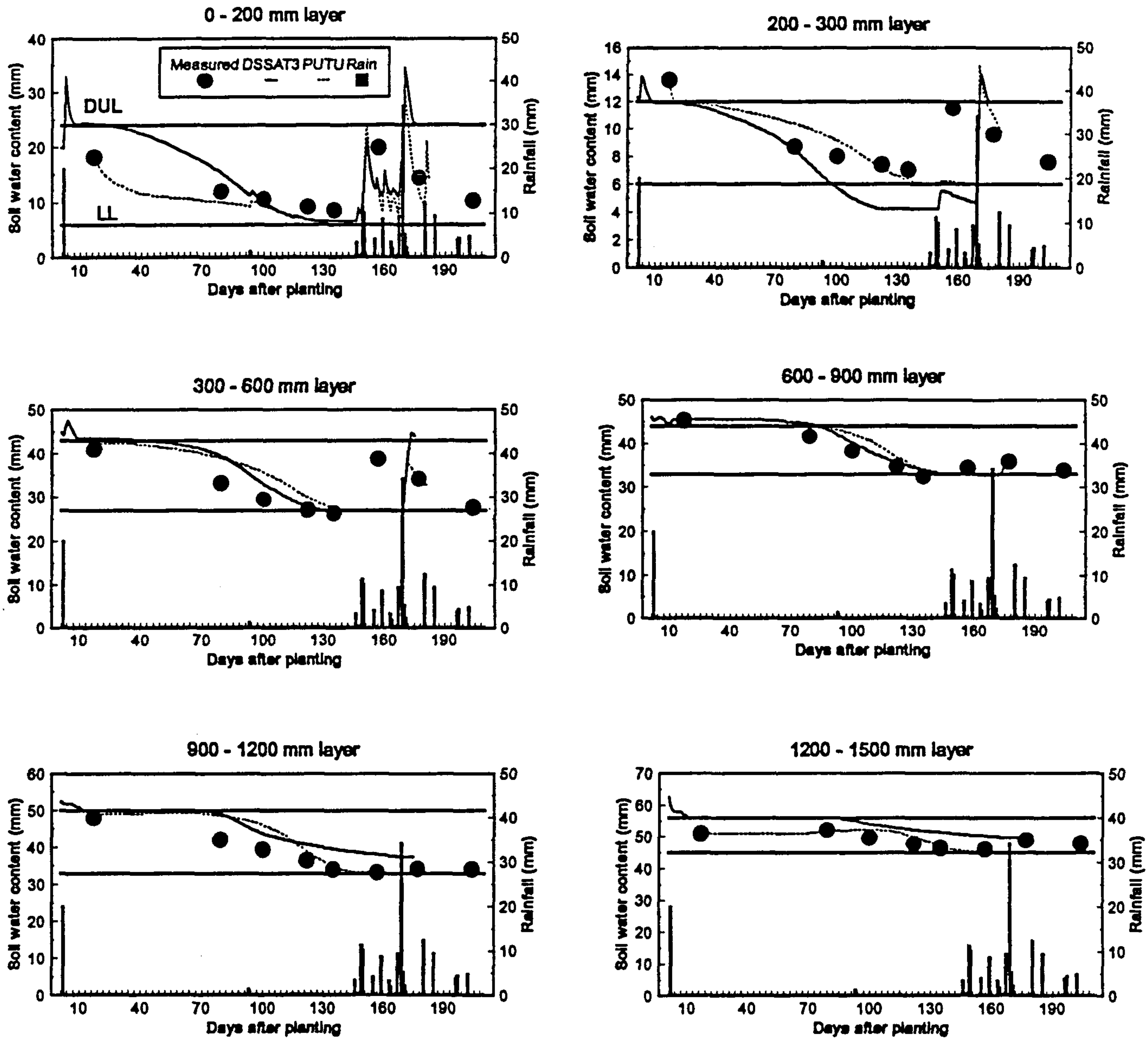


Fig. 5.7.3 Bultfontein / Clovelly ecotope : Measured and predicted changes in the soil water content of the individual layers during the 1994 season

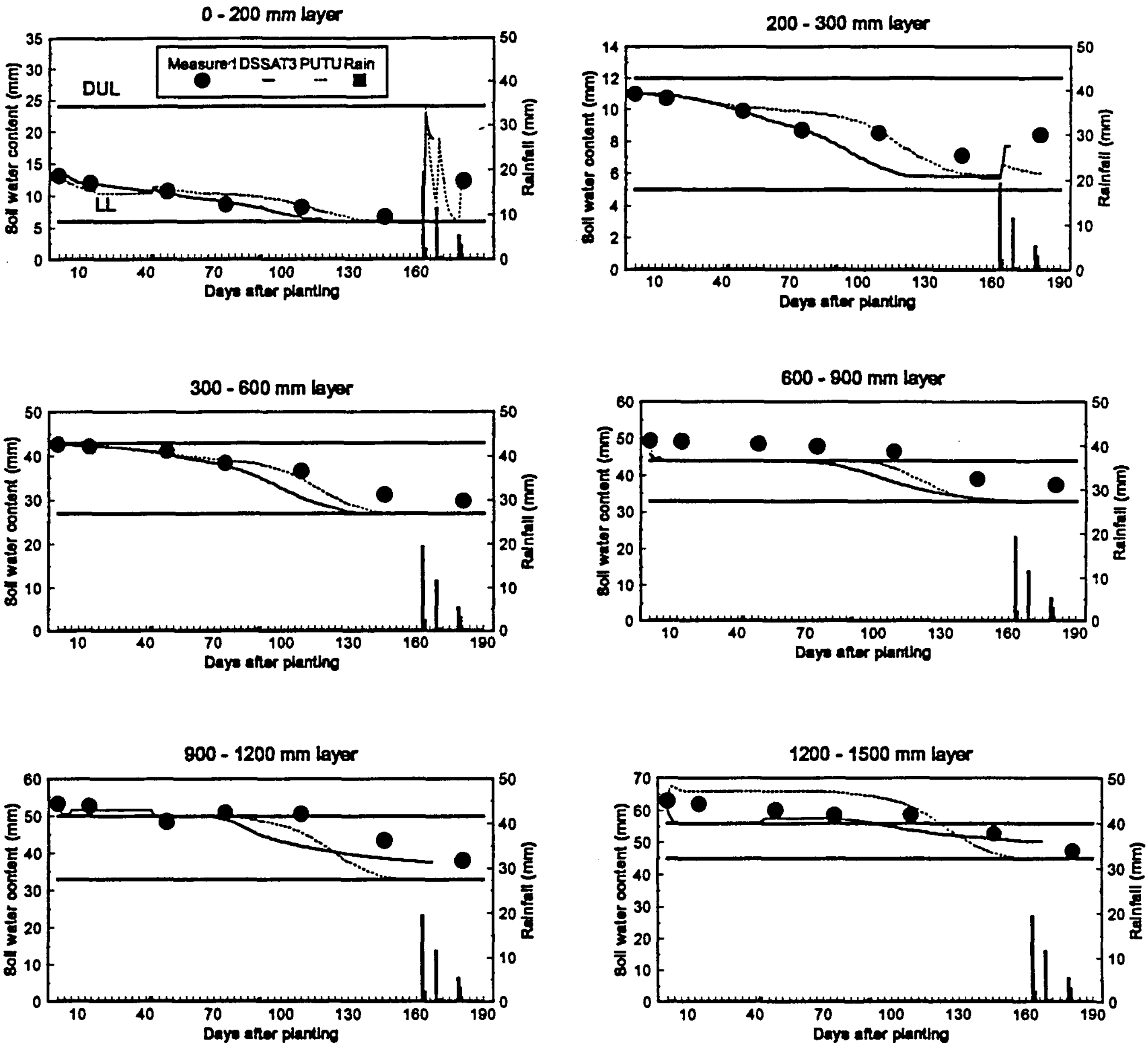
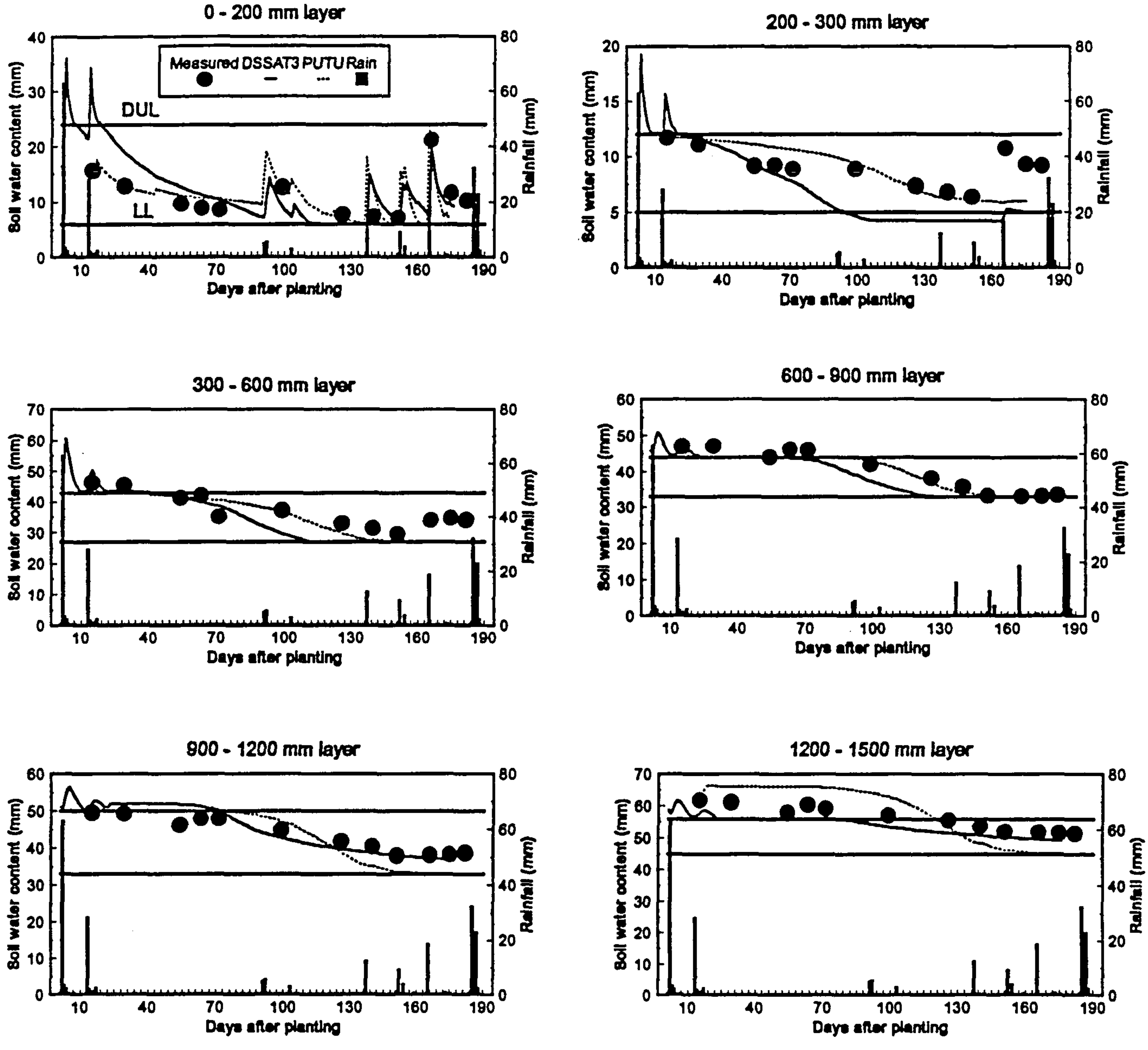


Fig. 5.7.4 Bultfontein / Clovelly ecotope : Measured and predicted changes in the soil water content of the individual layers during the 1995 season



5.7.3 Measured and predicted soil water extraction

Yield simulations on this ecotope are complicated by the presence of a water table which varies in depth between about 2000 and 2600 mm. In an attempt to simplify the system it was assumed that although root water extraction deeper than 1500 mm may help to keep wheat alive through a drought period, it would not have a significant influence on yield. The effective root zone was therefore set at 1500 mm to avoid the issue of capillary rise water feeding the deep roots. It seems now that this was an unwise decision as low yield predictions by the models could be attributed to the absence of this deep available water in their simulations.

It is necessary to record that neither of the models tested have a subroutine to cater for poor secondary root development, which actually occurred on this ecotope in all three seasons. This factor should promote overestimates of yield by the models, which was generally not observed, probably indicating the presence of some other compensating model weakness.

The following refinements were made to the PUTU wheat model in order to obtain more realistic simulations of measured situations. (A. Singels, Personal communication, 1996).

Crop evaporation coefficients

An algorithm was developed for the calculation of crop evaporation coefficients for wide rows. The crop coefficient is calculated using equations 1 and 2.

$$Fle = 1 - \exp(-k^* \ GLAI) \quad \text{.........} (1)$$

where:

k = extinction coefficient
GLAI = green leaf area index
FLe = crop evaporation coefficient

$$k = -0.7^*Frow \quad \text{.........} (2)$$

where Frow is a zero to unity row spacing control factor

Frow is calculated using equation 3:

$$Frow = \exp[-0.7^* (GLA\ row - 0.6)] \text{ and } Frow \text{ not } > 1 \quad \text{.........} (3)$$

where: GLA row = green leaf area per meter in row ($m^2\ m^{-1)}$

The value of Frow is not allowed to exceed 1.

Leaf growth

The value of the maximum leaf area expansion rate (DLAPMAX) has been reduced by 25%. This causes the simulated rate of leaf growth to be reduced by 25%.

1993 Season

At planting (11/5/1993) the root zone water content was slightly below DUL at all depths down to 1200 mm. There was therefore a good reserve of water for the rainless five month period which followed, until a few small showers fell around day 148. This was a good test of the root growth subroutines of the models. Simulations of water extraction were reasonably good, both models predicting values close to the measured critical LL value around day 130 in all the layers. Secondary root development was very poor.

The measured yield was 2174 kg ha^{-1}, and predictions by PUTU and DSSAT3 were 1709 and 124 kg ha^{-1} respectively. Yields above 1500 kg ha^{-1} are generally not expected in this kind of ecotope when secondary root development is poor. The higher than expected yields obtained during this and the 1994 season, both with poor secondary root development, may well have been due to the beneficial effect of the water table.

1994 Season

At planting (18/5/1994) the surface soil was very dry; and secondary root development was poor. Deeper in the rootzone the water content increased with increasing depth, and from 600 mm to 1500 mm the water content was slightly above DUL. There was no rain until 163 days after planting. Soil water extraction for all the layers was reasonably well simulated by both models,but both PUTU and DSSAT3 seem to have predicted serious stress too early, predicting far lower yields (662 and 79 kg ha^{-1} respectively) than the measured value of 2660 kg ha^{-1}.

1995 Season

There were good rains, totalling 116 mm during the planting month of May (Table 5.7.1). The root zone was full of water at planting on 17/5/1995. As before there was then virtually no rain until flowering when only a few small showers fell. Secondary root development was poor. Water extraction from all the layers, excepting 1200-1500 mm, was reasonably well simulated by both models. As before DSSAT3 predicted excessive stress to give the very low yield of 195 kg ha^{-1} compared to the measured value of 1400 kg ha^{-1}. The result by PUTU was good i.e. 1598 kg ha^{-1}.

5.8 PETRUSBURG/BLOEMDAL ECOTOPE

5.8.1 Seasonal rainfall

The relevant data are presented in Table 5.8.1

Table 5.8.1 Petrusburg/Bloemdal ecotope rainfall distribution for the wheat growing seasons 1993, 1994, 1995, and MMP

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOT
1992	4	0	29	17	0	0	1	13	0	28	77	8	177
1993	91	156	17	18	2	0	0	27	0	161	51	58	581
1994	128	110	30	7	0	1	0	0	0	0	15	36	327
1995	97	106	48	17	46	2	0	0	18	49	31	66	480
MMP*	69	65	72	41	18	6	7	10	14	36	51	54	443

* For the relevant Land Type climate zone (Soil and Irrigation Research Institute, 1991)

5.8.2 Measured and predicted yields.

These are presented in Table 5.8.2 and discussed in conjunction with the water extraction patterns presented in section 5.8.3

Table 5.8.2 Measured and predicted wheat yields (kg ha^{-1}) for the Petrusburg/Bloemdal ecotope

	Season		
	1993	1994	1995
Measured	1613	1400	870
DSSAT3	1644	155	467
PUTU	3479	130	3590

5.8.3 Measured and predicted soil water extraction

1993 Season

All the layers of the root zone were close to DUL at planting on 10/5/93, excepting the deepest (1800-2100 mm) one which was about ⅔ full. Secondary root development was poor. The first significant rains fell after flowering at around day 145. The root water extraction pattern was reasonably well predicted by PUTU but poorly by DSSAT3, up to a depth of 1500 mm. The DSSAT3 predicted root water uptake rate between 300 and 900 mm was far too rapid between days 40 and 100; and similarly between day 70 and day 140 from the 900 - 1500 mm depth. Comparing the predictions here with those at the Bultfontein/Clovelly ecotope, where similar stress levels occurred at flowering, and the DSSAT3 predicted yield was 124 kg ha^{-1}, the comparable result here was surprisingly high i.e. 1644 kg ha^{-1}, very close to the measured value of 1613 kg ha^{-1}. The prediction by PUTU was 3479 kg ha^{-1}, 116% too high.

1994 Season

This was an extremely dry season with virtually no rain until 30 days after flowering (Table 5.8.1. and Figure 5.8.1. The ability of wheat to withstand extreme drought stress is clearly shown by the results of this season. At planting on 18/5/1994 the root zone as a whole contained 118 mm of available water (approximately half full) with the water content increasing slightly with depth (Figure 5.8.3). Secondary roots developed reasonably well. The two deepest layers were close to DUL. The soil water extraction diagrams for the last part of the season show the value of this available water stored deep in the root zone for preventing complete crop failure. The presence of secondary roots may well have been of considerable benefit to this crop. The available water in the top 900 mm was used up by the time flowering started at around day 130. From then until physiological maturity there were only light showers which only wet the 0-200 mm soil layer (Figure 5.8.3), and this water was probably mainly lost as soil evaporation. The measured yield was 1400 kg ha^{-1}, attained with virtually only the use of the 118 mm of stored soil water that was present at planting.

This was an extreme test of the correctness of the drought stress subroutine of the crop models, and at the same time a valuable opportunity to adapt them. The root water uptake subroutine of PUTU seems to be correct for all the layers excepting 1800-2100 mm, where extraction was slightly too rapid. It seems reasonable to conclude that the excessively low yield of 130 kg ha^{-1} predicted by PUTU, must be due to a shortcoming in the way in which the model relates leaf water stress and photosynthesis.

Excessively rapid soil water extraction is predicted by DSSAT3 for the 0-900 mm layer. For the layers between 900 and 1800 mm the predicted extraction rate is too slow. For the 1800-2100 mm the model predicts negligible extraction, which indicates incorrect prediction of the depth and intensity of root ramification. A low yield of 155 kg ha^{-1} was predicted by this model, indicating that its stress/photosynthesis algorithm is probably also not satisfactory for these extreme conditions.

1995 Season

Rainfall was well distributed (Table 5.8.1) with the 46 mm during May being particularly significant. The root zone was at DUL at planting, and secondary root development was favourable. The wheat grew well until the flag leaf stage. Hot dry winds during the following period, around flowering, damaged the crop, and low temperatures during the last part of the season probably also caused a 5-10% yield depression. (Personal communication, J. Purchase and W.H.O. du Toit, 1996). This was unfortunate as there was plenty of available water in the root zone at flowering (Figure 5.8.1), and there were good spring rains. The measured yield was only 870 kg ha^{-1} .

The root water extraction rate predicted by DSSAT3 in all layers was far too high. This resulted in all available water in the surface soil to a depth of 900 mm being used up by day 100. This was probably the reason for the severe stress predicted by the model, and the low predicted yield of 467 kg ha^{-1} .

The PUTU prediction of water extraction was reasonably good up to about day 120; after that the rate was overestimated. It may be that the injurious hot dry wind around the flag leaf stage caused permanent damage to the leaves in such a way that transpiration was impaired. The harmful influence of the hot dry winds and the low temperature was evidently not sensed by PUTU which predicted the approximate yield level (3590 kg ha^{-1}) which could have been expected had it not been for these two factors.

Fig. 5.8.1 Petrusburg / Bloemdal ecotope : Measured and predicted changes in the water content of the whole rootzone (2100 mm) ; 1993, 1994 and 1995 seasons

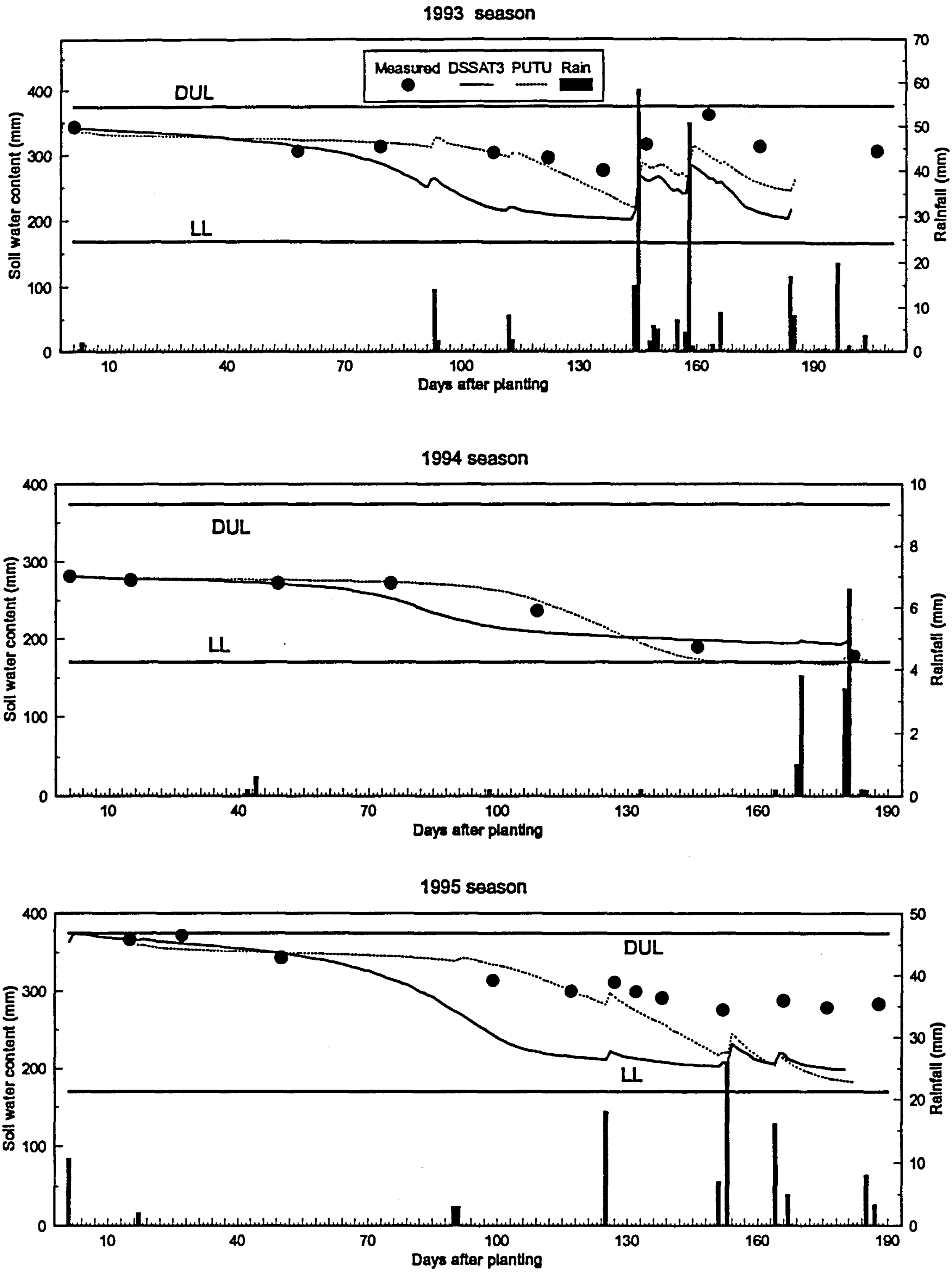


Fig. 5.8.2 Petrusburg / Bloemdal ecotope : Measured and predicted changes in the soil water content of the individual layers during the 1993 season

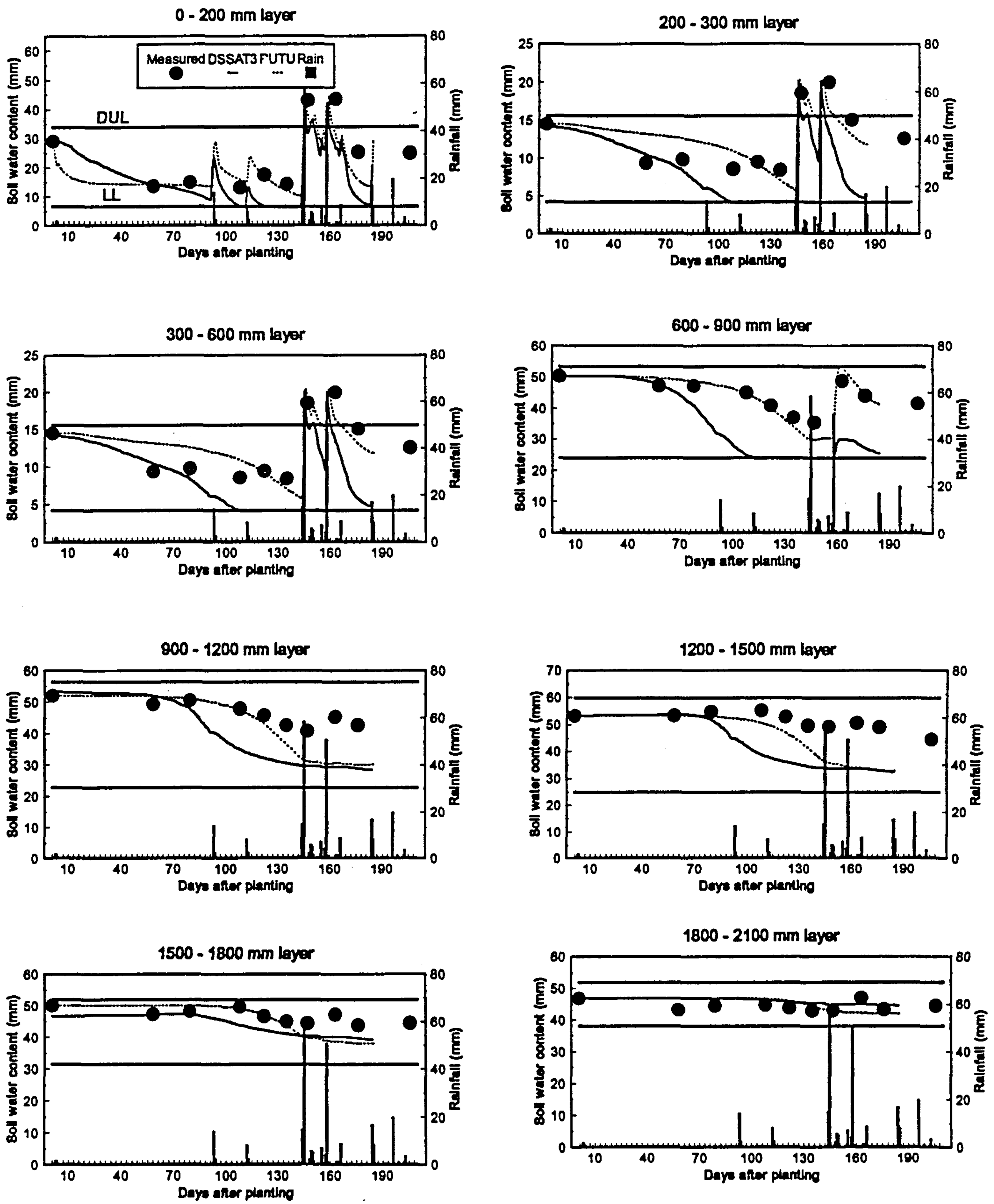


Fig. 5.8.3 Petrusburg / Bloemdal ecotope : Measured and predicted changes in the soil water content of the individual layers during the 1994 season

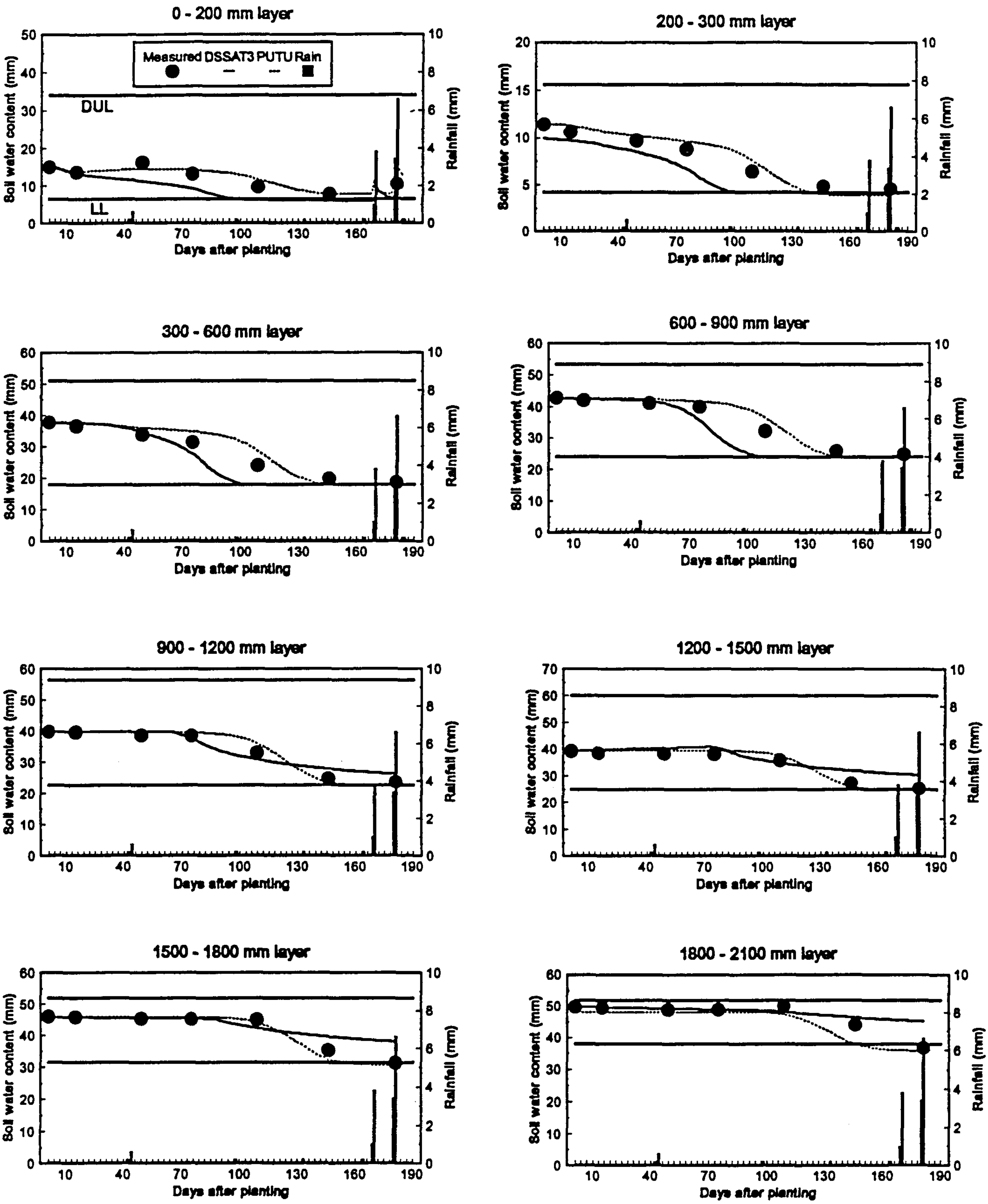
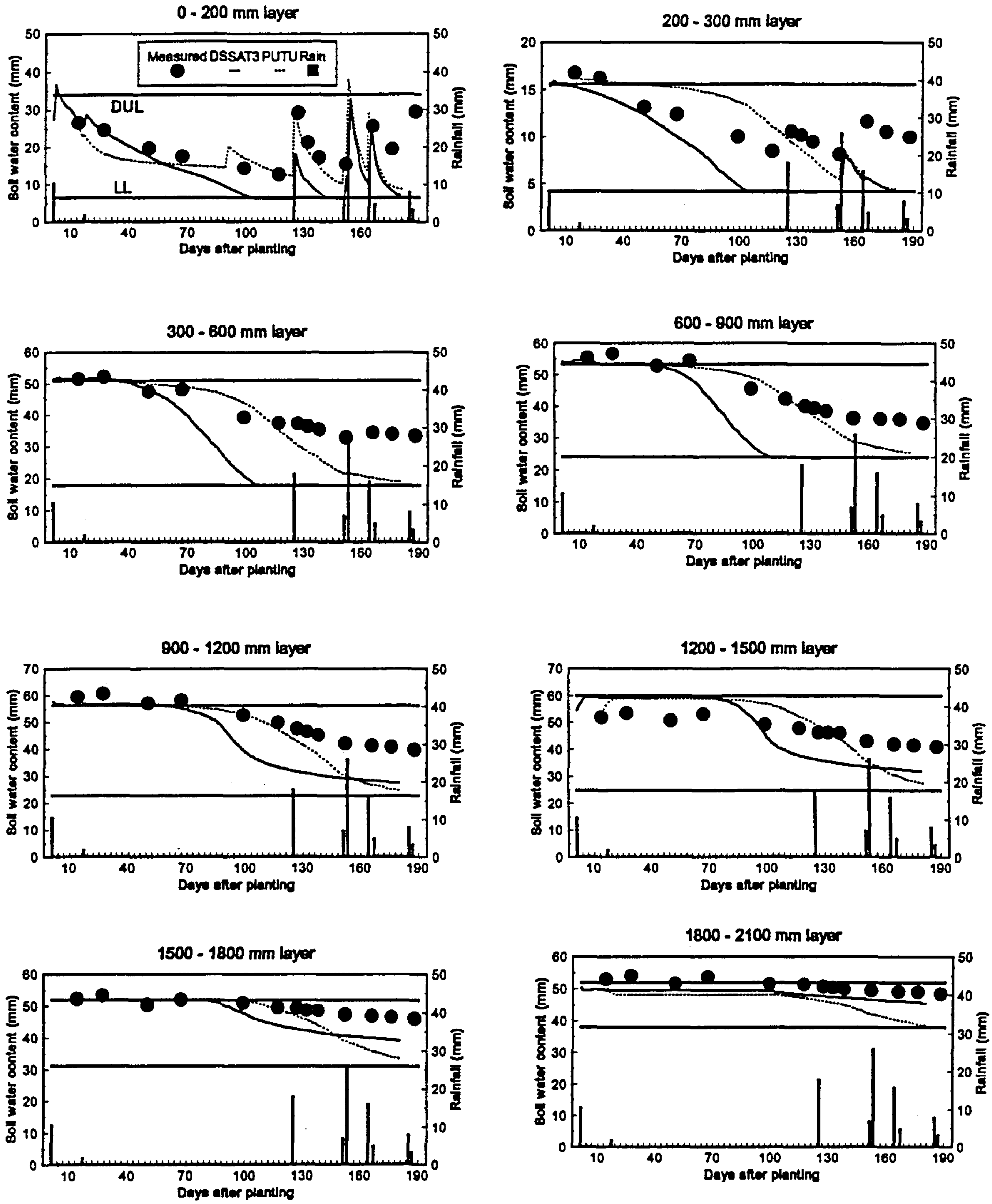


Fig. 5.8.4 Petrusburg / Bloemdal ecotope : Measured and predicted changes in the soil water content of the individual layers during the 1995 season



6. STATISTICAL TESTS OF MODEL RELIABILITY

6.1 Prediction of soil water content

All the water content determinations for each soil layer for all the growing seasons at a particular ecotope were compared with the equivalent values simulated by each model. Because of the relative inaccuracy of neutron water meter measurements above DUL, such values have been excluded from the analysis. The statistical procedures proposed by Wilmott (1981), and supported by Savage (1993), were used. The following indices were compared: root mean square error (RMSE), systematic root mean square error ($RMSE_s$), unsystematic root mean square error ($RMSE_u$), index of agreement (D-index), and correlation coefficient (R^2). The following are suitable criteria for these indices for assessing model reliability (Wilmott 1981, Savage 1993): (1) $RMSE_s$ should be as small as possible, a large $RMSE_s$ indicates bias; (2) $RMSE_u$ should be as close as possible to RMSE, indicating that the deviations of predicted from measured values are random; (3) The D-index should be as close as possible to 1. Results are presented in Figures 6.1 to 6.4. There are some cases (e.g. Wolmaransstad/Hutton) more water content measurements in the diagram for one model, than for the other model. This is because the one model sometimes predicted a longer growing period than the other, resulting in more measurements being made during the predicted growing season. This also accounts for the slight differences in the scale of the diagrams for certain ecotopes.

DSSAT3-maize

There is relatively little bias evident in the predicted values for Setlagole/Clovelly and Wolmaransstad/Hutton; in both cases $RMSE_u$ is reasonably close to RMSE with fairly small $RMSE_s$ values. (Figure 6.1) There is considerable bias (relatively high $RMSE_s$ values) evident in the results for Bethal/Hutton, Bethal/Avalon and Ermelo/Longlands (Figure 6.2). The scatter diagrams show that the predicted values are generally too high in the 10-40 mm range for the former two ecotopes, and generally too low for the latter one. $RMSE_s$ values in these cases are either close to or more than $RMSE_u$ values, and RMSE values are relatively high. The influence of lateral water movement in the sp1 and E horizons of the Bethal/Avalon and Ermelo/Longlands ecotopes respectively has probably played an important role in causing relatively high measured water content values for these two ecotopes, and has therefore a tendency to confound the statistics. This factor however makes the predictions on Bethal/Avalon even more inaccurate as most of the values are too high (Figure 6.2), but could contribute to the underpredictions for Ermelo/Longlands (Figure 6.2). The D-index is favourable for all the ecotopes.

When the water content data for all the ecotopes is pooled (Figure 6.4) results show reasonably good overall predictions by DSSAT3. (D-index = 0,90 and $RMSE_u$ is 94% of RMSE). The relatively wide distribution of points on the figure is reflected in a fairly high RMSE value of 10,00.

PUTU-maize

The statistics (Figures 6.1 and 6.2) indicate reliable water content predictions on the Setlagole/Clovelly, Wolmaransstad/Hutton, Kroonstad/Avalon and Bethal/Hutton ecotopes ($RMSE_u$ > 85% of RMSE; $RMSE_s$ < 3.1; D-index > 0,96). Considerable bias is evident in the results (Figure 6,2) for Bethal/Avalon and Ermelo/Longlands, i.e. relatively high $RMSE_s$ values of 3,5 and 5,5 respectively, although the D-index's are high. The comments regarding lateral water movement made under the assessment of DSSAT3 are also relevant here as the prediction patterns of the two models are similar.

Analysis of the pooled data (Figure 6.4) indicates overall reliable predictions of soil water content.

DSSAT-wheat

Water content predictions on Bultfontein/Clovelly are shown to be reliable with low $RMSE_s$ values, high $RMSE_u$ values, and high D-index of 0,98. (Figure 6.3). On Petrusburg/Bloemdal water contents are frequently underpredicted producing an RMSE value of 8,65, almost twice that for Bultfontein/Clovelly (4,48), and a high $RMSE_s$ value of 5,26. (Figure 6.3). This weakness is probably due to the excessive root water extraction which this model predicts during the last part of the growing season (see Figures 5.8.2, 5.8.3 and 5.8.4).

PUTU-wheat

The pattern is similar to that for DSSAT3 on the two ecotopes.

6.2 Yield prediction

Results are presented in Figure 6.5.

MAIZE

DSSAT3 tended to overpredict yields in the range between 2000 - 3000 kg ha^{-1}. This bias has resulted in a relatively high $RMSE_s$ value. Very high yields, i.e. above 800 kg ha^{-1}, are well predicted. The D-index and r^2 values (0.64 and 0.67 respectively) are reasonable but not good.

PUTU tended to slightly overpredict yields below 2500 kg ha^{-1} , and seriously underpredict yields above 6000 kg ha^{-1}. This has resulted in a high $RMSE_s$ value. The D-index is similar to that of DSSAT3, and the r^2 value (0.53) is unsatisfactory.

WHEAT

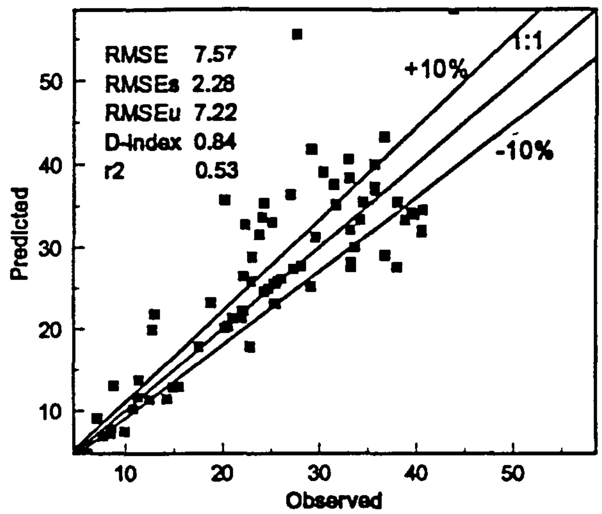
DSSAT3 grossly underpredicted yields causing all the statistical measures to be unsatisfactory.

Yield predictions by PUTU were sometimes far too low and sometimes far too high. The result was a very high RMSE value and all other statistics also unsatisfactory.

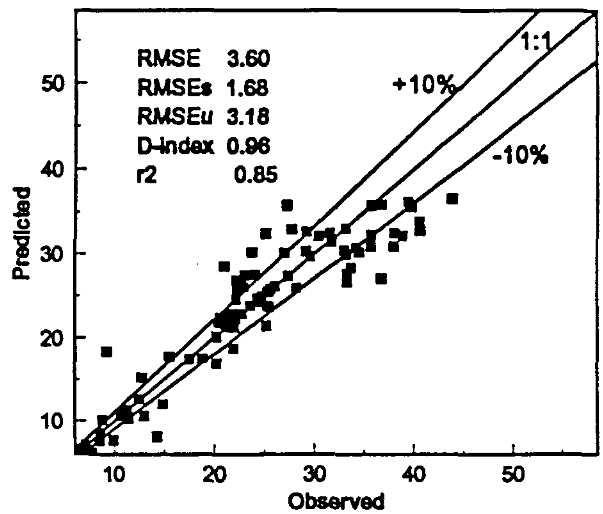
Figure 6.1 Statistical evaluation of the ability of the DSSAT3 and the PUTU maize models to predict the water content (mm) in different layers of the rootzone, during three growing seasons from 1993 to 1996, on three ecotopes

Setlagole / Clovelly

DSSAT3

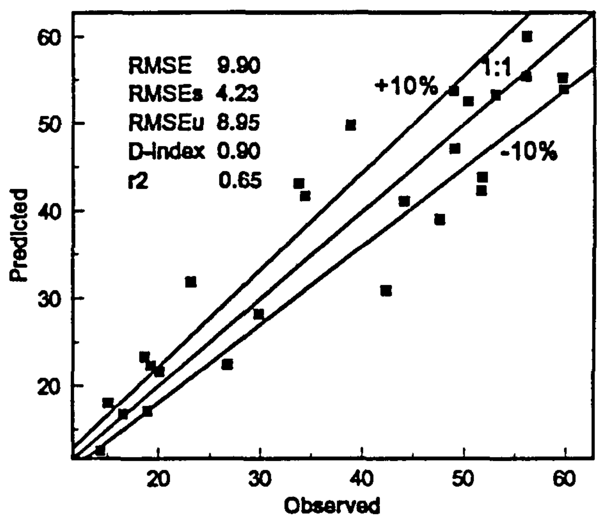


PUTU

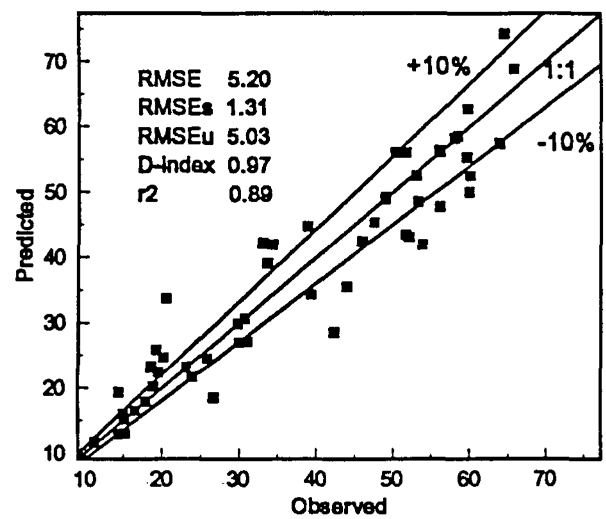


Wolmaransstad / Hutton

DSSAT3



PUTU



Kroonstad / Avalon

PUTU

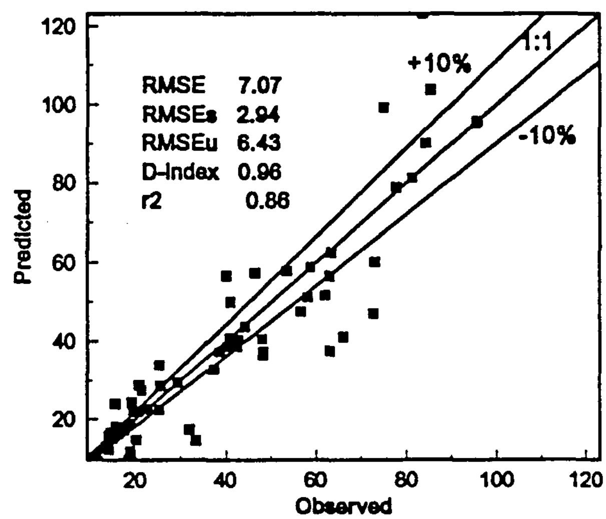


Figure 6.2 Statistical evaluation of the ability of the DSSAT3 and the PUTU maize models to predict the water content (mm) in different layers of the rootzone, during three growing seasons from 1993 to 1996, on three ecotopes

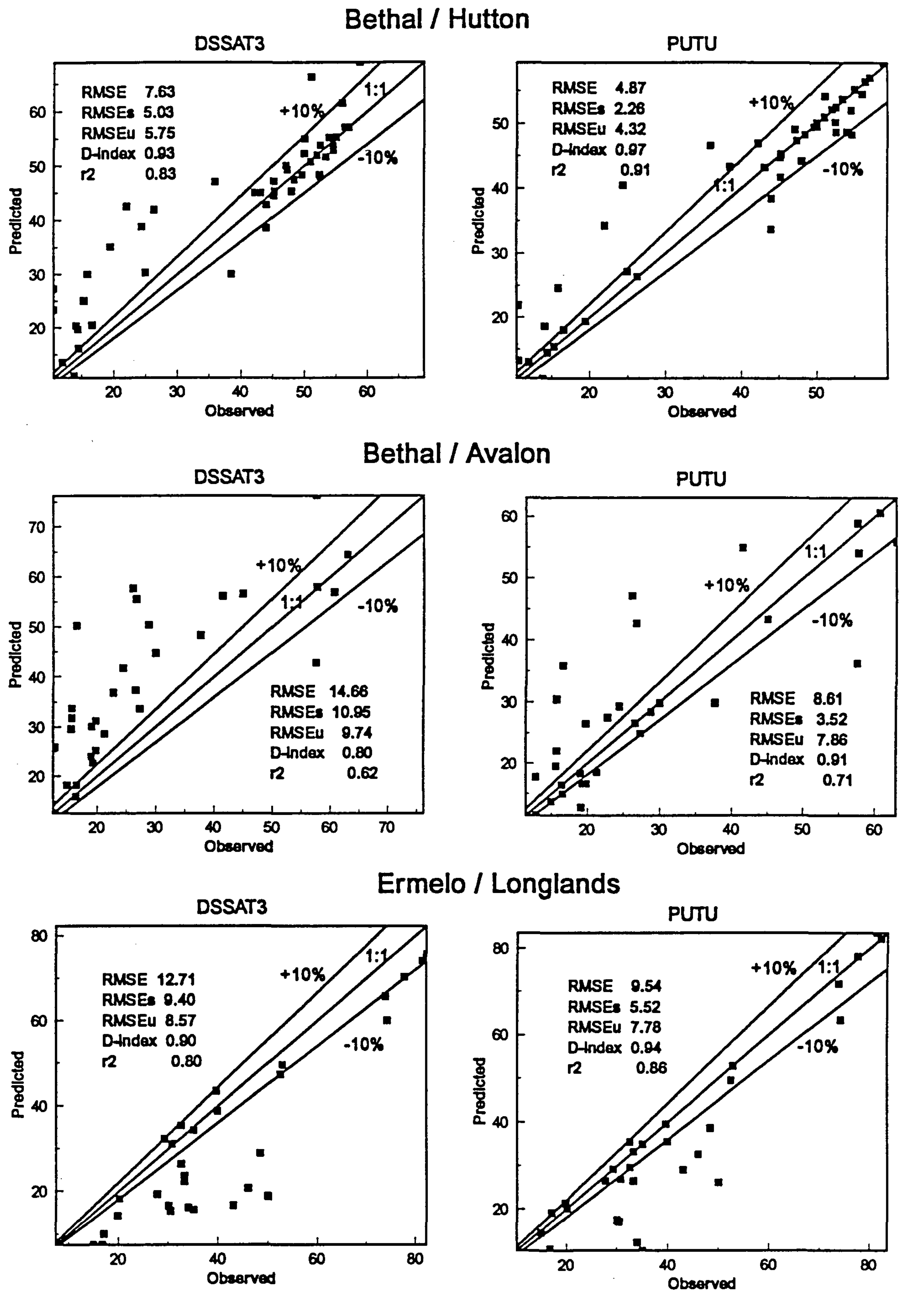


Figure 6.3 Statistical evaluation of the ability of the DSSAT3 and the PUTU wheat models to predict the water content (mm) in different layers of the rootzone, during three growing seasons from 1993 to 1995, on three ecotopes

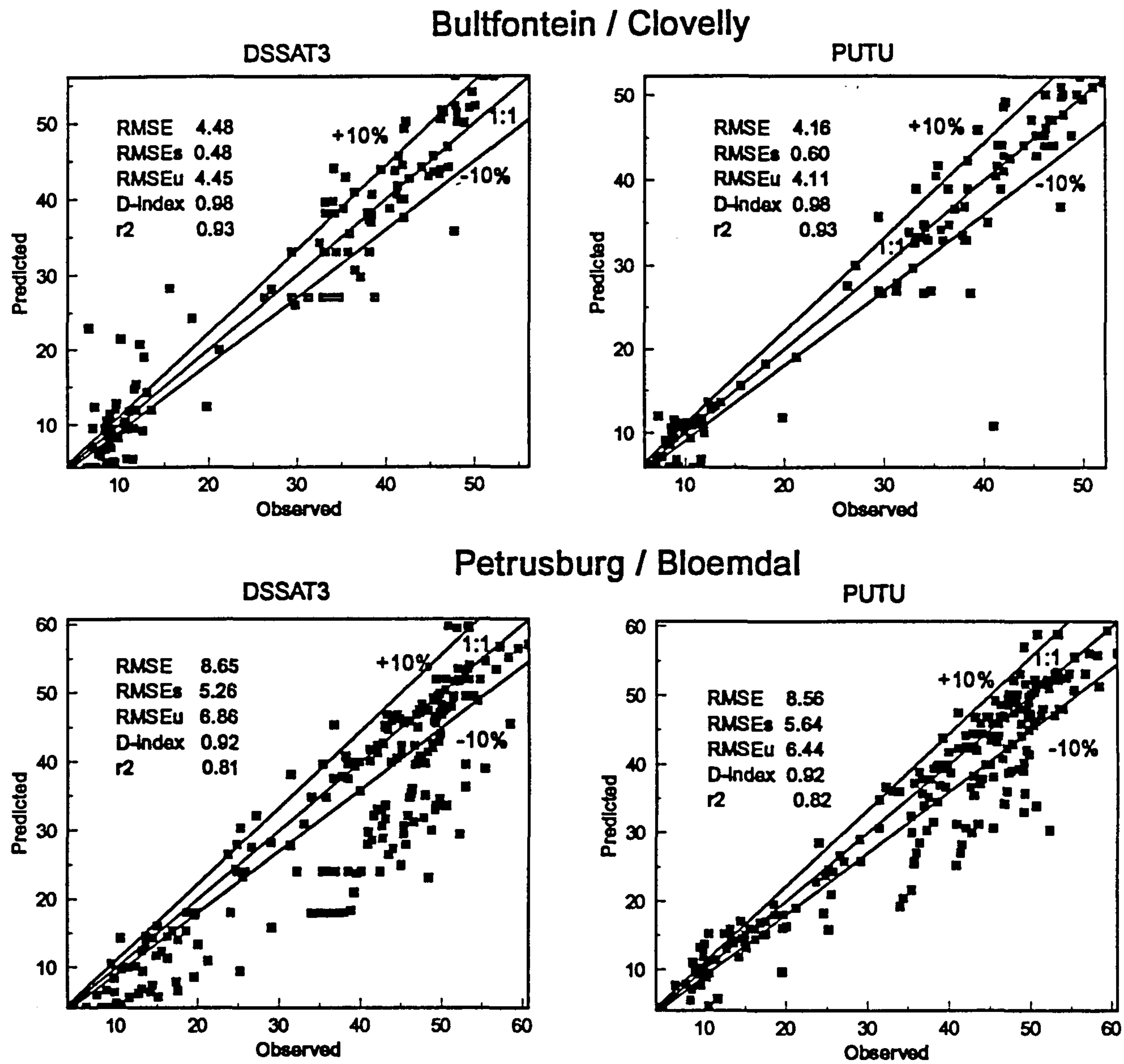


Figure 6.4 Predicted versus observed soil water content (mm) for all ecotopes for the period 1993 - 1996

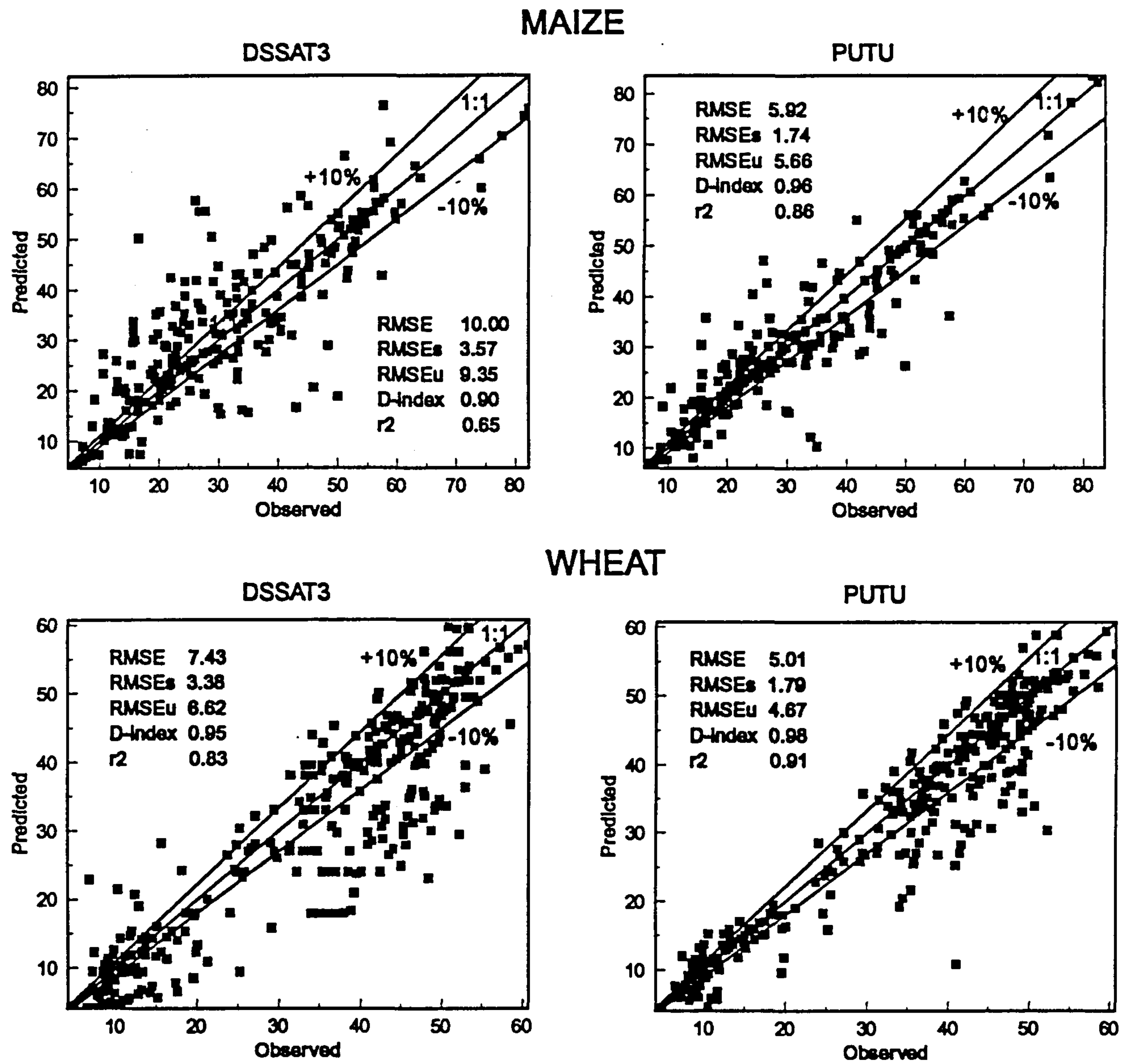
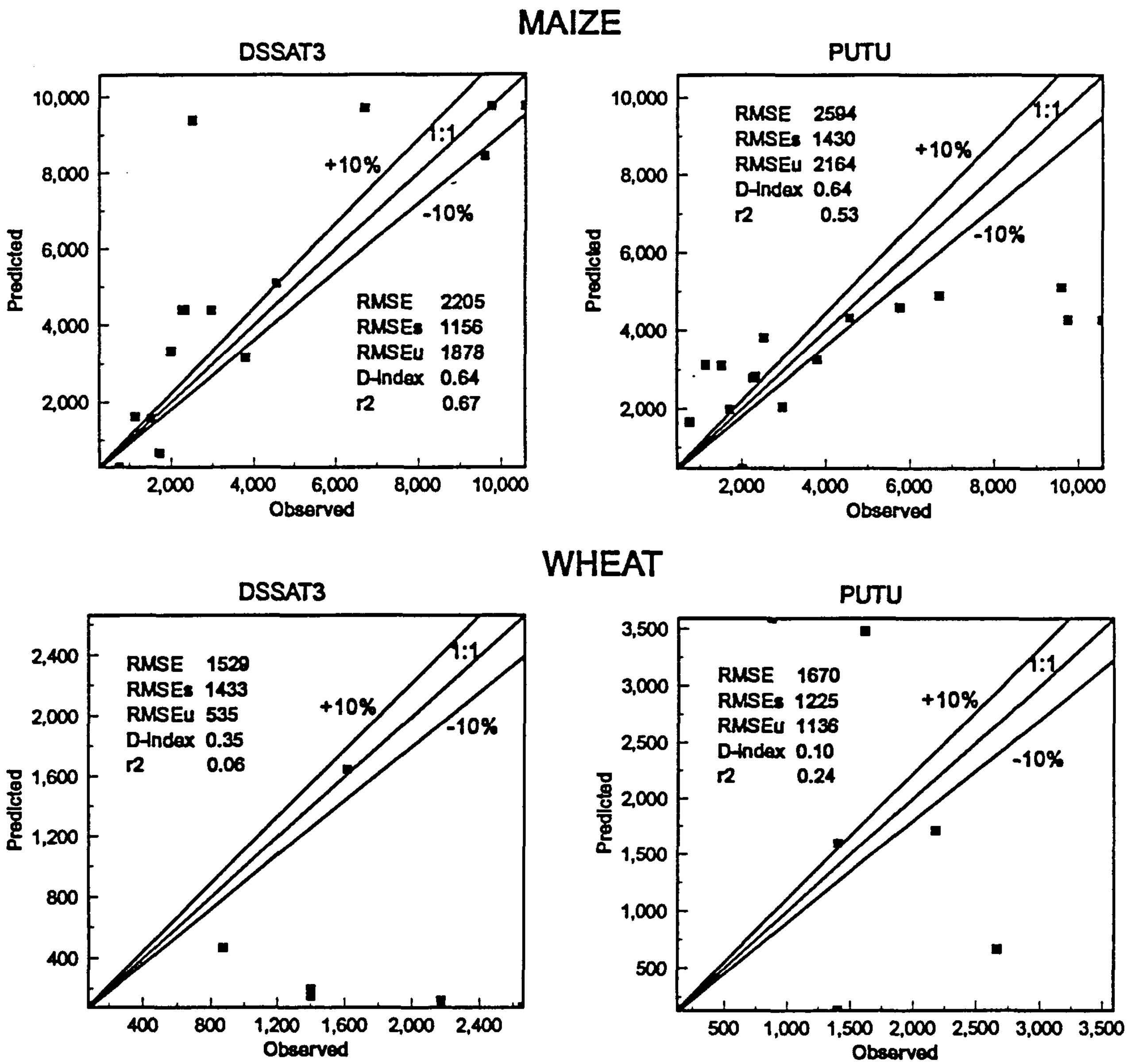


Figure 6.5 Predicted versus observed maize and wheat yields on all ecotopes for the period 1993 - 1996



7. LONG-TERM RISK ASSESSMENT

A valuable property of crop models is their ability to utilize long-term climate data to provide long-term yield simulations which can serve to quantify risk. Although the results in Chapter 6 show that model reliability needs to be improved before they can be used with confidence for making important land use decisions, long-term yields have nevertheless been computed to demonstrate the value of the strategy and also to show the differences in productivity between the ecotopes.

A problem which arises when making long-term simulations is that the water content at planting in each of the growing seasons is unknown. Another problem is that the models do not simulate the water balance well during fallow seasons. The result is that if one makes an uninterrupted long-term simulation including fallow seasons, and starting with some guessed initial water content in the first year, the water content at planting in any particular year could be incorrect by a significant amount. Especially in the drier ecotopes, and particularly with wheat where the initial water content is very important, this could lead to significant errors. An alternative strategy has been employed here. The long-term simulations for each ecotope have been repeated four times with each model. For each simulation a different root zone water content at planting was used, for each season viz., ¼, ½, ¾ and full. Ecotopes on which production is marginal even when using the last two strategies, must certainly be considered as unsatisfactory. This strategy could also be used to identify ecotopes suitable for long fallow practices.

Cumulative probability functions (CPF's), or in another terminology, cumulative distribution functions (CDF's), for the different ecotopes, and using both models, are presented in Appendix 2.2 (the usual order of ecotopes is followed). The probability as presented in the figures is that of non-exceedance of the specified yield intercept on the graph. For example, for the PUTU simulation for the Setlagole/Clovelly ecotope in Appendix 2.2 it is predicted that when starting with a ½ full profile there is a 25% (cumulative probability = 0.25) chance that a yield of 1500 kg ha^{-1} will not be exceeded and a 75% chance that a yield of 3062 kg ha^{-1} will not be exceeded. The closer the graph is to the right hand bottom corner of the figure the higher is the potential of the ecotope.

Although there are considerable differences in the shapes and positions of the lines predicted by the two models, there are also similarities for particular ecotopes. For example, both models predict relatively small advantages of full vs. ¼-full root zones at cumulative probabilities above about 0,6. This is logical since as the rainfall during the growing season increases, promoting higher yields, the importance of the root zone water content at planting must decrease. The DSSAT3 simulations for the two wheat ecotopes are clearly very unreliable.

The results presented in Appendix 2.1 have been extracted from the raw CPF data to simplify interpretation of the results. The "probability of non-exceedance" has been replaced by the simpler "probability of specified yield being exceeded", expressed as a percentage. Only the 75%, 50% and 25% probabilities are reported for each water content, for each model, and for each ecotope. For some of the ecotopes e.g. Setlagole/Clovelly there is reasonable agreement between the two models, which may signify that both are reasonably close to the truth, whereas for others, e.g. Bethal/Hutton and Kroonstad/Avalon, there are very large differences.

In the latter case additional information is needed in order to obtain a reliable CPF.

An attempt was made to describe the production risks for each ecotope as well as possible, with the available data. Judging by their overall performance, a "most reliable" model was chosen for each ecotope, and the predicted grain yield at 50% probability recorded for each root zone water content at planting. Results are presented in Table 7.1 together with the maximum predicted yield. There is surprisingly little difference, except in the case of Kroonstad/Avalon, between the maize yields for "¼-full" and "full". This is understandable for the last three semi-humid ecotopes, but seems to be a spurious result for Setlagole/Clovelly and Wolmaransstad/Hutton. The maximum yields for Bethal/Hutton and Bethal/Avalon are underpredicted, but the other yields in the table seem to be reasonable.

The difference in production risk on the different ecotopes is shown in what appears to be a realistic way. If one was sure of the reliability of these results, they could be used to great advantage to assist in decision making, especially with regard to economic aspects on marginal ecotopes.

Table 7.1 The simulated long-term productivity of eight benchmark ecotopes using four different rootzone water contents at planting

Ecotope	Predicted grain yield (kg ha^{-1}) at 50% probability					Predicted max. yield (kg ha^{-1})
	GSP*	¼ full	½ full	¾ full	Full	
Maize eotopes:						
Setlagole/Clovelly	407	1682	2156	2272	2302	4298
Wolmaransstad/Hutton	494	3548	3679	3742	3757	3998
Kroonstad/Avalon	504	2364	2595	2656	4908	6360
Bethal/Hutton	614	6022	6583	6768	6768	8609
Bethal/Avalon	614	4933	6010	6354	6768	8600
Ermelo/Longlands	614	5001	5451	6090	6765	8823
Wheat ecotopes:						
Bultfontein/Clovelly	124	1058	1215	1594	2102	4127
Petrusburg/Bloemdal	142	578	675	1607	2985	4525

* GSP = growing season (long-term mean) precipitation

8. COMPARING OVERALL WATER BALANCE MEASUREMENTS AND SIMULATIONS

Results are presented in Table 8.1 for the maize ecotopes and Table 8.2 for the wheat ecotopes. The differences in rainfall for a particular season are due to the fact that it was generally not possible to make the first soil water measurement on the day of planting, due to the distances involved and sometimes the communication gap with those who did the planting. This resulted in different starting times between the models and measurements. Physiological maturity was also sometimes predicted to occur at different times by the two models, which did not necessarily coincide with observed physiological maturity or the date of the final measurement of soil water content. To facilitate comparisons of predicted and measured values of the components of the water balance, the percentage which each forms of the rainfall is presented in brackets.

It is useful in some cases to consider these results together with the water content diagrams in Chapter 5 and the statistical analyses in Chapter 6.

The data collected for constructing the field determined drainage curves presented in Chapter 4 provides information about the rate at which water moves through each soil layer at any specified water content above DUL. This is the primary information needed to determine deep drainage (D). D only occurs when the water content of the deepest layer of the root zone exceeds DUL. The periods and extent during the growing season when this occurred at each ecotope can be identified, and the necessary estimates made, by studying the soil water content graphs presented in Chapter 5. Combining this information with the drainage curve data makes it possible to make an estimate of D based on measured values.

Although grain yields have been included here for the sake of completeness, they will not be discussed in detail as this has already been done in Chapter 5.

Setlagole/Clovelly

As this is a sandy soil (6% clay in the A horizon), with very little slope (± 1%), runoff is expected to be negligible in the long-term. Runoff measurements were not made and rainfall intensity was not measured. It was therefore not possible to estimate R for the very wet 1995/96 season. A very low value is however expected, and is supported by field observations. The simple "fraction of rainfall" procedure used by PUTU to simulate runoff gave excessively high values here because of what has already been said. The predictions of D by PUTU are also slightly too high. The combination of these two factors seems to have led to slightly low predicted values for Ev + Es. Both models made good yield predictions for the two relatively wet seasons.

Wolmaransstad/Hutton

The influence of excessive root water extraction by DSSAT3 during the last part of the season (Figure 5.2.1) is reflected here in high ΔS values and the relatively large scatter of points in the statistical analysis diagram (Figure 6.1), resulting in a high RMSE value of 9.9 compared to the equivalent value of 5.2 for PUTU. Excessive deep drainage is again predicted by PUTU, and has contributed to relatively low Ev + Es values. Reasons for the unsatisfactory values for measured yields for the 1993/94 and 1995/96 seasons are given in Chapter 5.

Kroonstad/Avalon

Reliable predictions of all the water balance components and yield were made by PUTU for the 1993/94 season. The 1995/96 season was characterised by very heavy rain during the early season which caused waterlogging damage to the crop, and resulted in considerable, unmeasurable lateral water movement in the soft plinthic horizon, confounding water balance measurements and predictions.

Bethal/Hutton

In spite of some problems, the simulations of the percentage of rainfall available for Ev + Es were for both models, and for all seasons, relatively reliable. Reasonably accurate predictions of soil water content, especially by PUTU, are also reflected in the statistical analysis (Figure 6.2).

Bethal/Avalon and Ermelo/Longlands

Considerable lateral water movement in the root zone during all seasons is a complicating factor. Because of this it was not possible to estimate D with any degree of reliability, and because of high rainfall this would have a marked influence on the estimation of Ev + Es. Another complicating factor is that rainfall intensity and runoff measurements were not successful on the Ermelo/Longlands ecotope during the 1994/95 season due to problems with the automatic weather station.

Bultfontein/Clovelly and Petrusburg/Bloemdal

Whereas in the maize ecotopes the subroutines for R and D are often important to ensure reliable prediction of Ev + Es, in these wheat ecotopes the subroutine for ΔS is of prime importance because of the crop's heavy reliance on stored soil water. Note the high percentages which Ev + Es form of the rainfall (generally >150 %). Runoff is negligible on these ecotopes, and so is deep drainage on the Petrusburg/Bloemdal ecotope; the latter is only of some importance for Bultfontein/Clovelly because of a deep water table.

Faulty simulation of root water extraction by DSSAT3 (excessive towards the end of the season - see Figure 5.8.1, and statistical analysis results in Figure 6.3) on the Petrusburg/Bloemdal ecotope produced significantly incorrect ΔS values, and therefore Ev + Es values, for the 1993 and 1994 seasons. Water balance predictions by PUTU for these ecotopes was relatively reliable.

Long-term predictions of runoff and deep drainage

One of the aims of the project was to obtain long-term predictions of runoff and deep drainage to provide surface and sub-surface hydrological information. This was very ambitious, and was based on the assumption that the models would be able to produce reasonably reliable predictions of these processes after 3 years of experimentation. The results in Table 8.1 show that this is generally not correct. Long-term estimates have nevertheless been made, and results for selected ecotopes are presented in Table 8.3. Deep drainage estimates have been excluded on the three ecotopes in which considerable lateral water movement occurs in the root zone, as it is considered that long-term estimates in these cases would be meaningless at this stage. In the case of the wheat ecotopes it is considered that deep drainage and runoff will be negligible in the long-term.

Although the runoff predictions for the last four ecotopes may be reasonably correct, there is little doubt that the values for the first two are far too high. The deep drainage predictions for the latter two ecotopes are also probably far too high.

Table 8.1 Measured, or estimated, and predicted values for water balance components and grain yield on six benchmark maize ecotopes. The symbols for the water balance components are as in Equation 1. Values for D have been estimated using drainage curve data. Where runoff measurements were not available the Morin and Cluff equation was used with rainfall intensity data to simulate runoff. For the "measured" data set, Ev + Es was obtained by subtraction. Values in brackets are percentages of P.

Setlagole/Clovelly ecotope

	P (mm)	ΔS (mm)	D (mm)	R (mm)	Ev + Es (mm)	Grain Yield (kg ha^{-1})
1993/94						
Measured	339	25 (7)	0 (0)	0 (0)	364 (107)	3800
DSSAT3	339	40 (12)	19 (6)	22 (6)	339 (100)	3151
PUTU	339	25 (7)	56 (17)	41 (12)	275 (81)	3256
1994/95						
Measured	241	-9 (4)	0 (0)	0 (0)	232 (96)	750
DSSAT3	123	14 (11)	0 (0)	1 (1)	135 (110)	285
PUTU	221	-15 (7)	0 (0)	26 (12)	180 (81)	1659
1995/96						
Measured	485	-28 (6)	102 (21)	?	<355 (<73)	4570
DSSAT3	591	-26 (4)	31 (5)	15 (3)	520 (88)	5089
PUTU	534	1 (0)	127 (24)	54 (10)	331 (62)	4239

Wolmaransstad/Hutton ecotope

	P (mm)	ΔS (mm)	D (mm)	R (mm)	Ev + Es (mm)	Grain Yield (kg ha^{-1})
1993/94						
Measured	430	29 (7)	40 (9)	98 (23)	321 (75)	1140
DSSAT3	450	87 (19)	71 (16)	66 (15)	396 (88)	1601
PUTU	428	32 (7)	183 (43)	36 (8)	241 (56)	3118
1994/95						
Measured	309	17 (6)	0 (0)	39 (13)	287 (93)	1720
DSSAT3	220	54 (25)	21 (10)	27 (12)	227 (103)	654
PUTU	269	2 (1)	42 (16)	26 (10)	203 (75)	1989
1995/96						
Measured	420	20 (5)	96 (23)	65 (15)	279 (66)	1520
DSSAT3	504	86 (17)	108 (21)	71 (14)	414 (82)	1560
PUTU	430	25 (6)	180 (42)	41 (10)	234 (54)	3104

(Table 8.1 continued)

Kroonstad/Avalon ecotope

	P (mm)	ΔS (mm)	D (mm)	R (mm)	Ev + Es (mm)	Grain Yield (kg ha^{-1})
1993/94						
Measured	387	54 (14)	0 (0)	48 (12)	393 (102)	5763
PUTU	384	75 (20)	3 (1)	30 (8)	423 (110)	4854
1995/96						
Measured	354	0 (0)	?	52 (15)	<302	2970
DSSAT3	350	50 (14)	0 (0)	69 (20)	333 (95)	4396
PUTU	354	79 (22)	32 (9)	31 (9)	341 (96)	2051

Bethal/Hutton ecotope

	P (mm)	ΔS (mm)	D (mm)	R (mm)	Ev + Es (mm)	Grain Yield (kg ha^{-1})
1993/94						
Measured	667	67 (10)	54 (8)	66 (10)	614 (92)	9756
DSSAT3	646	94 (15)	84 (13)	23 (4)	635 (98)	9741
PUTU	646	57 (9)	66 (10)	56 (9)	585 (91)	4279
1994/95						
Measured	518	6 (1)	0 (0)	60 (12)	464 (90)	2275*
DSSAT3	414	-74 (18)	0 (0)	4 (1)	337 (81)	4398
PUTU	422	49 (12)	2 (0)	32 (8)	382 (91)	2791
1995/96						
Measured	560	-30 (5)	31 (6)	72 (13)	427 (76)	9600
DSSAT3	711	10 (1)	39 (5)	54 (8)	629 (88)	8504
PUTU	637	69 (11)	37 (6)	73 (11)	596 (94)	5101

* Serious hail damage at flowering

Bethal/Avalon ecotope

	P (mm)	ΔS (mm)	D (mm)	R (mm)	Ev + Es (mm)	Grain Yield (kg ha^{-1})
1993/94						
Measured	618	60 (10)	?	122 (20)	<556 (<90)	10575
DSSAT3	646	87 (13)	39 (6)	38 (6)	657 (103)	9741
PUTU	557	59 (11)	104 (19)	47 (8)	525 (94)	4272
1994/95						
Measured	430	0 (0)	?	55 (13)	<375 (<87)	2326*
DSSAT3	414	-56 (-14)	4 (1)	9 (2)	344 (83)	4398
PUTU	427	23 (5)	21 (5)	32 (7)	391 (92)	2826
1995/96						
Measured	676	-15 (-2)	?	69 (10)	<592 (<88)	6700
DSSAT3	711	47 (7)	8 (1)	75 (11)	675 (95)	9698
PUTU	682	90 (13)	92 (13)	73 (11)	607 (89)	4903

* Serious hail damage at flowering

(Table 8.1 continued)

Ermelo/Longlands ecotope

	P (mm)	ΔS (mm)	D (mm)	R (mm)	Ev + Es (mm)	Grain Yield (kg ha^{-1})
1993/94						
Measured	575	5 (1)	?	94 (16)	<486 (<84)	0-2512
DSSAT3	624	116 (19)	11 (2)	89 (14)	641 (103)	9375
PUTU	536	81 (15)	127 (24)	48 (9)	448 (84)	3821
1994/95						
Measured	447	28 (6)	?	?	<475 (<106)	2000
DSSAT3	302	120 (40)	13 (4)	14 (5)	401 (133)	3318
PUTU	263	116 (44)	38 (14)	15 (6)	321 (122)	463

Table 8.2 Measured, or estimated, and predicted values for water balance components and grain yield on two benchmark wheat ecotopes. The symbols for the water balance components are as in equation 1. Values for D have been estimated using drainage curve data. Where runoff measurements were not available the Morin and Cluff equation was used with rainfall intensity data to simulate runoff. For the "measured" data set, Ev + Es was obtained by subtraction. Values in brackets are percentages of P.

Bultfontein/Clovelly ecotope

	P (mm)	ΔS (mm)	D (mm)	R (mm)	Ev + Es (mm)	Grain Yield (kg ha^{-1})
1993						
Measured	136	55 (40)	27 (20)	0 (0)	164 (121)	2174
DSSAT3	119	36 (30)	38 (32)	0 (0)	128 (108)	124
PUTU	102	45 (44)	7 (7)	0 (0)	140 (137)	1709
1994						
Measured	46	61 (133)	19 (41)	0 (0)	88 (191)	2660
DSSAT3	29	51 (176)	13 (45)	0 (0)	74 (255)	79
PUTU	41	70 (170)	13 (32)	0 (0)	98 (239)	662
1995						
Measured	70	55 (79)	19 (27)	0 (0)	106 (151)	1400
DSSAT3	170	67 (39)	87 (51)	1 (1)	153 (90)	195
PUTU	70	75 (107)	12 (17)	0 (0)	133 (190)	1598

Petrusburg/Bloemdal ecotope

	P (mm)	ΔS (mm)	D (mm)	R (mm)	Ev + Es (mm)	Grain Yield (kg ha^{-1})
1993						
Measured	242	38 (16)	0 (0)	0 (0)	280 (116)	1613
DSSAT3	207	124 (60)	0 (0)	1 (0)	331 (160)	1644
PUTU	199	94 (47)	0 (0)	0 (0)	293 (147)	3479
1994						
Measured	17	103 (606)	0 (0)	0 (0)	120 (706)	1400
DSSAT3	16	81 (506)	0 (0)	0 (0)	98 (613)	155
PUTU	13	99 (762)	2(15)	0 (0)	110 (846)	130
1995						
Measured	87	84 (97)	0 (0)	0 (0)	171 (197)	870
DSSAT3	85	165 (194)	3 (4)	0 (0)	250 (294)	467
PUTU	75	187 (249)	5 (7)	0 (0)	254 (339)	3590

Table 8.3 Long-term estimates of runoff and deep drainage on selected ecotopes using PUTU, and assuming the root zone was ½-full at planting

Ecotope	Runoff (mm/season)	Deep drainage (mm/season)
Setlagole/Clovelly	38	38
Wolmaransstad/Hutton	51	98
Kroonstad/Avalon	44	?
Bethal/Hutton	54	10
Bethal/Avalon	54	?
Ermelo/Longlands	60	?

9. SUPPORTING STUDIES

9.1 Runoff

Since runoff is obviously closely linked to rainfall intensity, crop modellers were faced with a difficult task when having to formulate a runoff subroutine using daily rainfall data. With rainfall intensity data becoming more widely available, and with the possibility of a model being available fairly soon with which to predict rainfall intensity data from daily rainfall data, the time is ripe for improving the runoff subroutines of crop models so that when and where it is available they can make use of rainfall intensity data. This was the motivation for testing the runoff equation of Morin & Cluff (1980).

Automatic weather stations were present at most of the ecotopes studied. They provided rainfall intensity data. Automatic tipping bucket runoff measuring devices made it possible to measure the runoff from 3 m x 20 m runoff plots. These devices worked well during the first rain season but failed at most sites for a variety of reasons during the following two seasons. This was due partially to the long distances to the test sites, and therefore infrequent visits, and partially to the lack of expertise available to find and rectify the problems with recording the runoff data on the loggers at the automatic weather stations.

Runoff was successfully measured at 1 minute intervals for 57 storms on 7 ecotopes during the 1993/94 rain season. The relevant rainfall intensity data was used for these storms to obtain predicted runoff using the Morin & Cluff equation. The runoff predicted by CERES (which presumably has the same runoff subroutine as DSSAT3) and PUTU was also extracted for these storms. Results are presented in Table 9.1. It needs to be kept in mind that the results from one storm at each ecotope was used to calibrate the Morin & Cluff (1980) equation, whereas the two crop models were uncalibrated. A wide range of soils and rainfall intensities are included. Predictions by CERES are very poor, by PUTU fairly good but slightly low, and by Morin & Cluff equation fairly good but slightly high. The degree of agreement between the measured values and those predicted by the three models has been computed by means of a linear regression analysis. The R^2 values for Morin & Cluff, PUTU and CERES are 0,61, 0,60 and 0,003 respectively. The curve number technique used by the CERES family of models is clearly unsatisfactory. Further research is needed in this connection. This will hopefully be undertaken at Glen during 1996/97 with improved runoff measuring equipment.

Table 9.1 Measured and predicted runoff from selected storms on 7 ecotopes during the 1993/94 rain season

Ecotope	Crop	Number of storms	I *** (mm h⁻¹)	Total rain (mm)	Runoff (mm)			
					meas.	M & C*	CERES	PUTU
Wolmaransstad/Hutton	maize	6	24-84	55	1.2	6.2	0	0.3
Kroonstad/Avalon	maize	11	<12-96	183	34.9**	36.7	0	17.4
Bethal/Hutton	maize	7	<12-140	108	0.1	0.7	0	5.8
Bethal/Avalon	maize	7	<12-140	108	5.4	13.3	0	8.6
Ermelo/Longlands	maize	5	12-36	63	0.4	0.1	12.3	4.7
Petrusburg/Bloemdal	fallow	9	<12-84	61	9.3	8.1	0	4.4
Glen/Oakleaf	maize	14	24-84	254	31.9	28.2	0.04	27.0
TOTALS		59	<12-140	832	83.2	93.3	12.3	68.2

* Using the Morin & Cluff (1980) equation and rainfall intensity
** one M & C predicted value included here
*** I = rainfall intensity; the range which occurred during the storms is presented

9.2 Plant available water

9.2.1 The upper limit

The procedure for obtaining a crop modified upper limit of available water (CMUL) has been described by Hattingh (1993) and by Hensley, Hattingh & Bennie (1993). Relevant values for seven of the benchmark ecotopes studied during this project are presented in Table 9.1. The Ermelo/Longlands ecotope is excluded because of difficulties in deciding how to determine a meaningful drainage curve. The problem is the very rapid lateral water movement in the E-horizon.

9.2.2 The lower limit

Both the PUTU and DSSAT3 models use the lower limit of available water (LL) as defined by Ratliff, Ritchie & Cassel (1983), i.e. the point in the drying cycle when the plant cannot extract any more water from the soil and is virtually dead. Although this is a valuable parameter, for reliable yield prediction it is necessary to have measured field data for particular ecotopes to describe how stress develops in a particular crop-ecotope as the soil dries out and root water extraction decreases. A review of relevant literature is presented in Chapter 2.

An experiment with wheat was conducted during the 1995 season on the Bultfontein/Clovelly and Petrusburg/Bloemdal ecotopes to try to define the stress curve. The experiments were not successful for a number of reasons. The wheat grew poorly inside the shelters erected to protect the "drying out" plots from rain. The extent to which wheat can become hardened against drought by the treatment it receives before flowering was also not fully appreciated. Examples of the results obtained are presented in Figure 9.2.1. The very low leaf water potential values (all below -2000 kPa) show to what extent adaptation to drought had already taken place when measurements were started. Because of this it was considered that the results are unsatisfactory and that the experiment should be repeated.

Fig. 9.1 Changes in the leaf water potential and relative water content on two wheat plots on the Bultfontein / Clovelly ecotope, 1995 season; the one was kept wet after flowering (WW) and the other one was allowed to dry out (SS)

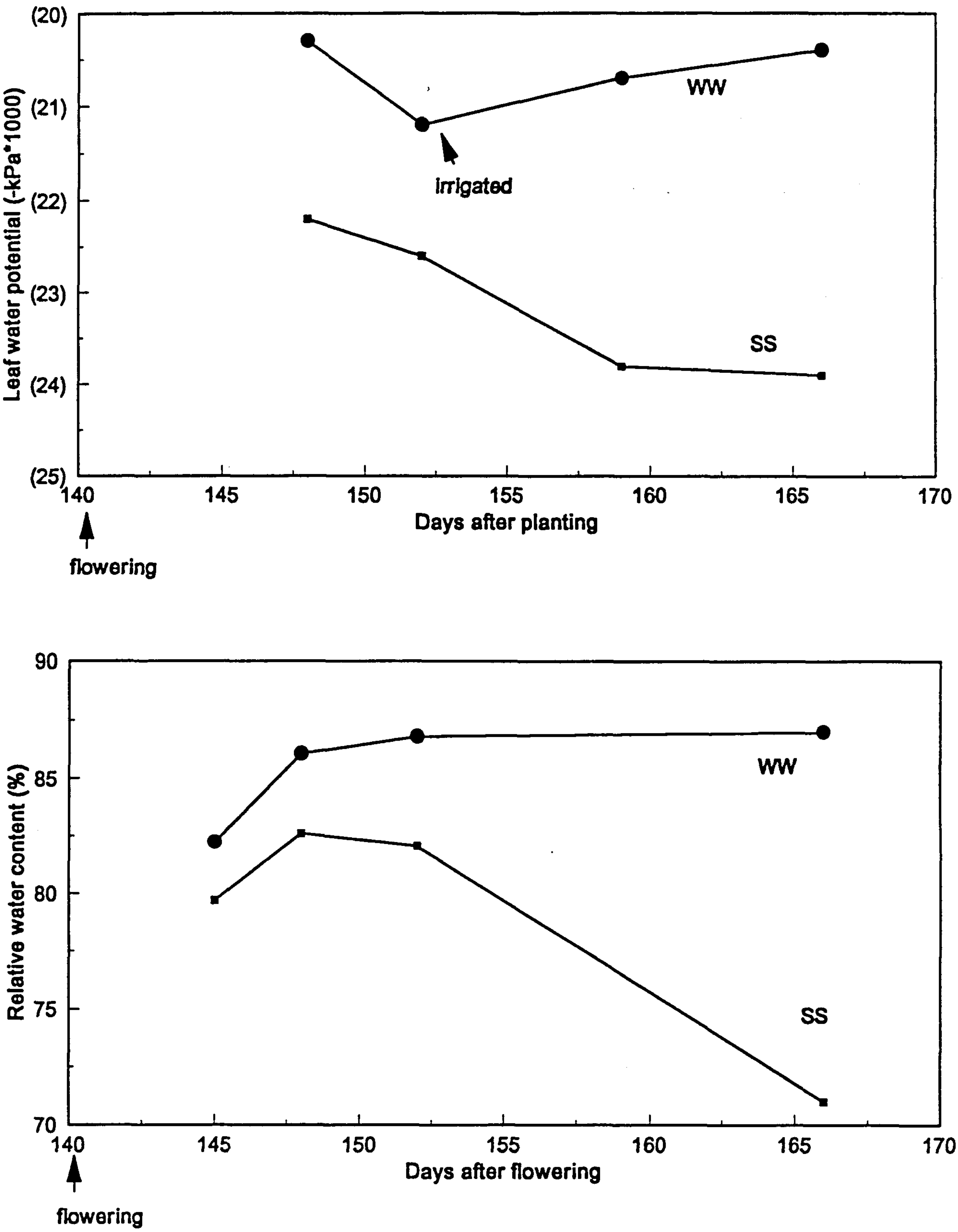


Table 9.2 Crop modified upper limit of available water (CMUL) values for benchmark crop-ecotopes

Ecotope	ET max. ($mm\ day^{-1}$)		Root zone depth (mm)	DUL (mm)	drainage curve			MAIZE		WHEAT	
	maize	wheat			Intercept (mm)	slope ($mm\ lnT^{-1}$)	r^2	CMUL*[1] (mm)	CMUL - DUL (mm)	CMUL*[1] (mm)	CMUL - DUL (mm)
Setlagole/Clovelly	10.0	-	2100	224	318	-11.71	-	299	75	-	-
Wolmaransstad/Hutton	10.0	7.0	900	134	212	-10.26	0.99	149	15	145	10
Kroonstad/Avalon	9.5	6.8	1200	393	436	-5.95	0.93.	420	27	418	25
Bethal/Hutton	8.0	6.0	1800	326	429	-16.66	0.99	364	38	359	33
Bethal/Avalon	8.0	6.0	1200	227	279	-7.35	0.97	256	29	254	27
Petrusburg/Bloemdal	10.0	7.0	2100	363	515	-21.68	0.95	457	94	421	58
Bultfontein/Clovelly*[2]	10.0	7.0	2100	319	474	-20.23	0.97	396	77	388	69

*[1] Maximum values for a mature crop
*[2]The maximum rooting depth for this ecotope is 2100 mm. Due to a fluctuating water table the rooting depth is given as 1500 mm in Chapter 4

10. CONCLUSIONS AND RECOMMENDATIONS

The necessary water balance and yield data were collected at eight benchmark ecotopes over three seasons wherever possible. Instrument failure, aggravated by the long distances to the test ecotopes impaired the collection of runoff data. It was, however, possible to collect enough data to test the reliability of the models. At two ecotopes, Kroonstad/Avalon and Ermelo/Longlands, it was possible to collect data for only two maize seasons. At the former the problem was drought and damage caused by cattle, and in the latter case the farmer planted beans on the experimental area during the 1995/96 season., which produced no yield because of waterlogging.

The aim of adapting the models "so that they are capable of making reliable long-term predictions of the water balance and crop yield" was a very ambitious one. Without the invaluable assistance received from Mr. M. Prinsloo and Mr. S. du Toit of the Grain Crops Institute (and Mr. W. Berry of that Institute for the 1993/94 season), and from Prof.. A. Singels of the Department of Agrometeorology, UFS, it would not have been possible to make any contribution in this respect. The results show how difficult it would be to achieve this aim, and also that it was not achieved. A significant contribution in this connection has nevertheless probably been made.

Comparisons between measured and simulated results showed that although the DSSAT3 and PUTU maize and wheat models sometimes gave reliable yield predictions, they were also sometimes very unreliable. Soil water content predictions were better than those of yield, but also at times unsatisfactory. Adjustments are needed to improve reliability. The following are important model weaknesses that have been exposed: (a) the lack of a subroutine to deal with waterlogging in maize ecotopes; (b) the lack of a subroutine for the absence of secondary roots in wheat; (c) in inability of PUTU to predict high yields on the Bethal/Hutton and Bethal/Avalon ecotopes; (d) the excessive maize root water extraction rate frequently simulated by DSSAT3 during the last part of the growing season; (e) unsatisfactory runoff subroutines in both models; (f) unsatisfactory stress prediction subroutines, especially in DSSAT3; (g) the lack of a subroutine to cater for lateral water movement in the root zone. It is recommended that these weaknesses be remedied by crop modellers.

Although long-term cumulative probability functions (CPF's) of yield have been computed, model reliability needs to be improved and these CPF's repeated before they can be considered as reliable assessments of risk. The same applies to the long-term predictions of runoff and deep-drainage.

Because of the wide range of ecotopes involved valuable experience has been gained regarding the functioning of the water balance processes at the ecotopes studied, how to measure them, and about the long-term influence of these processes during pedogenesis on soil physical, chemical and morphological characteristics. Expertise with regard to the latter will be a valuable pedotransfer tool in future practical applications of crop model technology for promoting rainfall use efficiency on a wide range of ecotopes.

The potential benefits of reliable crop models is described in detail in the Introduction. Because of these benefits it is recommended that research in this connection needs to be promoted. A particular need at present is a more integrated multidisciplinary approach. The effective APSRU team at Towoomba in Australia seems to be a good example of how to achieve this. The Biological Simulation Forum recently established by the Grain Crops Institute at Potchefstroom is a valuable advance in this connection. The fairly wide occurrence of considerable lateral, hillside water movement, which this project has exposed, shows clearly that any multidisciplinary approach needs to included comprehensive hydrological studies, including catchment hydrology and groundwater recharge. The overall results of such holistic multidisciplinary studies could make a valuable contribution towards the growing need for integrated resource management.

The large amount of measured data in this report offers a valuable data base to all interested crop modellers. If diligently employed it should be useful for adapting a wide variety of models. The data has been stored on diskette and is available from the following address:

The Director
Institute for Soil, Climate and Water
Private Bag X79
PRETORIA
0001.

11. REFERENCES

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APPENDIX 1

PROFILE DESCRIPTIONS AND ANALYTICAL DATA

SOIL PROFILE DESCRIPTION:

Profile No:
*Map/photo:*2624BB Mosita
*Latitude & Longitude:*26°18'22''/24°57'49''
*Land type No:*Ah17
*Climate zone:*8S
*Altitude:*1270m
*Terrain unit:*Footslope
*Slope:*1%
*Slope shape:*Straight
*Aspect:*North-west
*Microrelief:*None
*Parent material solum:*Origin single, aeolian
*Underlying material:*Mixed lithology

*Soil form:*Clovelly
*Soil family:*Setlagole
*Surface rockiness:*None
*Surface stoniness:*None
*Occurrence of flooding:*None
*Wind erosion:*Slight wind
Water erosion:
*Vegetation/Land use:*Agronomic cash crops
*Water table:*None
Described by: C J J Schmidt
*Date described:*1991-12
*Weathering of underlying material:*Advanced physical, strong chemical
*Alteration of underlying material:*Generalized

Horizon	*Depth(mm)*	*Description*	*Diagnostic horizons*
A1	0 - 460	Moist; dry brownish yellow 10YR6/8, moist yellowish brown 10YR5/6; disturbed; loamy fine sand; apedal massive; friable; few normal fine pores; water absorption: 1 second(s); few roots; gradual smooth transition.	Orthic
B1	460 - 800	Moist; dry brownish yellow 10YR6/8, moist brownish yellow 10YR6/6; undisturbed; loamy fine sand; apedal massive; friable; few normal fine pores; water absorption: 1 second(s); few roots; gradual smooth transition.	Yellow-brown apedal
B2	800 - 2000	Moist; dry yellow 10YR7/8, moist brownish yellow 10YR6/8; undisturbed; loamy fine sand; apedal massive; friable; few normal fine pores; water absorption: 1 second(s); few roots.	Yellow-brown apedal

*Survey name:*BENCHMARK ECOTOPE SETLAGOLE/CV3100
*NATIONAL SOIL PROFILE NO:*6142

Appendix 1.1.1

Appendix 1.1.2

SOIL ANALYTICAL DATA/ GRONDONTLEDINGSDATA

SURVEY/OPNAME: BENCHMARK ECOTOPE PROJEK
ECOTOPE/EKOTOOP: SETLAGOLE/Cv 3100

Horizon/Horison	Ap	B1	B2				
Profile No/Profiel Nr.							
Depth/Diepte (mm)	0-460	460-800	800-2000				
Bag no /Sak nr	31D	34D	107D				
Lab No/ nr	C9749	C9750	C9751				
PARTICLE SIZE DISTRIBUTION/ DEELTJIE GROOTTEVERSPREIDING%							
>2 mm							
c/g sand 2-0.5 mm	6.7	6.5	4.8				
m sand 0.5-0.25 mm	11.9	11.5	8.0				
f sand 0.25-0.106 mm	51.9	46.2	46.5				
v/b f sand 0.106-0.05 mm	18.6	22.0	24.5				
c/g silt/slik 0.05-0.02 mm	3.0	3.4	4.3				
f silt/slik 0.02-0.002 mm	1.0	1.5	1.2				
clay/klei 0.002 mm	6.3	8.7	10.4				
Texture/Tekstuur	FISA	LMFISA	LMFISA				
CHEMICAL ANALYSIS/ CHEMIESE ONTLEDINGS							
C %	0.20	-	-				
Titr. Acidity cmol(+)/kg							
Al (me %) cmol(+)/kg							
Resistance/Weerstand (ohm)	4200	4400	4000				
pH H2O	6.84	6.10	6.50				
pH KCl	5.58	4.68	5.06				
EXCHANGEABLE CATIONS/cmol (+) kg^{-1} soil UITRUILBARE KATIONE/cmol (+) kg^{-1} grond							
Na	0.01	0.02	0.02				
K	0.19	0.18	0.18				
Ca	1.17	1.09	0.92				
Mg	0.40	0.37	0.63				
S value/ S waarde	1.77	1.66	1.75				
T value (CEC/ T waarde (KUK)	1.90	2.11	2.02				
SATURATION EXTRACT SOL. CATIONS cmol (+) kg^{-1} soil VERSADIGDE EKSTRAK OPLOSBARE KATIONE cmol (+) kg^{-1} grond							
Na							
K							
Ca							
Mg							
Cond/Geleid mS/m							
Saturation/Versadiging							

SOIL PROFILE DESCRIPTION:

Profile No:
*Map/photo:*2726AA Leeudoringstad
*Latitude & Longitude:*27°04'00''/26°05'00''
*Land type No:*Bc19
*Climate zone:*11S
*Altitude:*1500m
*Terrain unit:*Lower Footslope
*Slope:*1%
*Slope shape:*Straight
*Aspect:*South
*Microrelief:*None
*Parent material solum:*local colluvium
*Underlying material:*Fine or extrusive igneous rocks (unspecified)
*Geological Group/Formation:*Ventersdorp.

*Soil form:*Hutton
*Soil family:*Ventersdorp
*Surface rockiness:*None
*Surface stoniness:*None
*Occurrence of flooding:*None
*Wind erosion:*None
*Water erosion:*None
*Vegetation/Land use:*Agronomic cash crops
*Water table:*0mm
Described by: J J Botha & M Hensley
*Date described:*1995-07
*Weathering of underlying material:*Weak physical, weak chemical
*Alteration of underlying material:*Ferruginised

Horizon	*Depth(mm)*	*Description*	*Diagnostic horizons*
A	0 - 300	Dry; dry red 2.5YR4/6, moist dark red 2.5YR3/6; fine sandy loam; few fine black oxidized iron oxide mottles; apedal massive; slightly hard; friable; few fine pores; fine cracks; very few angular gravel; many roots; gradual transition.	Orthic
B1	300 - 600	Moist; dry red 2.5YR4/6, moist dark red 2.5YR3/6; fine sandy clay loam; common medium black oxidized iron oxide mottles; apedal massive; friable; fine cracks; few angular gravel; common roots; gradual transition.	Red apedal
B2	600 - 900	Moist; dry red 2.5YR4/8, moist dark red 2.5YR3/6; fine sandy clay loam; many coarse yellow, red and black oxidized iron oxide mottles; apedal massive; common angular coarse gravel; very few angular stones; few medium sesquioxide concretions; clear transition.	Red apedal
C	900 - 900	Saprolite.	Saprolite

*Survey name:*BENCHMARK ECOTOPE WOLMARANSSTAD/HU3200
*NATIONAL SOIL PROFILE NO:*6145

SOIL ANALYTICAL DATA/ GRONDONTLEDINGSDATA

SURVEY/OPNAME: BENCHMARK ECOTOPE PROJEK
ECOTOPE/EKOTOOP: WOLMARANDSTAD/Hu3200

Horizon/Horison	A	B1	B2				
Profile No/Profiel Nr.							
Depth/Diepte (mm)	0-300	300-600	600-900				
Bag no /Sak nr	WOL 1A	WOL 2A	WOL 3A				
Lab No/ nr	D713	D714	D715				
PARTICLE SIZE DISTRIBUTION/ DEELTJIE GROOTTEVERSPREIDING%							
>2 mm							
c/g sand 2-0.5 mm	7.2	7.0	8.1				
m sand 0.5-0.25 mm	5.3	4.9	5.1				
f sand 0.25-0.106 mm	28.1	23.4	20.5				
v/b f sand 0.106-0.05 mm	33.0	30.4	27.6				
c/g silt/slik 0.05-0.02 mm	6.4	6.6	7.0				
f silt/slik 0.02-0.002 mm	3.4	4.9	5.6				
clay/klei 0.002 mm	14.8	21.5	23.8				
Texture/Tekstuur	FiSaLm	FiSaClLm	FiSaClLm				
CHEMICAL ANALYSIS/ CHEMIESE ONTLEDINGS							
C %	0.26	0.25	0.25				
Titr. Acidity cmol(+)/kg							
Al (me %) cmol(+)/kg							
Resistance/Weerstand (ohm)	3800	2200	2000				
pH H2O	5.39	6.32	6.82				
pH KCl	4.08	5.02	5.34				
EXCHANGEABLE CATIONS/cmol (+) kg^{-1} soil UITRUILBARE KATIONE /cmol (+) kg^{-1} grond							
Na	0.14	0.21	0.15				
K	0.35	0.18	0.21				
Ca	1.63	2.85	3.97				
Mg	0.80	2.26	3.13				
S value/ S waarde	2.92	5.50	7.46				
T value (CEC/ T waarde (KUK)	7.95	13.24	14.21				
SATURATION EXTRACT SOL. CATIONS cmol (+) kg^{-1} soil VERSADIGDE EKSTRAK OPLOSBARE KATIONE cmol (+) kg^{-1} grond							
Na							
K							
Ca							
Mg							
Cond/Geleid mS/m							
Saturation/Versadiging							

SOIL PROFILE DESCRIPTION:

Profile No:
*Map/photo:*2727AD Heuningspruit
*Latitude & Longitude:*27°29'18''/27°20'23''
*Land type No:*Bd21e
*Climate zone:*35S
*Altitude:*1420m
*Terrain unit:*Midslope
*Slope:*2%
*Slope shape:*Concave
*Aspect:*North-east
*Microrelief:*None
*Parent material solum:*Origin single, local colluvium
*Underlying material:*Sandstone (feldspathic)

*Soil form:*Avalon
*Soil family:*Kameelbos
*Surface rockiness:*None
*Surface stoniness:*None
*Occurrence of flooding:*None
*Wind erosion:*None
*Water erosion:*Sheet slight, partially stabilized
*Vegetation/Land use:*Agronomic cash crops
*Water table:*None
Described by: K C Snyman, P A L le Roux & M Hensley
*Date described:*1993-09
*Weathering of underlying material:*Strong physical, moderate chemical
*Alteration of underlying material:*Ferruginised

Horizon	*Depth(mm)*	*Description*	*Diagnostic horizons*
AP	0 - 230	Dry; dry yellowish brown 10YR5/4, moist brown to dark brown 10YR4/3; disturbed; loamy fine sand; apedal massive; slightly hard; few fine pores; water absorption: 1 second(s); many roots; gradual transition.	Orthic
A2	230 - 350	Dry; dry dark yellowish brown 10YR4/4, moist brown to dark brown 10YR4/3; disturbed; fine sandy loam; apedal massive; slightly hard; few fine pores; water absorption: 1 second(s); few roots; gradual transition.	Orthic
B1	350 - 600	Dry; dry yellowish brown 10YR5/4, moist dark yellowish brown 10YR4/4; undisturbed; fine sandy loam; few fine faint yellow, brown and red oxidized iron oxide mottles; apedal massive; hard; common fine pores; very few fine sesquioxide concretions; water absorption: 1 second(s); few roots; gradual transition.	Yellow-brown apedal
B2	600 - 750	Dry; dry yellowish brown 10YR5/6, moist dark yellowish brown 10YR4/4; undisturbed; fine sandy clay loam; common medium prominent red and black oxidized iron oxide mottles; common medium prominent grey and yellow reduced iron oxide mottles; weak medium subangular blocky; very hard; common fine pores; common fine sesquioxide concretions; water absorption: 2 second(s); few roots; gradual transition.	Soft plinthic
B3	750 - 1000	Dry; dry brown 10YR5/3; undisturbed; fine sandy clay; many medium prominent red and black oxidized iron oxide mottles; many medium prominent grey and yellow reduced iron oxide mottles; strong medium angular blocky; very hard; common fine pores; many clay cutans; few fine sesquioxide concretions; water absorption: 2 second(s); gradual transition.	Soft plinthic
C1	1000 - 1400	Dry; dry greyish brown 10YR5/2; undisturbed; clay; many medium prominent red and black oxidized iron oxide mottles; many medium prominent grey and yellow reduced iron oxide mottles; strong medium angular blocky; very hard; few fine pores; many clay cutans; very few fine sesquioxide concretions; water absorption: 2 second(s).	Soft plinthic

*Survey name:*BENCHMARK ECOTOPE KROONSTAD/AV3100

Appendix 1.3.2

SOIL ANALYTICAL DATA/ GRONDONTLEDINGSDATA

SURVEY/OPNAME: BENCHMARK ECOTOPE PROJEK
ECOTOPE/EKOTOOP: KROONSTAD/Av3100

Horizon/Horison	AP	A2	B1	B2	B3	C1	
Profile No/Profiel Nr.							
Depth/Diepte (mm)	0-230	230-350	350-600	600-750	750-1000	1000-1400	
Bag no /Sak nr	243C	276C	265E	263D	260E	259E	
Lab No/ nr	D194	D195	D196	D197	D198	D199	
PARTICLE SIZE DISTRIBUTION/ DEELTJIE GROOTTEVERSPREIDING%							
>2 mm							
c/g sand 2-0.5 mm	5.2	4.2	4.1	4.5	3.0	4.6	
m sand 0.5-0.25 mm	11.5	10.2	11.5	10.6	6.7	7.3	
f sand 0.25-0.106 mm	32.9	33.5	31.5	23.4	18.8	16.1	
v/b f sand 0.106-0.05 mm	29.5	27.8	25.8	20.1	17.2	16.3	
c/g silt/slik 0.05-0.02 mm	8.0	7.7	6.9	6.2	5.5	6.0	
f silt/slik 0.02-0.002 mm	3.3	2.7	2.2	1.9	3.4	4.9	
clay/klei 0.002 mm	7.4	11.8	15.7	31.9	44.7	44.5	
Texture/Tekstuur	LMFISA	FISALM	FISALM	FISACL	FISACL	CL	
CHEMICAL ANALYSIS/ CHEMIESE ONTLEDINGS							
C %	0.28	0.30	0.30	0.39	0.21	0.05	
Titr. Acidity cmol(+)/kg	0.49	0.37	0.13	0.18	0.20	0.02	
Al (me %) cmol(+)/kg	0.39	0.34	0.12	0.14	0.16	0.01	
Resistance/Weerstand (ohm)	3800	3200	2800	1600	1600	1200	
pH H20	5.48	5.58	6.21	5.94	6.01	7.06	
pH KCl	4.40	4.44	4.96	4.98	5.08	5.67	
EXCHANGEABLE CATIONS/cmol (+) kg^{-1} soil UITRUILBARE KATIONE/cmol (+) kg^{-1} grond							
Na	0.12	0.13	0.11	0.17	0.16	0.24	
K	0.40	0.45	0.50	0.78	0.90	1.11	
Ca	1.28	1.92	2.53	2.82	5.25	7.18	
Mg	0.26	0.68	0.85	3.15	6.18	7.88	
S value/ S waarde	2.06	3.18	3.99	6.92	12.49	16.41	
T value (CEC/ T waarde (KUK)	3.04	4.24	4.60	9.92	14.67	17.44	
SATURATION EXTRACT SOL. CATIONS cmol (+) kg^{-1} soil VERSADIGDE EKSTRAK OPLOSBARE KATIONE cmol (+) kg^{-1} grond							
Na							
K							
Ca							
Mg							
Cond/Geleid mS/m							
Saturation/Versadiging							

SOIL PROFILE DESCRIPTION:

Profile No:
*Map/photo:*2629BA Hendrina
*Latitude & Longitude:*26°10'49''/29°34'13''
*Land type No:*Bb4
*Climate zone:*24S
*Altitude:*1550m
*Terrain unit:*Upper Midslope
*Slope:*2%
*Slope shape:*Straight
*Aspect:*South
*Microrelief:*None
*Parent material solum:*Origin single, local colluvium
*Underlying material:*Basic extrusive rocks

*Soil form:*Hutton
*Soil family:*Hayfield
*Surface rockiness:*None
*Surface stoniness:*None
*Occurrence of flooding:*None
*Wind erosion:*None
*Water erosion:*None
*Vegetation/Land use:*Agronomic cash crops
*Water table:*None
Described by: K C Snyman, P A L le Roux, M Hensley
*Date described:*1993-09
*Weathering of underlying material:*Advanced physical, strong chemical
*Alteration of underlying material:*Ferruginised

Horizon	*Depth(mm)*	*Description*	*Diagnostic horizons*
AP	0 - 250	Dry; dry reddish brown 5YR4/4, moist dark reddish brown 5YR3/3; disturbed; fine sandy loam; apedal massive; slightly hard; common fine pores; water absorption: 1 second(s); common roots; gradual smooth transition.	Orthic
A2	250 - 350	Dry; dry dark reddish brown 5YR3/4, moist dark reddish brown 5YR3/3; undisturbed; medium sandy clay loam; apedal massive; slightly hard; common fine pores; water absorption: 1 second(s); common roots; gradual smooth transition.	Orthic
B1	350 - 850	Dry; dry red 2.5YR4/8, moist dark reddish brown 2.5YR3/4; undisturbed; fine sandy clay loam; apedal massive; slightly hard; common fine pores; very few fine sesquioxide concretions; very few medium sesquioxide concretions; water absorption: 1 second(s); common roots; clear smooth transition.	Red apedal
B2	850 - 1400	Dry; dry red 2.5YR5/8, moist dark red 2.5YR3/6; undisturbed; fine sandy clay loam; few fine faint yellow oxidized iron oxide mottles; apedal massive; slightly hard; common fine pores; very few fine sesquioxide concretions; very few medium sesquioxide concretions; water absorption: 1 second(s); common roots; gradual smooth transition.	Red apedal
B3	1400 - 2000	undisturbed; fine sandy clay loam; many medium prominent yellow, red and black oxidized iron oxide mottles; apedal massive; hard; few fine pores; few coarse pores; many coarse sesquioxide concretions; water absorption: 1 second(s); few roots.	Red apedal

*Survey name:*BENCHMARK ECOTOPE BETHAL/HU2100
*NATIONAL SOIL PROFILE NO:*6141

Appendix 1.4.1

SOIL ANALYTICAL DATA/ GRONDONTLEDINGSDATA

SURVEY/OPNAME: BENCHMARK ECOTOPE PROJEK
ECOTOPE/EKOTOOP: BETHAL/Hu2100

Horizon/Horison	Ap	A2	B1	B2	B3	
Depth/Diepte (mm)	0-250	250-350	350-850	850-1400	1400-2000	
Bag no /Sak nr	116B	241C	405D	407D	426D	
Lab No/ nr	D215	D216	D217	D218	D219	
>2 mm						
c/g sand 2-0.5 mm	6,2	7,6	6,4	4,2	3,4	
m 0.5-0.25 mm	18,7	18,5	16,6	13,3	10,8	
f sand 0.25-0.106 mm	30,7	26,4	23,6	22,2	20,2	
v/b f sand 0.106-0.05 mm	12,0	11,0	11,4	12,3	15,3	
c/g silt/slik 0.05-0.02 mm	8,7	7,5	8,3	9,9	11,6	
f silt/slik 0.02-0.002 mm	3,1	3,2	4,1	5,4	6,1	
clay/klei 0.002 mm	18,2	23,3	27,7	31,3	30,9	
Texture/Tekstuur	FISALM	MESACLLM	FISACLLM	FISACLLM	FISACLLM	
CHEMICAL ANALYSIS/ CHEMIESE ONTLEDINGS						
C %	0,85	1,01	0,54	0,25	0,12	
Titr. Acidity cmol(+)/kg	0,36	0,53	0,07	0,05	0,54	
Al (me %) cmol(+)/kg	0,31	0,49	0,05	0,04	0,09	
Resistance/Weerstand (ohm)	1800	2200	200	1800	2200	
pH H2O	5,61	5,49	6,70	6,79	5,00	
pH KCl	4,84	4,61	5,94	5,94	5,04	
EXCHANGEABLE/EXTRACTABLE CATIONS/ cmol (+) kg^{-1} soil UITRUILBARE/EKSTRAHEERBARE KATIONE/cmol (+) kg^{-1} grond						
Na	0,20	0,11	0,13	0,13	0,13	
K	0,26	0,16	0,14	0,14	0,17	
Ca	2,42	2,40	3,03	2,37	1,14	
Mg	1,11	0,78	0,76	1,80	2,78	
S value/ S waarde	3,99	3,45	4,06	4,44	4,22	
T value (CEC/ T waarde (KUK)	4,73	4,79	4,08	4,42	6,34	
SATURATION EXTRACT SOL. CATIONS cmol (+) kg^{-1} soil VERSADIGDE EKSTRAK OPLOSBARE KATIONE cmol (+) kg^{-1} grond						
Na						
K						
Ca						
Mg						
Cond/Geleid/mS/m						
Saturation/Versadiging						

SOIL PROFILE DESCRIPTION:

Profile No:
*Map/photo:*2629BA Hendrina
*Latitude & Longitude:*26°10'49''/29°34'13''
*Land type No:*Bb4
*Climate zone:*24S
*Altitude:*1550m
*Terrain unit:*Lower Midslope
*Slope:*2%
*Slope shape:*Concave
*Aspect:*South-west
*Microrelief:*None
*Parent material solum:*Origin single, local colluvium
*Underlying material:*Sandstone (feldspathic)

*Soil form:*Avalon
*Soil family:*Mafikeng
*Surface rockiness:*None
Surface stoniness:
*Occurrence of flooding:*None
*Wind erosion:*None
*Water erosion:*None
*Vegetation/Land use:*Agronomic cash crops
*Water table:*0mm
Described by: K C Snyman, P A L le Roux & M Hensley
*Date described:*1993-09
*Weathering of underlying material:*Advanced physical, strong chemical
*Alteration of underlying material:*Ferruginised

Horizon	*Depth(mm)*	*Description*	*Diagnostic horizons*
AP	0 - 300	Dry; dry brown 10YR5/3, moist dark brown 10YR3/3; disturbed; loamy medium sand; apedal massive; hard; few fine pores; water absorption: 1 second(s); few roots; gradual wavy transition.	Orthic
A2	300 - 420	Dry; dry brown 10YR5/3, moist dark brown 10YR3/3; undisturbed; medium sandy loam; apedal massive; hard; few fine pores; water absorption: 1 second(s); few roots; clear wavy transition.	Orthic
B1	420 - 650	Moist; dry yellowish brown 10YR5/8, moist dark brown 10YR3/3; undisturbed; medium sandy clay loam; apedal massive; slightly firm; common fine pores; water absorption: 1 second(s); few roots; gradual wavy transition.	Yellow-brown apedal
B2	650 - 850	Moist; dry yellow 10YR7/8, moist red 2.5YR5/6; undisturbed; coarse sandy clay loam; many coarse prominent grey reduced iron oxide mottles; many coarse prominent red and yellow oxidized iron oxide mottles; apedal massive; slightly firm; common fine pores; very few medium sesquioxide concretions; water absorption: 1 second(s); clear wavy transition.	Soft plinthic
B3	850 - 1170	Moist; moist light red 2.5YR6/6; undisturbed; medium sandy clay loam; many coarse prominent grey reduced iron oxide mottles; many coarse prominent red and yellow oxidized iron oxide mottles; apedal massive; friable; few fine pores; few coarse pores; common medium sesquioxide concretions; water absorption: 1 second(s); gradual wavy transition.	Soft plinthic
C1	1170 - 1500	Moist; undisturbed; coarse sandy clay loam; many medium prominent grey and yellow reduced iron oxide mottles; many coarse oxidized iron oxide mottles; weak medium subangular blocky; firm; few fine pores; few coarse pores; few medium sesquioxide concretions; water absorption: 1 second(s); wavy transition.	Unconsolidated material, with signs of wetness

*Survey name:*BENCHMARK ECOTOPE BETHAL/AV3200
*NATIONAL SOIL PROFILE NO:*6140

Appendix 1.5.2

SOIL ANALYTICAL DATA/ GRONDONTLEDINGSDATA

SURVEY/OPNAME: BENCHMARK ECOTOPE PROJEK
ECOTOPE/EKOTOOP: BETHAL/Av3200

Horizon/Horison	Ap	A2	B1	B2	B3	C1
Depth/Diepte (mm)	0-300	300-420	420-650	650-850	850-1170	1170-1500
Bag no /Sak nr	242C	239C	228D	224D	217C	216E
Lab No/ nr	D209	D210	D211	D212	D213	D214
PARTICLE SIZE DISTRIBUTION/ DEELTJIE GROOTTEVERSPREIDING%						
>2 mm						
c/g sand 2-0.5 mm	12,3	9,4	11,6	14,5	9,7	12,7
m 0.5-0.25 mm	33,9	20,4	18,8	23,8	17,8	21,5
f sand 0.25-0.106 mm	27,2	32,2	25,1	20,5	20,4	17,9
v/b f sand 0.106-0.05 mm	7,5	10,0	8,6	7,4	11,1	11,2
c/g silt/slik 0.05-0.02 mm	5,1	7,4	7,0	6,1	9,5	9,1
f silt/slik 0.02-0.002 mm	3,0	2,6	2,6	3,1	5,1	5,5
clay/klei 0.002 mm	9,0	16,2	23,8	22,9	24,6	20,5
Texture/Tekstuur	LMMESA	MESALM	MESACLLM	COSACLLM	MESACLLM	COSACLLM
CHEMICAL ANALYSIS/ CHEMIESE ONTLEDINGS						
C %	0,46	0,61	0,50	0,43	0,38	0,11
Titr. Acidity cmol(+)/kg	1,29	0,32	0,16	0,06	0,10	0,34
Al (me %) cmol(+)/kg	1,15	0,30	0,15	0,05	0,08	0,28
Resistance/Weerstand (ohm)	2400	1800	2200	2000	1800	1400
pH H2O	4,71	5,67	6,31	6,53	6,23	5,64
pH KCl	3,97	4,64	5,39	5,60	5,41	5,08
EXCHANGEABLE/EXTRACTABLE CATIONS/cmol (+) kg^{-1} soil UITRUILBARE/EKSTRAHEERBARE KATIONE/cmol (+) kg^{-1} grond						
Na	0,12	0,12	0,12	0,14	0,14	0,21
K	0,34	0,25	0,18	0,17	0,22	0,25
Ca	1,29	2,23	2,96	3,14	2,50	1,52
Mg	0,39	0,65	0,83	1,01	2,00	2,53
S value/ S waarde	2,14	3,25	4,09	4,46	4,86	4,51
T value (CEC/ T waarde (KUK)	3,35	4,03	5,02	5,48	5,65	4,85
SATURATION EXTRACT SOL. CATIONS/cmol (+) kg^{-1} soil VERSADIGDE EKSTRAK OPLOSBARE KATIONE/ cmol (+) kg^{-1} grond						
Na						
K						
Ca						
Mg						
Cond/Geleid mS/m						
Saturation/Versadiging						

SOIL PROFILE DESCRIPTION:

Profile No:
*Map/photo:*2629DB Ermelo
*Latitude & Longitude:*26°38'30''/29°48'47''
*Land type No:*Ca3
*Climate zone:*24S
*Altitude:*1670m
*Terrain unit:*Midslope
*Slope:*3%
*Slope shape:*Concave
*Aspect:*East
*Microrelief:*None
*Parent material solum:*Origin single, local colluvium
*Underlying material:*Sandstone (feldspathic)

*Soil form:*Longlands
*Soil family:*Ermelo
*Surface rockiness:*None
*Surface stoniness:*None
*Occurrence of flooding:*None
*Wind erosion:*None
*Water erosion:*Sheet slight, stabilized
*Vegetation/Land use:*Agronomic cash crops
*Water table:*0mm
Described by: M Hensley, K C Snyman & P A L le Roux
*Date described:*1993-08
*Weathering of underlying material:*Strong physical, strong chemical
*Alteration of underlying material:*Ferruginised

Horizon	*Depth(mm)*	*Description*	*Diagnostic horizons*
A1	0 - 350	Dry; dry brown 10YR5/3, moist dark brown 10YR3/3; disturbed; loamy medium sand; apedal massive; friable; few fine pores; water absorption: 1 second(s); few roots; gradual smooth transition.	Orthic
AE	350 - 600	Dry; dry yellowish brown 10YR5/4, moist dark yellowish brown 10YR4/4; undisturbed; loamy medium sand; few medium faint grey and yellow reduced iron oxide mottles; apedal massive; friable; few fine pores; very few fine sesquioxide concretions; very few medium sesquioxide concretions; water absorption: 1 second(s); few roots; gradual smooth transition.	Orthic
E	600 - 800	Dry; dry light yellowish brown 10YR6/4, moist dark yellowish brown 10YR4/4; undisturbed; loamy medium sand; many medium distinct grey and yellow reduced iron oxide mottles; apedal massive; friable; common fine pores; few fine sesquioxide concretions; few medium sesquioxide concretions; water absorption: 1 second(s); few roots; clear smooth transition.	E-horizon
B1	800 - 1100	Dry; dry light grey 10YR7/2, moist light brownish grey 10YR6/2; undisturbed; medium sandy clay loam; many coarse prominent yellowish brown oxidized iron oxide mottles; few medium prominent black oxidized iron oxide mottles; apedal massive; slightly firm; common fine pores; common fine sesquioxide concretions; common medium sesquioxide concretions; water absorption: 3 second(s).	Soft plinthic

*Survey name:*BENCHMARK ECOTOPE ERMELO/LO2000
*NATIONAL SOIL PROFILE NO:*6144

Appendix 1.6.2

SOIL ANALYTICAL DATA/ GRONDONTLEDINGSDATA

SURVEY/OPNAME: BENCHMARK ECOTOPE PROJEK
ECOTOPE/EKOTOOP: ERMELO/Lo2000

Horizon/Horison	A1	AE	E	B1			
Profile No/Profiel Nr.							
Depth/Diepte (mm)	0-350	350-600	600-800	800-1100			
Bag no /Sak nr	320E	305E	309D	299B			
Lab No/ nr	D173	D174	D175	D177			
PARTICLE SIZE DISTRIBUTION/ DEELTJIE GROOTTEVERSPREIDING%							
>2 mm							
c/g sand 2-0.5 mm	12.5	9.9	10.8	11.9			
m 0.5-0.25 mm	30.6	26.3	26.3	21.0			
f sand 0.25-0.106 mm	31.4	35.1	35.1	24.3			
v/b f sand 0.106-0.05 mm	10.4	13.9	13.9	9.1			
c/g silt/slik 0.05-0.02 mm	2.6	7.0	7.0	5.3			
f silt/slik 0.02-0.002 mm	2.4	2.0	2.0	4.3			
clay/klei 0.002 mm	7.6	4.1	4.1	23.3			
Texture/Tekstuur	LMMESA	LMMESA	LMMESA	MESACLLM			
CHEMICAL ANALYSIS/ CHEMIESE ONTLEDINGS							
C %	0.51	-	-	-			
Titr. Acidity cmol(+)/kg							
Al (me %) cmol(+)/kg							
Resistance/Weerstand (ohm)	2900	2600	2800	1800			
pH H20	6.05	5.94	5.76	5.79			
pH KCl	5.38	5.15	5.17	4.63			
EXCHANGEABLE/EXTRACTABLE CATIONS/cmol (+) kg^{-1} soil UITRUILBARE/EKSTRAHEERBARE KATIONE/cmol (+) kg^{-1} grond							
Na	0.03	0.06	0.05	0.23			
K	0.09	0.09	0.06	0.33			
Ca	1.80	1.49	0.46	2.16			
Mg	0.43	0.45	0.14	2.41			
S value/ S waarde	2.41	2.09	0.71	5.13			
T value (CEC/ T waarde (KUK)	2.89	2.42	0.46	6.75			
SATURATION EXTRACT SOL. CATIONS/cmol (+) kg^{-1} soil VERSADIGDE EKSTRAK OPLOSBARE KATIONE/cmol (+) kg^{-1} grond							
Na							
K							
Ca							
Mg							
Cond/Geleid mS/m							
Saturation/Versadiging							

SOIL PROFILE DESCRIPTION:

Profile No:
Map/photo:2826AD Vendusiespruit
Latitude & Longitude:28°16'24''/26°26'13''
Land type No:Ah20
Climate zone:13S
Altitude:1310m
Terrain unit:Lower Midslope
Slope:1%
Slope shape:Straight
Aspect:East
Microrelief:None
Parent material solum:Origin single, aeolian
Underlying material:Sandstone (feldspathic)
Geological Group/Formation:Beaufort Sandstone

Soil form:Clovelly
Soil family:Mooilaagte
Surface rockiness:None
Surface stoniness:
Occurrence of flooding:None
Wind erosion:Slight wind, partially stabilized
Water erosion:None
Vegetation/Land use:Agronomic cash crops
Water table:2200mm
Described by: K C Snyman, P A L le Roux & M Hensley
Date described:1993-10
Weathering of underlying material:Advanced physical, strong chemical
Alteration of underlying material:Generalized

Horizon	*Depth(mm)*	*Description*	*Diagnostic horizons*
AP	0 - 250	Dry; dry yellowish brown 10YR5/4, moist dark yellowish brown 10YR4/4; disturbed; fine sand; apedal massive; slightly hard; few normal fine pores; water absorption: 1 second(s); few roots; gradual transition.	Orthic
A1	250 - 550	Dry; dry yellowish brown 10YR5/4, moist dark yellowish brown 10YR4/4; undisturbed; loamy fine sand; apedal massive; hard; few normal fine pores; water absorption: 1 second(s); few roots; gradual transition.	Orthic
B1	550 - 900	Moist; dry strong brown 7.5YR5/6, moist brown to dark brown 7.5YR4/4; undisturbed; fine sandy loam; apedal massive; hard; common normal fine pores; water absorption: 1 second(s); few roots; gradual transition.	Yellow-brown apedal
B2	900 - 1200	Moist; dry strong brown 7.5YR5/8, moist strong brown 7.5YR5/6; undisturbed; fine sandy loam; common fine faint yellow oxidized iron oxide mottles; apedal massive; slightly hard; common normal fine pores; very few fine sesquioxide concretions; water absorption: 1 second(s); few roots; gradual transition.	Yellow-brown apedal
B3	1200 - 1500	Moist; moist yellowish brown 10YR5/6; undisturbed; fine sandy clay loam; many medium faint yellow, red and black oxidized iron oxide mottles; apedal massive; friable; common normal fine pores; few fine sesquioxide concretions; few medium sesquioxide concretions; water absorption: 1 second(s); few roots; gradual transition.	Yellow-brown apedal
B4	1500 - 1800	Moist; moist yellowish brown 10YR5/6; undisturbed; fine sandy clay loam; many medium faint yellow oxidized iron oxide mottles; apedal massive; friable; common normal fine pores; few fine sesquioxide concretions; few medium sesquioxide concretions; water absorption: 1 second(s); few roots; gradual transition.	Yellow-brown apedal

Survey name:BENCHMARK ECOTOPE BULTFONTEIN/CV3200

Appendix 1.7.2

SOIL ANALYTICAL DATA/ GRONDONTLEDINGSDATA

SURVEY/OPNAME: BENCHMARK ECOTOPE PROJEK
ECOTOPE/EKOTOOP: BULTFONTEIN/Cv3200

Horizon/Horison	Ap	A1	B1	B2	B3	B4	
Profile No/Profiel Nr.							
Depth/Diepte (mm)	0-250	250-550	550-900	900-1200	1200-1500	1500-1800	
Bag no /Sak nr	149D	38B	137B	143C	D134	146A	
Lab No/ nr	D188	D189	D190	D191	D192	D193	
PARTICLE SIZE DISTRIBUTION/ DEELTJIE GROOTTEVERSPREIDING%							
>2 mm							
c/g sand 2-0.5 mm	0.5	0.5	0.6	0.6	0.6	0.5	
m 0.5-0.25 mm	14.6	15.8	14.2	17.5	14.0	14.4	
f sand 0.25-0.106 mm	52.2	49.8	42.0	41.5	40.5	41.1	
v/b f sand 0.106-0.05 mm	20.1	16.5	17.8	16.8	17.3	15.6	
c/g silt/slik 0.05-0.02 mm	2.6	2.4	5.1	4.0	4.8	4.2	
f silt/slik 0.02-0.002 mm	1.4	1.4	0.6	0.6	1.2	1.1	
clay/klei 0.002 mm	7.0	11.4	18.0	16.8	20.0	21.5	
Texture/Tekstuur	FISA	LMFISA	FISALM	FISALM	FISACLLM	FISACLLM	
CHEMICAL ANALYSIS/ CHEMIESE ONTLEDINGS							
C %	0.22	0.26	0.24	1.17	0.14	0.11	
Titr. Acidity cmol(+)/kg	0.99	0.21	0.16	0.14	0.19	0.20	
Al (me %) cmol(+)/kg	0.93	0.18	0.14	0.10	0.16	0.14	
Resistance/Weerstand (ohm)	3400	3600	3200	2600	2200	2000	
pH H20	5.10	5.79	7.65	6.18	6.033	5.86	
pH KCl	4.11	4.54	6.08	5.14	5.17	4.98	
EXCHANGEABLE/EXTRACTABLE CATIONS/cmol (+) kg^{-1} soil UITRUILBARE/EKSTRAHEERBARE KATIONE/cmol (+) kg^{-1} grond							
Na	0.02	0.02	0.01	0.11	0.15	0.14	
K	0.35	0.42	0.46	0.27	0.23	0.28	
Ca	1.01	1.76	2.00	1.59	1.92	2.24	
Mg	0.43	0.85	2.08	2.21	2.49	2.54	
S value/ S waarde	1.81	3.05	4.55	4.18	4.79	5.20	
T value (CEC/ T waarde (KUK)	2.50	3.87	5.84	5.45	6.09	7.88	
SATURATION EXTRACT SOL. CATIONS/cmol (+) kg^{-1} soil VERSADIGDE EKSTRAK OPLOSBARE KATIONE/cmol (+) kg^{-1} grond							
Na							
K							
Ca							
Mg							
Cond/Geleid mS/m							
Saturation/Versadiging							

SOIL PROFILE DESCRIPTION:

Profile No:
*Map/photo:*2925BA Immigrant
*Latitude & Longitude:*29°06'10''/25°37'27''
*Land type No:*Ae461
*Climate zone:*42S
*Altitude:*1277m
*Terrain unit:*Upper Footslope
*Slope:*1%
*Slope shape:*Straight
*Aspect:*North-west
*Microrelief:*0% Windblown depressions and mounds,0.0m
*Parent material solum:*Origin binary, aeolian, local colluvium
*Underlying material:*Sandstone (feldspathic)
*Geological Group/Formation:*Beaufort sandstone

*Soil form:*Bloemdal
*Soil family:*Vrede
*Surface rockiness:*None
*Surface stoniness:*None
*Occurrence of flooding:*None
*Wind erosion:*Moderate wind, partially stabilized
*Water erosion:*Sheet moderate, Rill slight, Gully slight, partially stabilized
*Vegetation/Land use:*Agronomic cash crops
*Water table:*0mm
Described by: K C Snyman, P A L le Roux, M Hensley
*Date described:*1993-10
*Weathering of underlying material:*Advanced physical, moderate chemical
*Alteration of underlying material:*Ferruginised

Horizon	*Depth(mm)*	*Description*	*Diagnostic horizons*
A1	0 - 230	Dry; dry yellowish red 5YR4/6, moist reddish brown 5YR4/4; disturbed; loamy fine sand; apedal massive; hard; many normal fine pores; water absorption: 1 second(s); few roots; clear smooth transition.	Orthic
B1	230 - 400	Dry; dry yellowish red 5YR4/6, moist reddish brown 5YR4/4; undisturbed; loamy fine sand; apedal massive; very hard; many normal fine pores; water absorption: 1 second(s); few roots; gradual smooth transition.	Red apedal
B2	400 - 770	Dry; dry red 2.5YR4/6, moist dark red 2.5YR3/6; undisturbed; fine sandy clay loam; apedal massive; very hard; many normal fine pores; few clay cutans; fine sesquioxide concretions; water absorption: 1 second(s); few roots; gradual smooth transition.	Red apedal
B3	770 - 1500	Dry; dry red 2.5YR4/8, moist red 2.5YR4/6; undisturbed; fine sandy loam; few fine distinct grey reduced iron oxide mottles; few medium distinct oxidized iron oxide mottles; apedal massive; very hard; many normal fine pores; few clay cutans; very few fine sesquioxide concretions; water absorption: 1 second(s); few roots; gradual smooth transition.	Red apedal
C	1500 - 1900	Dry; dry red 2.5YR4/8, moist red 2.5YR4/6; undisturbed; fine sandy clay loam; many fine prominent grey reduced iron oxide mottles; many medium prominent yellow, red and black oxidized iron oxide mottles; apedal massive; friable; many normal fine pores; very few fine sesquioxide concretions; water absorption: 1 second(s); few roots; gradual smooth transition.	Unspecified material, with signs of wetness

*Survey name:*BENCHMARK ECOTOPE PETRUSBURG/BD3100
*NATIONAL SOIL PROFILE NO:*6138

Appendix 1.8.2

SOIL ANALYTICAL DATA/ GRONDONTLEDINGSDATA

SURVEY/OPNAME: BENCHMARK ECOTOPE PROJEK
ECOTOPE/EKOTOOP: PETRUSBURG/Bd3100

Horizon/Horison	A1	B1	B2	B3	C	
Profile No/Profiel Nr.						
Depth/Diepte (mm)	0-230	230-400	400-770	770-1500	1500-1900	
Bag no /Sak nr	4D	21D	23D	37D	45D	
Lab No/ nr	D204	D205	D206	D207	D208	
PARTICLE SIZE DISTRIBUTION/ DEELTJIE GROOTTEVERSPREIDING%						
>2 mm						
c/g sand 2-0.5 mm	0.1	0.0	0.1	0.0	0.1	
m 0.5-0.25 mm	3.4	4.9	6.5	4.4	6.6	
f sand 0.25-0.106 mm	55.8	52.5	44.7	17.4	44.4	
v/b f sand 0.106-0.05 mm	26.1	22.6	19.3	20.9	20.3	
c/g silt/slik 0.05-0.02 mm	3.0	4.1	3.5	4.8	5.1	
f silt/slik 0.02-0.002 mm	2.1	2.0	1.5	1.4	2.9	
clay/klei 0.002 mm	7.6	11.6	21.8	18.8	20.5	
Texture/Tekstuur	LMFISA	LMFISA	FISACLLM	FISALM	FISACLLM	
CHEMICAL ANALYSIS/ CHEMIESE ONTLEDINGS						
C %	0.21	0.23	0.27	0.16	0.09	
Titr. Acidity cmol(+)/kg	0.50	0.16	0.13	0.05	0.00	
Al (me %) cmol(+)/kg	0.42	0.14	0.12	0.03	0.00	
Resistance/Weerstand (ohm)	2600	2000	1600	1800	1800	
pH H2O	5.44	5.97	6.35	6.78	7.28	
pH KCl	4.28	4.87	5.21	5.52	5.73	
EXCHANGEABLE/EXTRACTABLE CATIONS/cmol (+) kg^{-1} soil UITRUILBARE/EKSTRAHEERBARE KATIONE/cmol (+) kg^{-1} grond						
Na	0.12	0.11	0.20	0.18	0.16	
K	0.62	0.56	0.47	0.32	0.58	
Ca	1.49	2.17	3.08	2.96	4.01	
Mg	0.80	1.47	3.09	3.32	4.41	
S value/ S waarde	3.03	4.31	6.84	6.78	9.16	
T value (CEC/ T waarde (KUK)	4.09	4.90	7.75	7.51	10.20	
SATURATION EXTRACT SOL. CATIONS/cmol (+) kg^{-1} soil VERSADIGDE EKSTRAK OPLOSBARE KATIONE/cmol (+) kg^{-1} grond						
Na						
K						
Ca						
Mg						
Cond/Geleid mS/m						
Saturation/Versadiging						

APPENDIX 2

SIMULATED LONG-TERM PRODUCTIVITY

2.1 Tabulated results for each ecotope, for four water contents at planting, and three probabilities

2.2 CPF graphs for each ecotope

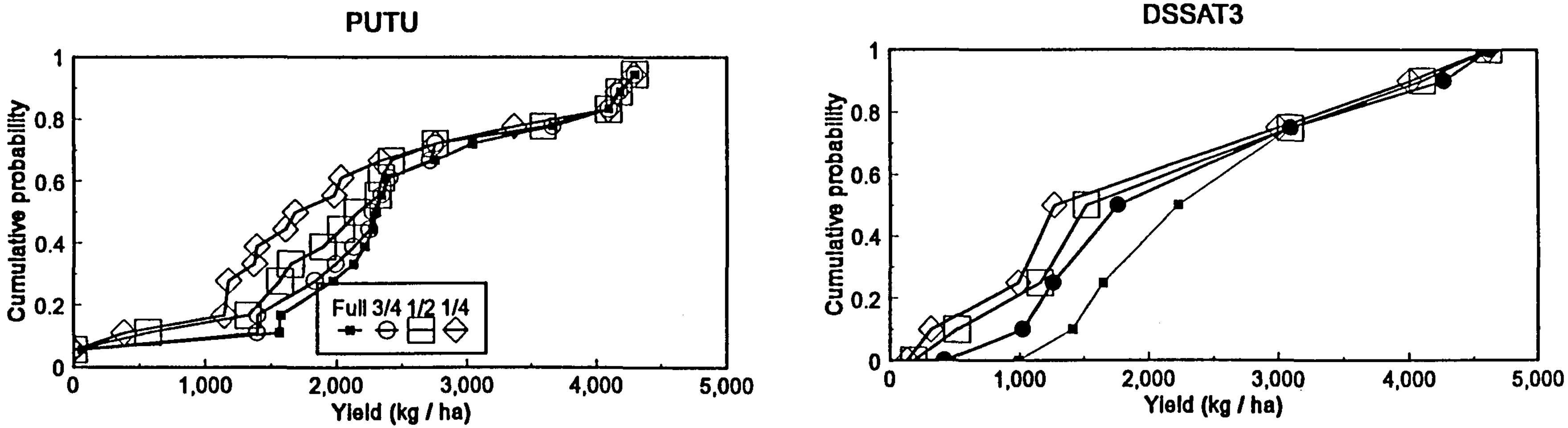
APPENDIX 2..1

The simulated long-term productivity of eight benchmark ecotopes, using DSSAT3 and PUTU with four different water contents at planting, and with results expressed in terms of three probabilities.

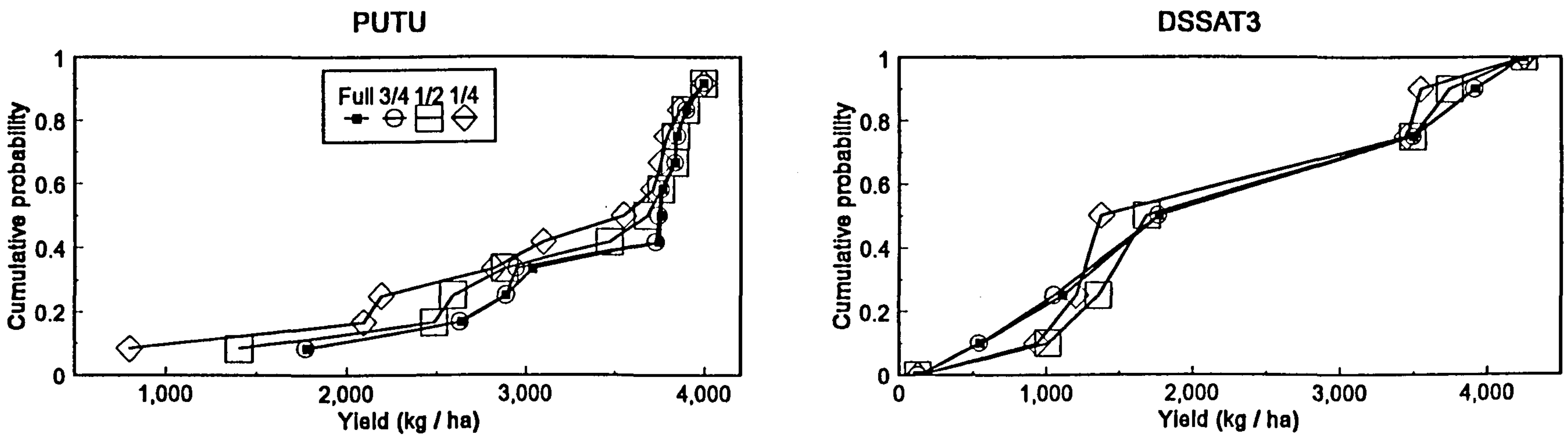
Ecotope	Model	probability of specified yield being exceeded (%)	Predicted grain yield (kg ha^{-1}) Water content of the root zone at planting			
			¼ full	½ full	¾ full	Full
Setlagole/ Clovelly	PUTU	75	1176	1568	1835	1972
		50	1682	2156	2272	2302
		25	3062	3173	3211	3355
	DSSAT3	75	992	1161	1262	1648
		50	1270	1515	1759	2229
		25	2997	3094	3096	3097
Wolmarans-stad/Hutton	PUTU	75	2190	2589	2887	2887
		50	3548	3679	3743	3757
		25	3789	3840	3848	3848
	DSSAT3	75	1207	1347	1052	1114
		50	1379	1687	1767	1774
		25	3452	3491	3493	3495
Kroonstad/ Avalon	PUTU	75	505	487	498	2614
		50	2364	2595	2656	4908
		25	3776	3968	4534	5527
	DSSAT3	75	1378	1644	2011	2430
		50	2862	3159	3298	3375
		25	4124	4182	4182	4247
Bethal/ Hutton	PUTU	75	2495	2710	3124	3754
		50	4107	4444	4902	4902
		25	5018	5018	5161	5218
	DSSAT3	75	3392	5372	6008	6069
		50	6022	6583	6768	6768
		25	7340	7340	4330	7343
Bethal/ Avalon	PUTU	75	2559	2727	3186	3612
		50	4215	4577	4818	4819
		25	4753	4876	4975	4975
	DSSAT3	75	2580	5147	5847	6069
		50	4933	6010	6354	6768
		25	7340	7340	7340	7340

Ecotope	Model	probability of specified yield being exceeded (%)	Predicted grain yield (kg ha^{-1})			
			Water content of the root zone at planting			
			¼ full	½ full	¾ full	Full
Ermelo/ Longlands	PUTU	75	3103	3305	3305	3305
		50	3834	3984	4079	4079
		25	4209	4531	4531	4546
	DSSAT3	75	3118	3378	3545	4405
		50	5001	5451	6090	6765
		25	6511	6725	7104	7487
Bultfontein /Clovelly	PUTU	75	475	599	801	1087
		50	1058	1215	1594	2102
		25	1372	1881	2534	2935
	DSSAT3	75	27	173	167	213
		50	154	313	398	479
		25	417	641	782	869
Petrusburg/ Bloemdal	PUTU	75	157	220	858	2216
		50	578	675	1607	2985
		25	980	1406	2581	3822
	DSSAT3	75	60	108	167	271
		50	103	169	264	380
		25	338	442	677	888

CPF graphs of long term maize yields on the Setlagole / Clovelly ecotope

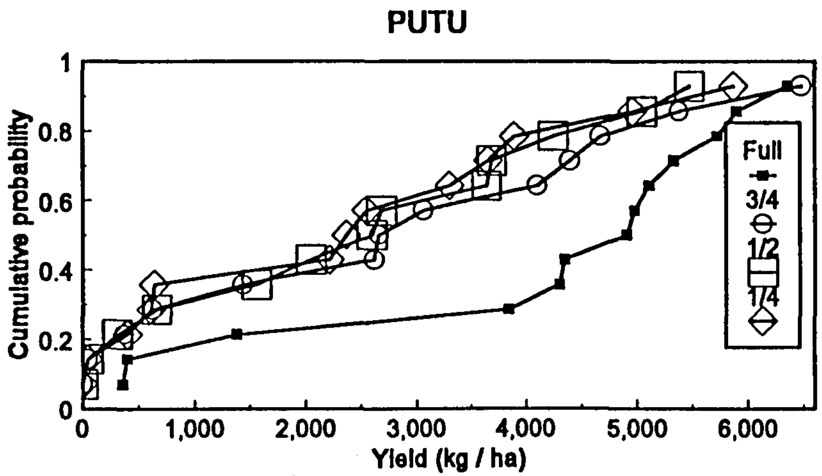


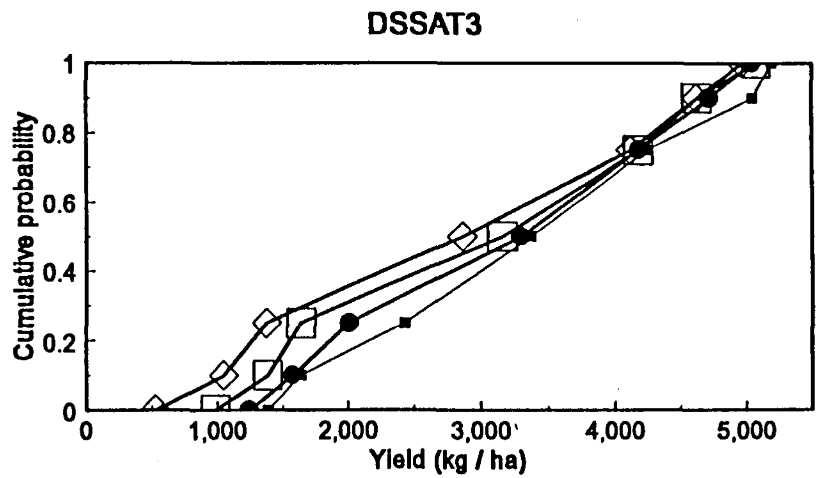
CPF graphs of long term maize yields on the Wolmaransstad / Hutton ecotope



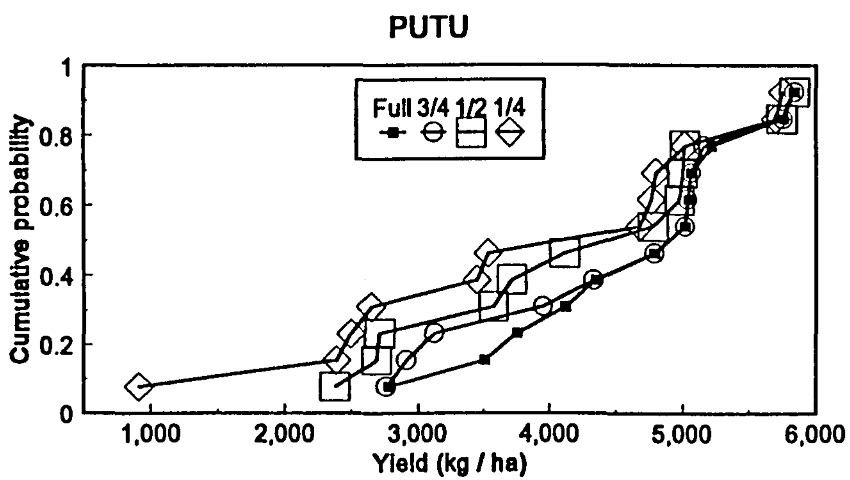
APPENDIX 2.2

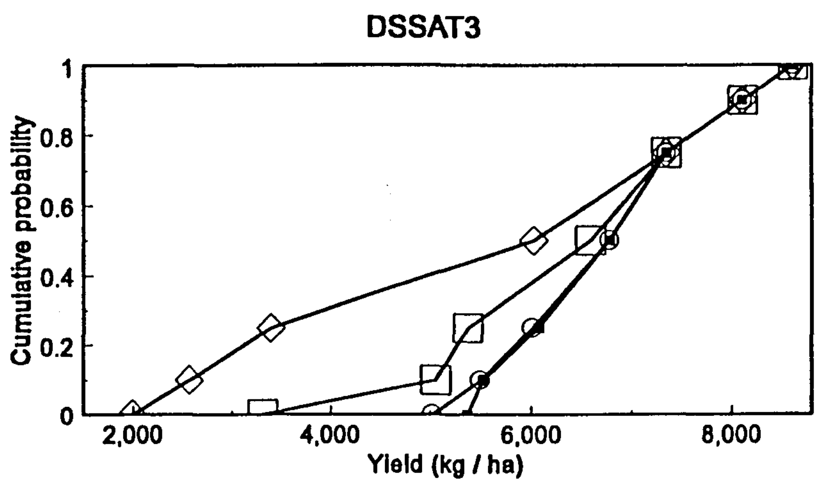
CPF graphs of long term maize yields on the Kroonstad / Avalon ecotope





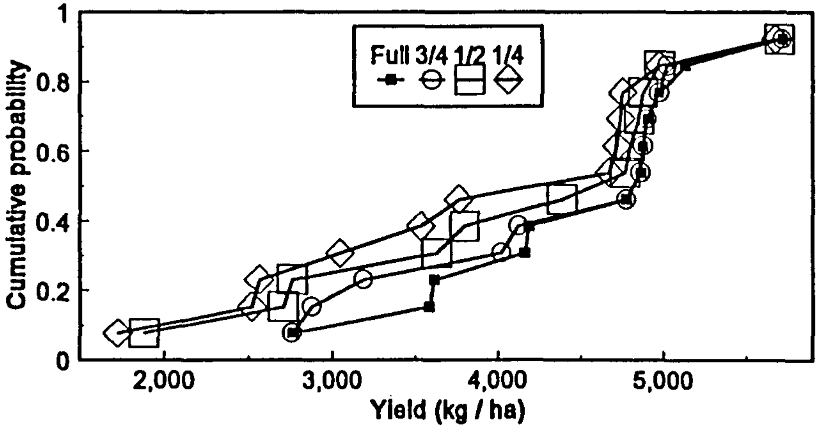
CPF graphs of long term maize yields on the Bethal / Hutton ecotope



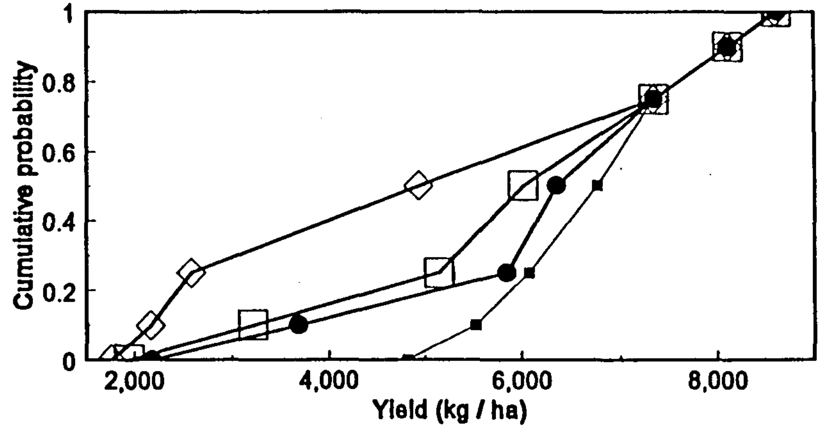


CPF graphs of long term maize yields on the Bethal / Avalon ecotope

PUTU

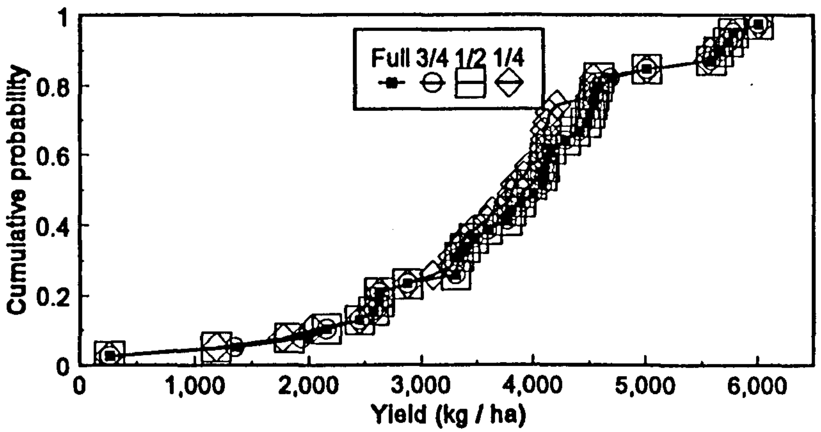


DSSAT3

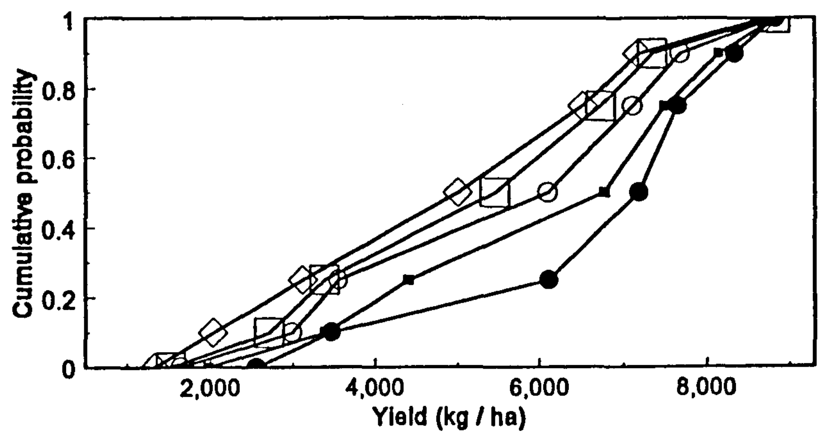


CPF graphs of long term maize yields on the Ermelo / Longlands ecotope

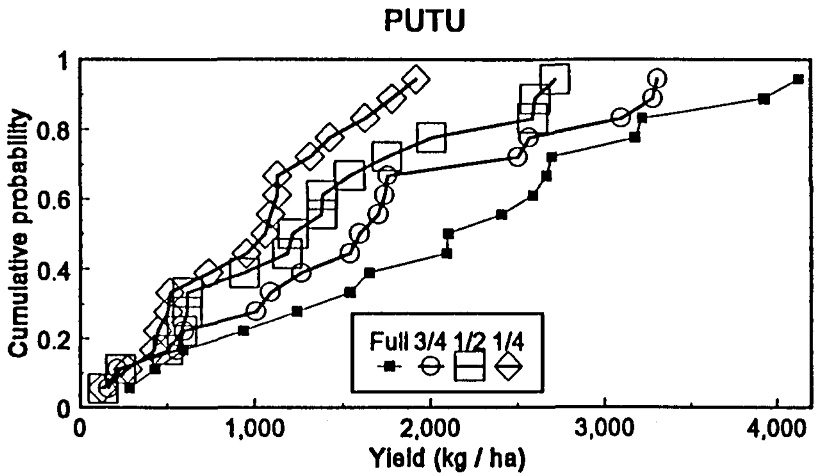
PUTU

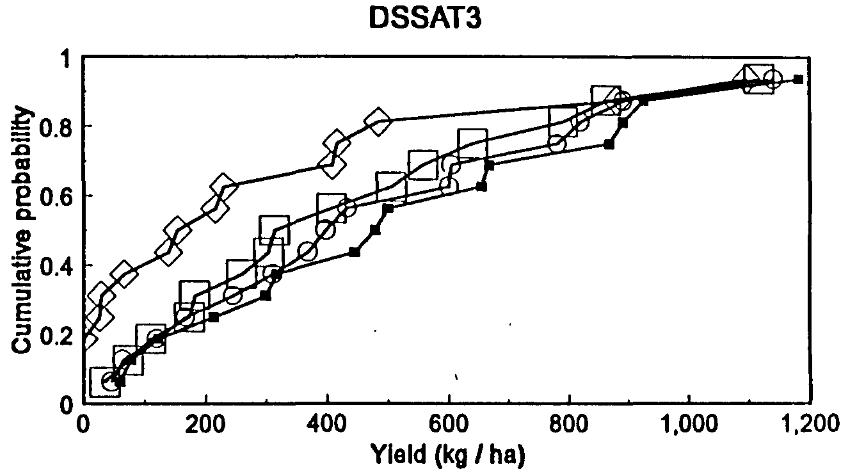


DSSAT3



CPF graphs of long term wheat yields on the Bultfontein / Clovelly ecotope





CPF graphs of long term wheat yields on the Petrusburg / Bloemdal ecotope