EVALUATING MAIZE PRODUCTION POTENTIAL OF SELECTED SEMI-ARID ECOTOPES USING A WATER BALANCE MODEL

by

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ABSTRACT

The quantitative evaluation of crop production potential is important for sustainable and wise land use as well as for food security where subsistence farmers are involved. It is of particular importance in arid and semi-arid areas where rainfall is marginal and variable. This study aims at making a quantitative evaluation of the maize production potential of the Glen/Hutton and Glen/Oakleaf ecotopes which are located at the Glen Agricultural Research Station in the semi-arid Free State Province of South Africa. The objective was to characterize the ecotopes, and to make long-term yield predictions with a yield prediction model using long-term climate data.

A detailed profile description, soil analyses and an *in situ* drainage curve were made for the Glen/Oakleaf ecotope. Similar data for the Glen/Hutton ecotope was obtained from previous research work (Hensley *et al*., 1993; Hattingh, 1993; Hensley, personal communication, 2002). A neutron water meter (NWM) was calibrated for each horizon of the Oakleaf soil on the Glen/Oakleaf ecootpe. The plant available water (PAW), defined as the differences between the drained upper limit (DUL) and the lower limit (LL), for maize grown on the Glen/Hutton and Glen/Oakleaf ecotopes was 133 mm and 120 mm respectively. Considering a mature maize crop growing in summer on these two ecotopes, PAW can be defined as the difference between the crop modified upper limit (CMUL) and LL. Results for this parameter were 183 mm and 192 mm for the Glen/Hutton and Glen/Oakleaf ecotopes respectively. The reason for the relatively high value of the latter is its slower drainage rate, which enables the crop to extract more water while drainage proceeds between field saturation and DUL than in the rapidly draining Hutton soil. Yields measured on experiments on the two ecotopes for 12 seasons on the Glen/Hutton and 10 seasons on the Glen/Oakleaf ecotope indicate that these two ecotopes have similar production potentials.

For the development of a yield prediction model it was necessary to find a way to estimate daily crop evapotranspiration (ET). Based on the semi-arid climate, soil morphological observations and results of soil analyses, deep drainage from these two maize ecotopes was considered to be negligible. Equations for predicting runoff from rainfall (P) were developed based on long-term runoff measurements made at nearby sites (Du Plessis and Mostert, 1965; Hensley, personal communication, 2002). Because of fairly good r^2 values (0.84 and 0.82) the equations can be considered as reliable enough for the purpose of this study. A procedure for estimating soil water content at planting, from the rainfall pattern during preceding fallow period and grain yield in the preceding season, was also developed based on measurements

from previous research work (De Jager and Hensley, 1988; Hattingh, 1993). Using all this information it was possible to make a fairly reliable estimation of daily ET.

Climate data was used to calculate daily potential evaporation (Eo) values. This enabled the degree of crop water stress to be defined as $\frac{\mathrm{ET}}{\mathrm{Eo}}$, on a daily basis. The maize growing season was divided into three stages *i.e.* the vegetative, flowering and seed filling stages. A stress index (SI), defined as the average $\frac{\mathrm{ET}}{\mathrm{Eo}}$ value for each period, was then calculated. To develop an integrated stress index (ISI) for the growing season eight different methods of integrating the three SI values were formulated. Measured maize yields from experimental plots on the two ecotopes were available for 22 seasons (De Wet and Engelbrecht, 1962; De Bruyn, 1974; De Jager and Hensley, 1988; Hattingh, 1993). Integrated stress index values were then calculated for these seasons and correlated with the biomass yields. This made it possible to choose the best method of calculating the ISI value from the individual SI's. The ISI with the best correlation ($r^2 = 0.69$) was the one with formula ISI = (2A + 3B + 2C)/7, where A, B and C are the SI values of the three growth periods respectively. The equation to predict total biomass (Yb) is Yb = 15238 ISI + 1067 kg ha^{-1}.

The biomass prediction equation was used to generate maize yields for 80 seasons (1922/23 – 2001/02). Yb was converted to grain yield using a harvest index regression equation based on 38 yields from Glen for which both total biomass and grain yield had been measured. Four production techniques were compared, *i.e.*, November planting with conventional tillage (CTN), January planting with conventional tillage (CTJ), November planting with in-field water harvesting and basin tillage (WHBN), and January planting with water harvesting and basin tillage (WHBJ). Cumulative probability functions (CPF's) of yields were computed for the four different production techniques. The CPF's indicated that the long-term mean yields (at 50% probability) were 2 653, 2 685, 3 108, and 3 355 kg ha^{-1} for CTN, CTJ, WHBN and WHBJ respectively. The CPF's were compared using the stochastic dominance and the Kolmogorov-Smirnov (K-S) tests (Anderson *et al.*, 1977; Steel *et al.*, 1997). Stochastic dominance results indicated that the WHBJ and WHBN production techniques have well defined first degree stochastic dominance over the CTN and CTJ techniques. January planting showed only second degree stochastic dominance over November planting. The K-S test indicated that the CPF's of the water harvesting techniques were significantly different from those of the conventional production techniques. No statistical significant difference was observed with the K-S test between the November and January plantings.

OPSOMMING

Kwantitiewe evaluering van gewasproduksie potensiaal is belangrik vir volhoubare grondgebruik en voedselsekuriteit waar kleinboere betrokke is. Dit is veral belangrik in ariede en semi-ariede gebiede waar reënval marginaal en wisselvallig is. Die doel van hierdie studie was om so 'n evaluering te maak vir mielies op die Glen/Hutton en Glen/Oakleaf ekotope geleë op die Glen Landbounavorsingstasie in 'n semi-ariede gebied in die Vrystaat Provinsie van Suid-Afrika. Die doel was om die ekotope te karakteriseer, en om lengtermyn oesopbrengs voorspellings te maak met behulp van 'n opbrengsmodel saam met langtermyn klimaatdata.

'n Gedetaileerde profielbeskrywing, grondontledings en veldbepaalde dreineringskurwe is gemaak vir die Glen/Oakleaf ekotoop. Vergelykbare inligting vir die Glen/Hutton ekotoop is verkry van vroeër navorsingswerk (Hensley et al,. 1993; Hattingh, 1993; Hensley, personal communication, 2002). 'n Neutron watermeter (NWM) is gekalibreer vir elke horison van die wortelsone van die Oakleaf grond. Die veldbepaalde plantbeskikbare water (PAW) vir mielies, gedefineer as die verskil tussen die gedreineerde boonste grens (DUL) en die onderste grense (LL), was 133 mm op die Glen/Hutton ekotoop en 120 mm op die Glen/Oakleaf ekotoop. Met 'n volwasse gewas op hierdie ekotope in die somer kan PAW gedefineer word as die verskil tussen 'n gewasaangepaste boonste grens (CMUL) en LL. Resultate vir hierdie parameter vir mielies op die Glen/Hutton ekotoop is 183 mm, en vir die Glen/Oakleaf ekotoop 192 mm. Die rede vir die relatiewe hoë waarde van laasgenoemde is die baie stadiger tempo van dreinering wat dan toelaat dat die mielies meer water bokant DUL kan ekstraheer terwyl dreinering nog plaasvind. Opbrengste gekry met veldproewe op die twee ekotope vir 12 seisoene op die Glen/Hutton en 10 seisoene op die Glen/Oakleaf ekotoop dui daarop dat die produksiepotentiaal vir mielies op die twee ekotope min of meer dieselfde is.

Vir die ontwikkeling van 'n opbrengsmodel was dit nodig om 'n prosedure te vind om daaglikse evapotranspirasie (ET) te beraam. Gebaseer op die morfologie en ontledings van die twee profiele, asook die semi-ariede klimaat, is daar besluit dat diep dreinering gewoonlik weglaatbaar klein sal wees. 'n Prosedure om afloop te voorspel vanaf reënvaldata is ontwikkel met behulp van langtermyn afloopbepalings gemaak deur Du Plessis en Mostert (1965) op 'n naasliggende terrein, asook ander plaaslike afloop bepalings (Hensley, persoonlike kommunikasie, 2002). Weens redelik goeie r^2 *waardes van 0.84 en 0.82 kan die ontwikkelde vergelykings beskou word as betroubaar genoeg vir die doel van die studie. 'n Prosedure om grondwaterinhoud by plant is ook ontwikkel. Dit is gebaseer op die reënvalpatroon gedurende die voorafgaande braakperiode, die graanopbrengs van die vorige* *groeiseisoen, en relevante resultate van vorige navorsing. Al hierdie inligting het dit moontlik gemaak om redelik betroubare voorspellings van daaglikse ET te maak.*

Klimaatdata is gebruik om daaglikse potensiële verdamping (Eo) te bepaal. Dit het dit moontlik gemaak om die mate van gewaswaterstremming, gedefinieer as $\frac{\text{ET}}{\text{Eo}}$, *op 'n daaglikse basis te beraam. Die mieliegroeiseisoen is in drie groeiperiodes gedeel, naamlik, vegatatiewe-, blom- en saadvulperiode. 'n Stremmingsindeks (SI), gedefinieer as die gemiddelde* $\frac{\text{ET}}{\text{Eo}}$ *waarde vir elke groeiperiode, is dan bereken. Agt verskillende formules is voorgestel om 'n geïntegreerde SI waarde (ISI) vir die groeiseisoen te bepaal. Gemete mielieopbrengste op die twee ekotope vir 'n totaal van 22 groeiseisoen is beskikbaar (De Wet & Engelbrecht 1962; De Bruyn, 1974; De Jager & Hensley, 1988; Hattingh 1993). Agt verskillende ISI waardes is bepaal vir elkeen van hierdie seisoene en gekorreleer met die biomassa opbrengs. Die ISI met die beste korrelasie* ($r^2 = 0.69$) *was die een met die formule* $ISI = (2A + 3B + 2C)/7$, *waar A B en C die SI waardes is vir die drie groeiperiodes. Die vergelyking om biomassa te voorspel van ISI is* $Yb = 15238\ ISI + 1067$ *kg totale biomassa per ha.*

Die genoemde vergelyking, saam met langtermyn klimaatdata om ISI waardes te bepaal, is gebruik om mielieopbrengste vir 80 seisoene (1922/23 – 2001/02) te simuleer. Yb is omgesit na graanmassa met behulp van 'n oesindeks regressievergelyking gebasseer op 38 oesresultate by Glen waar albei totale biomassa en graanmassa bepaal is. Vier produksietegnieke is vergelyk, naamlik, (a) plant in November met konvensionele bewerking (CTN); (b) plant in Januarie met konvensionele bewerking (CTJ); (c) plant in November met in-land afloopopgaring met bakkiesbewerking (WHBN); (d) plant in Januarie met in-land afloopopgaring met bakkiesbewerking (WHBJ). Kumulatiewe waarskynlikheidsfunksies (CPF's) van graanopbrengs is bereken vir elke produksietegniek. Die volgende resultate is verkry: langtermyn gemiddelde graanopbrengste vir die vier behandelings met 'n 50% waarskynlikheid was 2653, 2685, 3108 en 3355 kg ha^{-1} *vir CTN, CTJ, WHBN en WHBJ respektiewelik. Die CPF's is statisties vergelyk deur middel van die stogastiese dominancy en Kolmogorov-Smirnov (K-S) toetse (Anderson et al., 1977: Steel et al., 1997). Eersgenoemde toets het aangedui dat WHBJ en WHBN goed gedefineerde eerste orde stogastiese dominansie het oor CTN en CTJ, met die Januarie-plant behandelings slegs met tweede orde stogastiese dominansie oor die November-plant behandelings. Die K-S toets het aangedui dat die twee WHB tegnieke statisties betekenisvol beter was as die twee CT tegnieke, maar dat daar geen betekenisvolle verskille was tussen die Januarie-plant en November-plant behandelings nie.*

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LIST OF SYMBOLS AND ABBREVIATIONS

α	slope of the curve for $\sum E$ vs $t^{1/2}$ for stage 2 soil evaporation; level of confidence in statistical tests
AI	aridity index (rainfall/evaporation)
a.m.s.l.	above mean sea level
ARC	Agricultural Research Council
ARC-ISCW	Agricultural Research Council – Institute for Soil, Climate and Water
CEC	cation exchange capacity
Cl	clay content
CMUL	crop modified upper limit of plant available water
co	coarse (particle size fraction)
CPF	cumulative probability function
CR	count ratio
CV	coefficient of variation
CR_{max}	maximum observed count ratio
CTJ	production technique employing conventional tillage and January planting
CTN	November planting with conventional tillage
CV	coefficient of variation
ΔS	seasonal change in root zone water content ($\theta p - \theta h$)
D	deep drainage
D-index	Willmott index of agreement
Dr	drainage rate
DSSAT3	Decision Support System of Agrotechnology Transfer – version 3
D-statistic	maximum vertical deviation between two CPF graphs
DUL	drained upper limit of plant available water
$d\theta r/dt$	drainage rate at any point on the drainage curve
E	evaporation from the soil surface
E_1	evaporation from the soil surface during the first stage
E_2	evaporation from the soil surface during the second stage
Eo	potential evaporation
Eot	total potential evaporation for the whole growing season
ET	evapotranspiration
ETc	crop evapotranspiration under standard conditions
ETc adj.	ETc corrected for the water stress effects
ETo	reference evapotranspiration
ETr	evapotranspiration rate
ETt	total crop evapotranspiration for the whole growing season
fi	fine (particle size fraction)
FMS	first material stress
fSat	soil water content at field saturation
FSD	first-degree stochastic dominance
IBSNAT	International Benchmark Sites for Agrotechnology Transfer
ISI	integrated stress index
Kc	crop coefficient
K-S	Kolmogorov-Smirnov (statistical test)
Ks	water stress coefficient

LL	and the lower limit of plant available water
Lm	loam
MAE	mean absolute error
MAP	mean annual precipitation
me	medium (particle size fraction)
NWM	neutron water meter
ND	not determined
θ	volumetric soil water content
θh	soil water content at harvest
θm	gravimetric soil water content
θp	soil water content at planting
θr	root zone water content
ot	orthic A horizon
P	precipitation
ρ_b	bulk density
PAW	plant available water
Pe	effective precipitation
R	surface runoff
r^2	coefficient of determination
RAW	(plant) readily available soil water (DUL – FMS)
re	red apedal B horizon
RMSE	root mean square error
RMSEs	systematic root mean square error
RMSEu	unsystematic root mean square error
S value	the sum of exchangeable Na, K, Mg, and Ca ions
S	standard NWM readings
Sa	sand fraction
Si	silt content
SI	stress index (ET/Eo)
SPAC	soil-plant-atmosphere continuum
SS	root zone soil water content at which serious stress begins
SSD	second-degree stochastic dominance
SWAMP	Soil Water Management Program
TST	total soil tillage
TSTM	total soil tillage with mulch in the 1 m crop rows
vf	very fine (particle size fraction)
WHB	water harvesting with basins
WHBM	water harvesting with mulch between the basins
WHBN	November planting with in-field water harvesting and basin tillage
WHBJ	January planting with water harvesting and basin tillage
WRC	Water Research Commission
χ^2	goodness-of-fit
Yb	total above ground biomass
Yg	grain yield

CHAPTER 1
MOTIVATION AND OBJECTIVES

1.1 Motivation

Efficient land evaluation is important in every country, firstly because it leads to wise land use, which ensures sustainable use of the natural resources, and secondly because it promotes efficient planning with regard to the balance between food supply and demand and therefore facilitates the avoidance of food shortages. In the arid and semi-arid areas of Africa the lack of food security is a serious issue. Frequent droughts often seriously threaten people in these areas. In 2002 alone, tens of millions of people in eastern Africa as well as in southern Africa have been seriously affected by a lack of sufficient food. Quantitative knowledge of the agricultural resources, and their limitations, is a key tool for efficient planning and to counteract the impact of such catastrophic events. In these arid and semi-arid areas research focused on sound agricultural water management practices is highly needed. This can best be done with the help of computer models to predict yields from long-term climate data.

Quantitative evaluation of the production potential of an agricultural system is often accomplished in the form of long-term yield prediction using historical climate data with the help of computer models (Van Diepen *et al.*, 1991; Hensley, 1995b). Long-term yield prediction has the advantage that it is objective, quantitative and replicatable. Using this procedure it is possible to compare the productivity of different ecotopes, or different production techniques on the same ecotope (see Section 2.2.1 for the definition of an ecotope). The result of long-term yield prediction can efficiently be presented in the form of cumulative probability functions (CPF's) (Muchow *et al.*, 1991). This takes into account the effect of climatic variations on crop yield and provides a quantitative assessment of risk, which aids in making economic analyses.

The Glen Agricultural Research Station is situated in a semi-arid area with a population of at least 750 000 people within a 70 km radius. The staple food of most of these people is maize meal. Sustainable food production is therefore important and the best possible production techniques need to be employed. Because of the large annual variation in rainfall and therefore in yields, long-term yield data are essential for reliable assessment of production potential. The focus in any production system therefore needs to be on water conservation. With this in mind, it was decided to assess the production potential and production techniques for two ecotopes at the Glen experimental station in the Free State province of South Africa.

1.2 Objectives

The following hypothesis was formulated:

> It is possible to quantitatively evaluate the maize production potential of semi-arid ecotopes at Glen by making long-term yield predictions using a yield prediction computer model and long-term climate data.

To test the hypothesis, the following major objectives were set:

(i) To characterize the natural agricultural resources of the Glen/Hutton and Glen/Oakleaf ecotopes.

(ii) To develop a yield prediction procedure for maize production on these ecotopes.

(iii) To predict long-term maize yields for these ecotopes, using the selected production techniques.

(iv) To construct cumulative probability functions of maize yields on the selected ecotopes using different production techniques, and to use these to define maize production potential.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

In this chapter the nature of the agricultural resources, procedures for estimating the components of the soil water balance, and the application of computer models in this regard will be discussed. In the first section, the land type data of South Africa, and specifically the land type on which this research was conducted, will be described. The state of crop growth modelling, with special emphasis on water balance models, their application in making quantitative assessments of crop production and the risks associated with it, will be discussed in the second section. The final section will discuss some of the most prominent endeavours in estimating the components of the soil water balance and the problems they faced. This section will be given a stronger emphasis.

2.2 Natural resource data

2.2.1 Factors affecting agricultural productivity

Crop production takes place in the soil-plant-atmosphere continuum (SPAC). Plant growth and yield potential is, therefore, controlled by the soil, crop, and atmospheric characteristics, in addition to the management practices. Havlin *et al.* (1999) indicated that more than 50 factors affect productivity (Table 2.1). Many of these factors can be managed by the producer. Management practices need to focus on the identification and elimination of the yield limiting factor(s), where possible. All the natural resource factors affecting productivity can be grouped into three major factors namely climate, soil and topography. An area of land within which these factors are reasonably uniform is referred to as an ecotope (MacVicar *et al.*, 1974). Recently, Van der Watt and Van Rooyen (1995) defined an ecotope as follows: "A particular habitat in a region. Used in South Africa for a class of land within which the variation of natural resources is insufficient to influence significantly the agricultural products that can be produced on it, their potential yield (both quality and quantity) and the required production techniques." An ecotope may thus be considered as a three-dimensional extension of the SPAC. It is, therefore an appropriate unit for productivity evaluation as all the natural resource factors which determine productivity are, for practical purposes, homogeneous within its boundaries (Hensley, 1995a).

Table 2.1 Factors controlling crop production and yield (Havlin *et al.*, 1999).

Climate Factors	**Soil Factors**	**Crop Factors**
Precipitation	Organic matter	Crop species/variety
Quantity	Texture	Planting date
Distribution	Structure	Seeding rate and geometry
Air temperature	CEC	Row spacing
Relative humidity	Base saturation	Seed quality
Light	Slope and topography	Evapotranspiration
Quantity	Soil temperature	Water availability
Intensity	Soil management factors	Nutrition
Duration	Tillage	Pests
Altitude/Latitude	Drainage	Insects
Wind	Rooting depth	Diseases
Velocity		Weeds
Distribution		Harvest efficiency
CO_2 concentration		

2.2.2 Land type data

In South Africa, data on the land resources that determine agricultural productivity is available in the form of land type data (Land Type Survey Staff, 2000). A land type, as defined by Van der Watt and Van Rooyen (1995) is: "A class of land with specified characteristics. Used in South Africa as a map unit denoting land, mappable at 1:250 000 scale, over which there is a marked uniformity of climate, terrain form, and soil pattern." A land type is thus composed of one or more ecotopes. The aim of the land type survey in South Africa was to make a systematic inventory of the natural agricultural resources of the country.

The survey was carried out in the following manner: Each land area, covered by a 1:250 000 map, was surveyed in a stepwise fashion on each of its component 1:50 000 maps. First, areas displaying a marked uniformity of terrain form (called terrain types) were delineated based on existing information, maps, and, where available, satellite imagery. The major soils in each terrain type were then identified by traversing each terrain type, augering and observing exposures such as road cuttings and digging occasional soil pits. From this information areas displaying a uniform terrain and soil pattern (called pedosystems) were delineated. Modal profiles, representing a range of soils, were described and sampled for detailed analyses. Next, a separate map showing the distribution of climate zones was drawn based on data from available climate stations, natural vegetation, soils, crop performance, altitude and topography. The climate map was superimposed upon the pedosystem map to produce a land type map, where each land type displays a marked uniformity in terms of terrain, soil pattern and climate. The boundaries of the land types were transferred from the 1:50 000 to 1:250 000 maps. Finally, an inventory of each land type was compiled to describe the terrain, soil and climate (Land Type Survey Staff, 2000).

The land type data, which is available in the form of paper copy maps and memoirs as well as in GIS format, includes the following:

(i) Delineations of land types at a scale of 1:250 000.
(ii) Descriptions (called inventories) of the terrain and soil pattern in each terrain unit.
(iii) Detailed soil profile descriptions and detailed soil analyses of representative soil profiles (called modal profiles).
(iv) Detailed descriptions of the climate of each land type.

2.2.2.1 Soil and terrain inventory

The description of each land type is given in a soil and terrain inventory. An example of a soil and terrain inventory is given in Table 2.2. The inventory includes the land type number, the climate zone in which the land type occurs and the modal profiles described within the land type. The geology, soils, and terrain form of the land type is also described. For each land type, the approximate land area available for agriculture (and that which is not), is given. Land available for agriculture is described in terms of slope and the presence or absence of mechanical limitations. The soils in each terrain unit are described at series level (MacVicar *et al.*, 1977). More than one soil series may occur on a terrain unit. The soils are described as follows: For example, reading from left to right in Table 2.2 for the Bonheim and Glengazi series: 100 – 300 mm deep to depth limiting material; there are no mechanical limitations; 1 541 ha (5%) of these soils are located on terrain unit 3 and 5 425 ha (8%) are located on terrain unit 4; these soils occupy 5.7% or 6 966 ha of the whole land type; the clay percentages range between 35% and 45% in the A horizon and between 40% and 50% in the B21 horizon; the texture class of the A horizon is fine sandy clay and the depth limiting material is non-red structured materials.

Table 2.2 An example of the soil and terrain form inventory in the land type data (Land Type Survey Staff, 2000).

LAND TYPE : **Ea39**
CLIMATE ZONE : **45S**
Area : **123300 ha**

Occurrence (maps) and areas:
2826 Kimberley (12050 ha) **2826 Winburg (30780 ha)**
2926 Koffiefontein (27980 ha) **2926 Bloemfontein (19460 ha)**

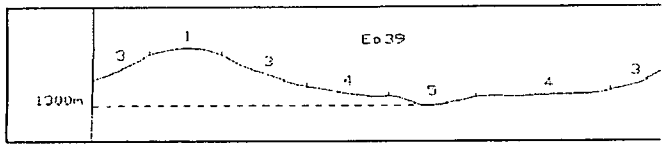
Inventory by:
J F Eloff & A T P Bennie
Modal Profiles:
P470 P471 P593 P594

Estimated area unavailable for agriculture: **20000 ha**

Terrain unit		1	3	4	5
% of land type	:	10	25	55	10
Area (ha)	:	12330	30825	67815	12330
Slope (%)	:	0-2	3-60	1-2	0-2
Slope length (m)	:	100-800	200-1000	200-1200	100-500
Slope shape	:	Z	Z-Y	Z	X-Z
MB0, MB1 (ha)	:	0	13255	67137	10480
MB2 - MB4 (ha)	:	12330	17570	678	1850

Soil series or land classes	Depth	MB :	ha	%	ha	%	ha	%	ha	%	Total ha	%	Clay content (%) A	E	B21	Hor	Texture Class	Depth limiting Material
Soil-rock complex :	(mm)																	
Rock		4:	8631	70	11714	38					20344	16.5						
Mispah Ms10, Williamson Gs16,		:																
Shorrocks Hu36,	100-250	3:	1850	15	1541	5					3391	2.8	10-18		15-20	A	LmfiSa-SaLm	R,so
Milkwood Mw11, Glengazi Bo31	300-600	3:	986	8	1850	6					2836	2.3	35-55		40-55	A	fiSaCl	R,vp
Swartland Sw31,		:																R,so
Sterkspruit Ss26,		:																R
Glendale Sd21	100-250	3:	863	7	1541	5					2404	2.0	10-15		35-45	B	fiSaCl	Vp,pr,R
Milkwood Mw11,Grythorne	300-900	0:			2158	7	18988	28	986	8	22132	18.0	45-55			A	FfSaCl-Cl	R
Mw21																		
Gelykvlakte Ar20	300-1200	0:			1233	4	14919	22	863	7	17015	13.8	45-55			A	fiSaCl-Cl	so
Waterval Va11,Carven Va21	100-350	0:					13563	20	5687	18	13563	11.0	8-15		35-45	B	fiSaCl	vr
Rasheni Bo21	100-300	0:			1850	6	5425	8			7275	5.9	35-40		40-50	A	fiSaCl	Vr
Bonheim Bo41,Glengazi Bo31	100-300	0:			1541	5	5425	8			6966	5.7	35-45		40-50	A	fiSaCl	vp
Dundee Du10, Limpopo Oa46,	>1200	0:							5302	43	5302	4.3	15-35			A	fisaLm-SaClLm	
Mutale Oa47																		
Kinross Sd20, Glendale Sd21	100-300	0:			1850	6	3391	5			5240	4.3	10-15		30-45	B	fiSaClLm-SaCl	So
Swaerskloof Ss 16,																		
Sterkspruit Ss26,																		
Skilderkrans Sw11																		
Broekspruit Sw21	100-250	0:			2158	7	2713	4			4870	4.0	10-15		35-45	B	fiSaCl	Pr, vr
Shorrocks Hu36, Mangano Hu33	300-1000	0:			2466	8	2034	3			4500	3.7	6-15		12-20	B	LmfiSa-SaLm	R
Lindely Va41, Ariston Va31	100-350	0:					678	1	2713	22	3391	2.8	10-18		40-55	B	fiSaCl-cl	vp
Mispah Ms10,Williamson Gs	100-250	3:			925	3	678	1			1603	1.3	10-18			A	Lmfisa-SaLm	R,so
Rensburg Rg20	300-900	0:							616	5	616	0.5	45-55			A	fiSaCl-Cl	G
Stream beds		4:									1850	15						

Terrain type : A2
Terrain form sketch



For an explanation of this table consult LAND TYPE INVENTORY (table of contents)

Geology: Sandsone, shale and mudstone of the beaufort Group, with dolerite intrusions.

2.2.2.2 Climate data

Climate is described in terms of 6 rainfall parameters, A-Pan evaporation, 8 temperature parameters, and 6 frost parameters. Data was only recorded where it was available. Monthly average rainfall and temperature data was included for all climate zones (Land Type Survey Staff, 2000).

Such information is valuable in crop productivity evaluation. Once the evaluation is made for the soil plant atmosphere continuum, it can safely be applied to the whole area, occupied by the same soil series and within the same terrain unit, because the climate is uniform. The reliability and level of detail of the land type data should, however, be viewed in context with its mode of collection.

2.3 Crop growth modelling

2.3.1 General aspects

Monteith (1996) defines a crop model as "a quantitative scheme for predicting the growth, development and yield of a crop". Previously De Wit (1982) described the terms 'system', 'model', and 'simulation' as follows: "A system is a limited part of reality that contains interrelated elements; a model is a simplified representation of a system; and simulation is the art of building mathematical models and the study of their properties in reference to those of the systems". Crop models have evolved over the last 40 years (Angus, 1991; Sinclair and Seligman, 1996). Sinclair and Seligman (1996) described the developmental stages of models as follows: an infancy stage where models promised to provide a substitute for field experimentation; a juvenile stage where models grew more and more complex, accompanied by computer sophistication; an adolescence stage characterized by intense activity, confusion, and excessive confidence, sometimes challenged by doubt; and finally the possibly emerging maturity stage where expectations will become adjusted to reality.

Crop models are often divided into two categories: mechanistic (also called theoretical or scientific models), and empirical (functional or engineering) models (Monteith, 1996; Passioura, 1996; Poluektov and Topaj, 2001). Mechanistic models are theoretical, composed of a series of equations that describe the crop and environmental processes based on physical and physiological principles. Empirical models, on the other hand, are based on observed relationships between plant behaviour and the major environmental variables. Both approaches have advantages and disadvantages. A reliable mechanistic model should be applicable under any conditions, irrespective of the conditions of its adjustment and validation. However, it may be very difficult to integrate all of the processes in the soil-plant-atmosphere system in a single mechanistic model. Besides, not all processes in the system have been sufficiently studied. Consequently, most mechanistic models often involve speculation about the processes (Passioura, 1996). This fact lead Poluektov and Topaj (2001) to recommend that mechanistic models should focus on the honest and detailed description of partial processes of the system. The most noticeable problem with empirical models is that they cannot be applied outside the range of environmental variables in which they were calibrated. Within their area of calibration, however, they often provide sound management advice (Passioura, 1996).

2.3.2 Applicability and performance of crop growth models

Crop growth models can potentially be very valuable in understanding research, crop management and policy questions (Boote *et al.*, 1996). In dryland agricultural areas, where productivity greatly depends on the vagaries of rainfall, short-term yield estimations may not give reliable results. This is because productivity variations from season to season, which are caused by climate changes, especially rainfall, are not reflected. Crop models, on the other hand, can help to make long-term yield estimations based on historical climate data.

Long-term simulated yield results are often displayed in the form of cumulative probability functions (CPF's) of yield. A CPF of long-term yields is generated for each crop-ecotope combination under specified management practices. From the CPF graphs, the best crop-ecotope combination and management option can be selected based on statistical analyses (Anderson *et al.*, 1977; Boehlje and Eidman, 1984; Steel *et al.*, 1997). Moreover, since the results are expressed as probabilities, they provide a quantitative assessment of risk and, therefore, they can be utilized by agricultural economists (Hensley, 1995b).

Prior to using crop growth models to evaluate productivity, they need to be calibrated and validated against measured data, generated under similar environmental and management conditions (Hensley, 1995b). Model performance can be tested using statistical indices. Willmott (1982) recommended that the differences between the predicted and the observed values be measured and that the index of agreement (D-index) be computed, interpreted and reported for appropriate evaluation of model performance. Statistical difference measures include the root mean square error (RMSE), along with its systematic (RMSEs) and unsystematic (RMSEu) components, and the mean absolute error (MAE).

According to Willmott (1982), a "good" model RMSEs should approach 0, while the D-index should approach 1.0. A large RMSEs indicates bias. The RMSEu should therefore be as close as possible to RMSE, indicating that the deviations of the predicted from the observed values are random. Approximate guidelines for the statistical indices for model performance were reported by Walker *et al.* (2002). According to these researchers, a good agreement is indicated by RMSEs less than 65% of RMSE, a D-index larger than 0.8, and r^2 larger than 0.8; deviations from these indicate less satisfactory agreement.

2.3.3 Examples of crop modelling applications

Despite the failure of many crop growth models to simulate biological systems (Passioura, 1996), a number of models have been developed and applied in the field of agronomy over the past several decades. Examples include the DSSAT (Tsuji *et al.*, 1994) and PUTU (Anderson, 1997) families of models as well as the more recent SWAMP model (Bennie *et al.*, 1998).

The acronym DSSAT stands for Decision Support System for Agrotechnology Transfer. DSSAT was first developed by the International Benchmark Sites for Agrotechnology Transfer (IBSNAT) Project (Tsuji *et al.*, 1994). The support system consists of (a) a database management system to enter, store and retrieve the "minimum data set" needed to validate and operate crop models; (b) validated crop models capable of simulating processes and outcomes of genotype, environment and management interactions; and (c) application programmes for analyzing and displaying outcomes of long-term simulated agronomic experiments (Tsuji *et al.*, 1994).

PUTU includes a family of mechanistic crop models first developed in South Africa during 1973. Since then the models have continuously been modified and new models have been added to accommodate more crops (Anderson, 1997).

Hensley *et al.* (1997) applied the DSSAT3 and PUTU maize and wheat models to generate CPF graphs of long-term yields on 8 ecotopes in South Africa. Figure 2.1 shows the CPF graphs for the Bethal/Hutton ecotope. The mean annual precipitation (MAP) is 680 mm. Four separate simulations were made by each model assuming four different initial soil water contents (full, ¾, ½, or ¼ of the drained upper limit (DUL)). This was done because the soil water contents at the beginning of the growing season, and therefore the simulation, was not known. Results for both models indicated that knowledge of the initial soil water content is important, especially at cumulative probabilities below 0.8. The CPF's for the DSSAT3 graph show that the lowest maize yield would be about 2 t ha^{-1} planting at ¼ full, about 3.5 t ha^{-1} at ½ full, 5 t ha^{-1} at ¾ full, and about 5.5 t ha^{-1} with the root zone at DUL. The PUTU model predicted similar yields but at higher probabilities of non-exceedance. The impact of initial water content seems to be more pronounced with DSSAT3 than with PUTU. DSSAT3 also generally predicted higher yields than PUTU. The inconsistency between the two models indicates that either both or one of the models has shortcomings.

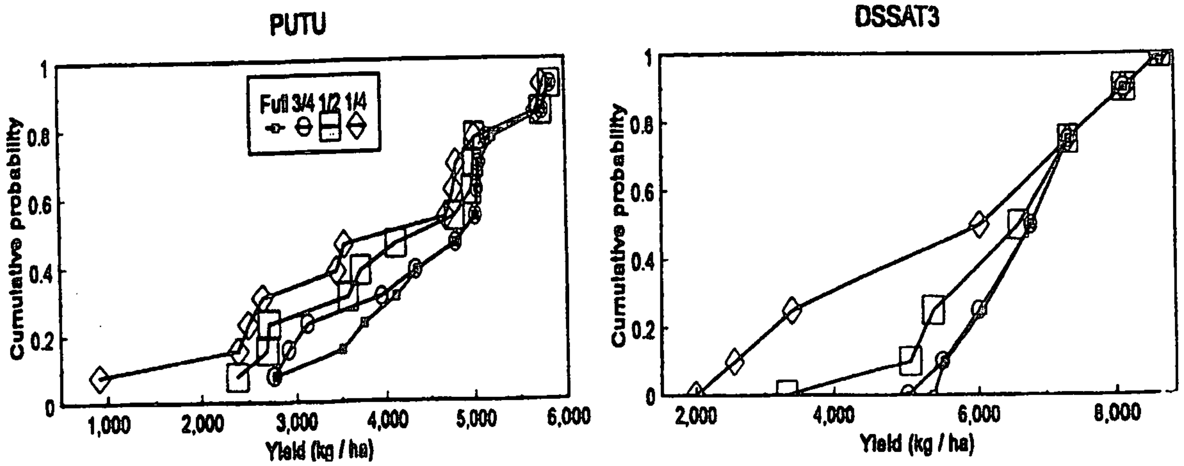


Figure 2.1 CPF graphs of long-term maize yields generated by the PUTU and DSSAT3 models on the Bethal/Hutton ecotope (Hensley *et al.*, 1997).

In a more recent study, Hensley *et al.* (2000) applied the DSSAT3 model to make long-term maize yield predictions for different production techniques in a semi-arid area in South Africa. Maize grain yield CPF graphs calculated for the Glen/Swartland-Rouxville ecotope based on 18 years of climate data are given in Figure 2.2. The mean annual precipitation of the ecotope is 545 mm. The different production techniques were: total soil tillage (TST), total soil tillage with mulch in the 1 m crop rows (TSTM), water harvesting with basins (WHB) – see Figure 6.1, and water harvesting with mulch between the basins (WHBM). The notation A indicates annual planting. The CPF graphs clearly show that water harvesting with or without basins results in higher yields than total soil tillage with or without basins. The importance of mulching is only slightly demonstrated at yield levels above 3.5 t ha^{-1} for the WHB treatments and above 3 t ha^{-1} for the TST treatments. The researchers suspected that this might be due to difficulty in modelling the benefit obtained from mulching.

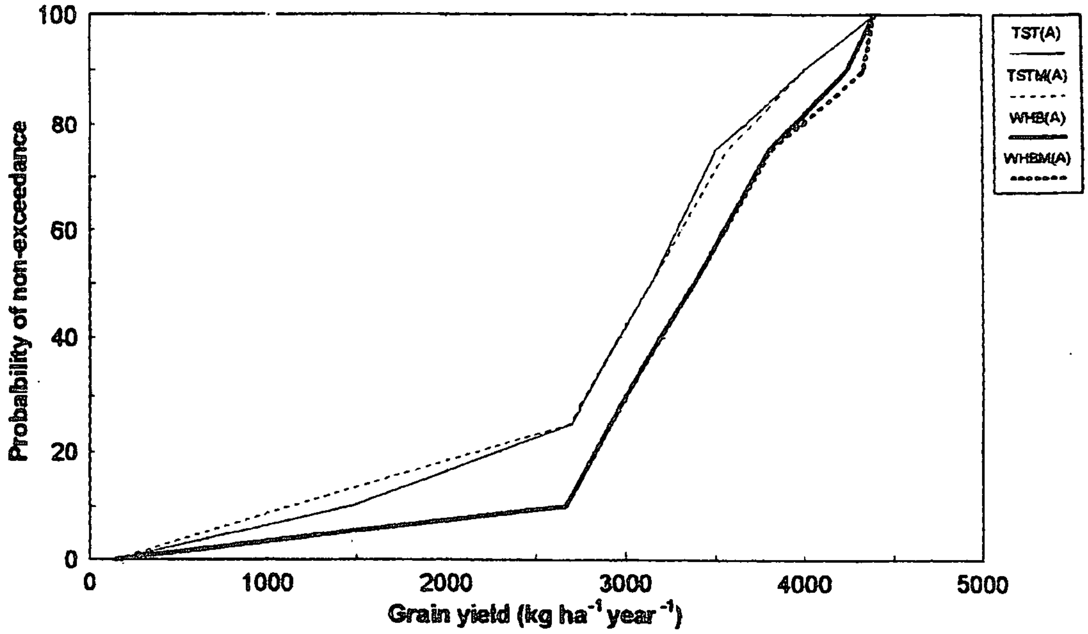


Figure 2.2 CPF graphs of long-term maize yields on the Glen/Swartland–Rouxville ecotope (Hensley *et al.*, 2000).

Monteith and Vermani (1991) used the SORGF model in India and obtained sorghum yield CPF's as shown in Figure 2.3. Probabilities were based on climate data over a 30 year period. The mean annual precipitation increases from 530 mm at Antapur to 1 000 mm at Indore. As indicated by Figure2.3, the expected yield at the four sites at 50% probability (and hence 50% risk level) are approximately 2.5, 4.5, 6.0, and 6.5 t ha^{-1}, respectively. The steep vertical lines in the case of Patancheru and Indore indicate that yields of 4.5 and 6.5 t ha^{-1} can virtually always be attained at these sites. The same researchers, using their RESCAP model tested the productivity of sorghum at Sholapur on three soils with different plant available water capacities (PAWC). The MAP is 684 mm. CPF's of the predicted sorghum yields are given in Figure 2.4. The importance of PAW at risk levels above 30% is clearly demonstrated. The CPF's indicate that at a probability of 50% the expected yields on the three soils are approximately 2, 3, and 3.5 t ha^{-1}, respectively.

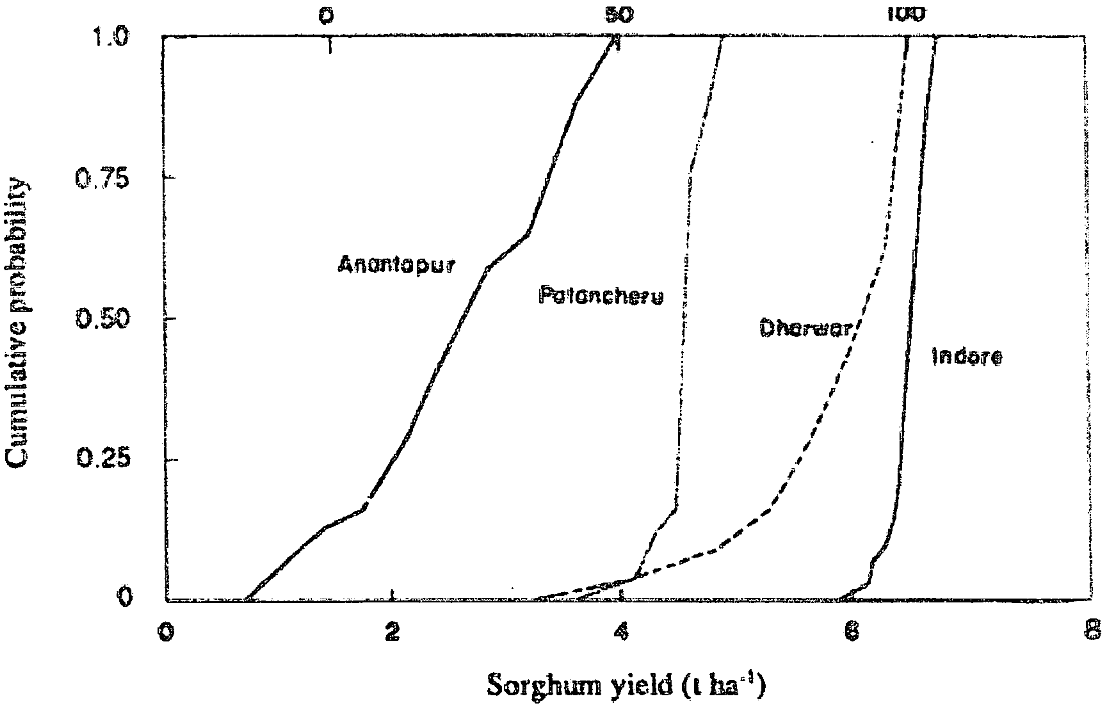


Figure 2.3 CPF graphs for sorghum yields at Antapur (MAP = 530 mm), Patancheru (MAP = 790 mm), Dharwar (MAP = 890 mm) and Indore (MAP = 1000 mm) (Monteith and Vermani, 1991).

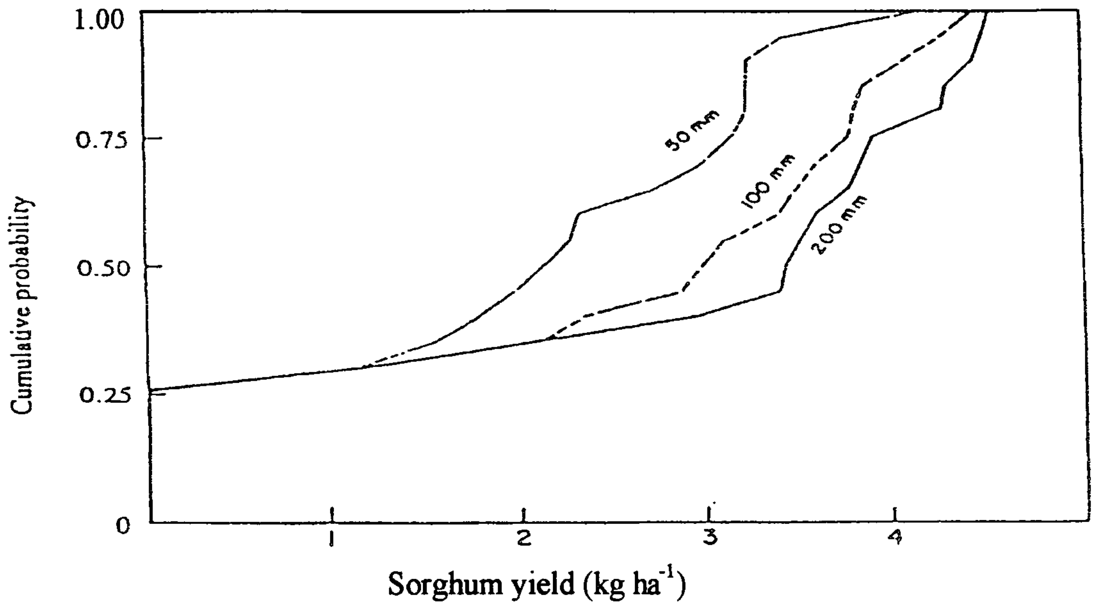


Figure 2.4 CPF graphs for sorghum grain yields at Sholaphur (MAP = 684 mm) for three values of total plant available water (Monteith and Vermani, 1991).

Muchow *et al.* (1991) used a crop model to assist in the choice between growing maize or sorghum in the semi-arid tropics of Australia. The mean annual rainfall is 948 mm with a coefficient of variation of 25%. CPF's of the predicted yields based on climate data over 100 years are presented in Figure 2.5. The graphs indicate that for low risk levels, *i.e.* below about 30%, sorghum was the more favourable crop, but that for less risk sensitive farmers maize was more favourable than sorghum.

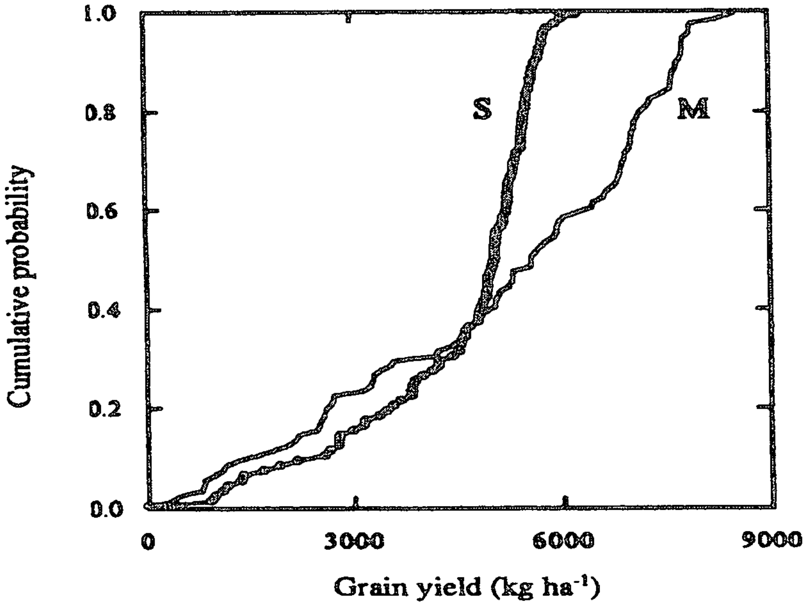


Figure 2.5 CPF graphs for grain yield of maize (M) and sorghum (S) at Katherine (MAP = 984), Australia (Muchow *et al.*, 1991).

2.3.4 The SWAMP model

The Soil Water Management Program (SWAMP) is a software package developed by the Department of Soil Science, University of Orange Free State (Bennie *et al.*, 1998). Its development was based on research results and practical experience in agricultural water management under dryland crop production conditions accumulated since 1975. SWAMP incorporates estimation procedures for the evaporation of water from the soil surface, runoff, water use by crops at specific target yields, and water loss by drainage below the root zone. The data required to run the model includes soil depth, texture, rainfall, an estimate of the root zone water content at planting, and target yield. SWAMP attempts to estimate the amount of rain stored in the soil during the fallow period. It can be used to calculate the expected yield from the stored plant available water in the soil at planting plus the expected rainfall during the growing season. It does this via the soil water balance equation (Section 2.4), and by converting the water available for evapotranspiration (ET) into daily yield gain. Results are based on the empirical relationship between maximum biomass production and maximum ET, determined from research results over a number of years in semi-arid ecotopes in the Free State Province. Figure 2.6 shows the relationship between evapotranspiration, maize grain yield and biomass production. This relationship is empirical and should only be applied to environmental conditions similar to those under which the model was developed. As indicated by the r values (Figure 2.6), the accuracy of prediction of the model can at most be 82% for maize grain yield and 69% for biomass production for a particular ecotope. Despite such limitations SWAMP is an easy-to-use, practical model (Bennie *et al.*, 1994; Bennie *et al.*, 1998).

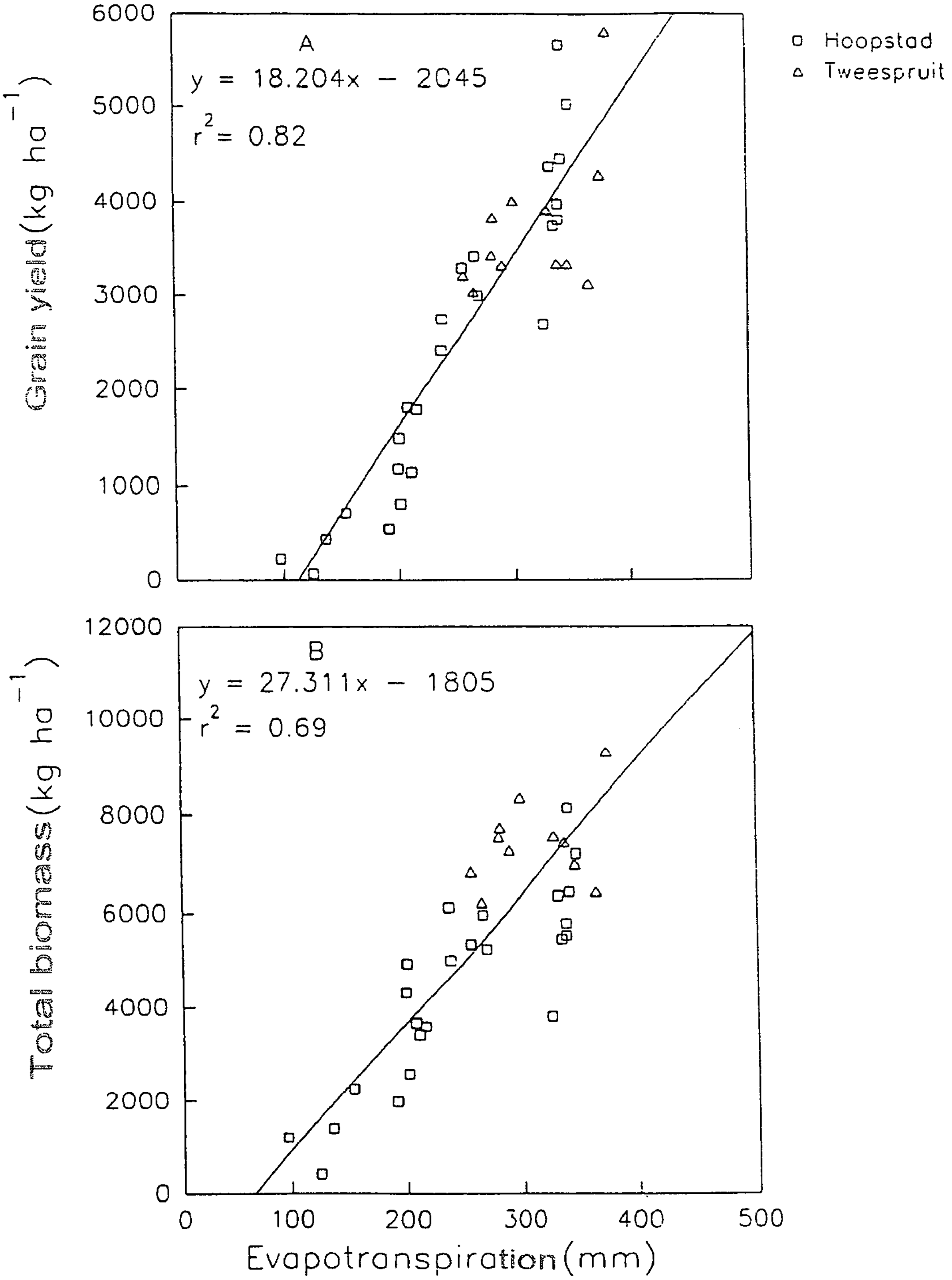


Figure 2.6 The relationship between evapotranspiration and the grain yield (A) and total biomass (B) of maize in the Hoopstad and Tweespruit ecotopes, Free State (Bennie *et al.*, 1994).

2.4 The soil water balance

2.4.1 Introduction

In dryland agriculture, water is the most important production limiting factor. Bennie *et al.* (1998) indicated that for sustainable dryland crop production the capture and efficient utilization of rainfall should be maximized. The soil water balance for dryland agriculture in semi-arid areas, in its simplest form for the growing season, can be expressed as follows (Hensley *et al.*, 1997):

$$T = (P \pm \Delta S) - (E + R + D) \tag{2.1}$$

$$\text{water for yield} = \text{water gains - water losses}$$

where
T = transpiration (mm)
P = precipitation (mm)
ΔS = water extracted from the root zone (mm)
E = evaporation from the soil (mm)
R = runoff (mm)
D = deep drainage (mm)

From Equation 2.1 it is clear that increasing the water gains and decreasing the water losses leaves more plant available water. Precipitation is beyond the control of the farmer. However, knowledge of long-term precipitation characteristics of an area, from measured (or extrapolated) climatic data, is crucial in predicting the risk of dry land crop production. Determination of the plant extractable root zone water content (ΔS), which is the difference in root zone water contents at planting and at harvest for a particular season, needs determination of the soil water limits. Estimation procedures for these limits and the other components (E, R, and D) are discussed below.

2.4.2 Plant available water

Plant available water (PAW) refers to the amount of water a soil profile can hold in a form that is accessible to the plant. Meinke *et al.* (1993) defined plant available soil water as the sum, for all layers within the plant rooting depth, of the difference between the volumetric water content at drained upper limit and the lower limit of plant available water. Knowledge of PAW therefore requires prior determination of the upper and lower limits.

2.4.2.1 Upper limit of plant available water

2.4.2.1.1 Drained upper limit (DUL)

Ratliff *et al.* (1983) defined DUL as: "The highest field-measured water content of a soil after it has been thoroughly wetted and allowed to drain until drainage becomes practically negligible *i.e.* when the water content decrease in the soil profile was about 0.1 to 0.2% of the water content per day". The drained upper limit, as defined here, is exclusively controlled by the water holding properties of the soil profile within a defined depth. The defined depth is determined by the crop rooting depth. DUL, therefore, depends on the soil texture, porosity, organic matter content and thickness of each of the horizons in a soil profile which constitute the specified rooting depth (Boedt and Laker, 1985).

Drained upper limit is measured in the field by thoroughly wetting a plot of about 3 m x 3 m, and measuring the water content throughout the root zone at time intervals until the decrease in water content becomes negligible. Evaporation loss from the plot is prevented by covering the plot with a plastic sheet (Hensley *et al.*, 1993).

There have been several endeavours to develop generic regression equations to estimate DUL, based on soil analytical data. Examples of such equations are given below.

a) Hutson (1983) developed Equation 2.2 based on water retention data for a large number of South African soils.

$$\theta_{-10} = 0.0558 + 0.0037\,\mathrm{Cl} + 0.0055\,\mathrm{Si} + 0.0303\,\rho_b \qquad (r^2 = 0.68) \qquad (2.2)$$

where θ_{-10} is the volumetric soil water content ($m^3\ m^{-3}$) at a soil water potential of −10 kPa, considered to represent "field water capacity", Cl and Si are clay and silt contents in %, and ρ_b is the bulk density ($Mg\ m^{-3}$).

b) Bennie *et al.* (1994) developed Equation 2.3 based on measurements of different soils in South Africa, mainly fairly coarse textured soils in the Free State province.

$$\theta = 0.0037\,(Si + Cl) + 0.139 \qquad (2.3)$$

where θ is the volumetric soil water content ($m^3\ m^{-3}$), Si and Cl are as defined in Equation 2.2.

c) Ritchie *et al.* (1999), using measured DUL data from 312 soils in the USA, developed the following equations:

$$\theta m = 0.186\,(Sa/Cl)^{-0.141} \qquad (2.4)$$

where θm is the gravimetric soil water content ($kg\ kg^{-1}$) at DUL for a particular horizon, and Sa and Cl are sand and clay contents (%), respectively. Equation 2.5 is then used to determine the volumetric water content (θ, $m^3\ m^{-3}$) at DUL for the specified layer.

$$\theta = \theta m \rho_b / \rho_w \qquad (2.5)$$

where ρ_w is the density of water ($Mg\ m^{-3}$), and the other symbols remain as defined for the previous equations.

The above equations were used to estimate DUL for ten South African soils, for which field measured DUL values are available. Results are presented in Appendix A. Measured DUL values and the soil analytical data were obtained from Hensley (1991), Bennie *et al.* (1994), Hensley *et al.* (1997), and Hensley *et al.* (2000). In the source data the measured DUL values were available in 300 mm depth intervals. To make meaningful comparisons the measured DUL values were recalculated as follows: The estimated DUL (mm) values for each horizon were obtained by multiplying the respective volumetric soil water content ($m^3\ m^{-3}$) by the depth (mm) of each horizon. Measured DUL values for soils 8, 9 & 10 in Appendix A were available only as totals for the profiles. Bulk density and cation exchange capacity (CEC) values for the latter were also not available. To make DUL estimates of these soils using the Hutson (1983) and Ritchie *et al.* (1999) equations an estimated average bulk density value of 1.65 $Mg\ m^{-3}$ was used.

The equation by Ritchie *et al.* (1999), which was developed for soils in the United States of America, showed considerable inconsistency compared to the measured values. The estimated DUL values were: considerably higher than the measured values for sandy soils (1, 2, 3 & 9); closer to the measured values for less sandy soils (8 & 10); and considerably lower than the measured values for medium textured to clayey soils (4, 5, 6 & 7). The equation by Bennie *et al.* (1994), which considers only the silt and clay contents, gave considerably higher values than the measured ones for all the soils except for the soils in which it was developed (soils 8, 9 & 10). Hutson's (1983) equation, which takes the bulk density into consideration in addition to the silt and clay contents, gave values closer to the measured values for the fine-textured soils (5, 6 & 7). However, it gave considerably higher values for soils 1 to 4 and considerably lower values for soils 8 to 10.

Streuderst (1985) developed Equation 2.6 to estimate DUL for freely drained medium textured soils.

$$Y = 0.1243 + 0.0053\, X_1 - 0.0098\, X_2^{1/2} \qquad (2.6)$$

where: Y = volumetric soil water content ($m^3\ m^{-3}$)
X_1 = cation exchange capacity ($\text{cmol}_c/\text{kg}^{-1}$) plus clay content (%)
X_2 = very fine sand plus clay content (%)

Using this equation, the DUL values would be 256, 365, 424, 413, 466, 475 & 581 for soils 1 through 7 in Appendix A. This equation could not be used for soils 8, 9 & 10 due to lack of CEC data. Compared to the measured values, Streuderst's (1985) estimates are close enough to the measurements for soils 1 & 2 which are both freely drained, but considerably higher for soils 4 through 7. The deviations from the measured values appear to grow larger as the clay content and CEC of the soils increase. Looking closely at the equation, it is suspected that the influence of CEC on the water content has been overestimated. Nevertheless, the results indicate the usefulness of this equation for freely drained soils.

From the above discussion, it is clear that regression equations developed from soil analytical data often do not give reliable estimates of DUL. The following is a possible explanation. If there is, at any depth in a soil profile, within the root zone or immediately below it, a layer of considerably lower permeability than the layers above it, the drainage rate and therefore the

DUL value will be significantly influenced by this layer. This condition is common in soils such as the Avalon and Westleigh soil forms (Soil Classification Working Group, 1991). This factor is not taken into account when estimating DUL using standard analytical parameters. The latter procedure would then strictly speaking only work satisfactorily for freely drained soils which have reasonably homogenous texture throughout the profile.

2.4.2.1.2 Crop modified upper limit (CMUL)

The fact that plants take up water while drainage is taking place has long been appreciated (Wilcox, 1962; Miller and Aarstad, 1973; Ritchie, 1981). Hattingh (1993) described the idea of equating the drainage rate of the root zone with the evapotranspiration rate of a growing crop to obtain a meaningful upper limit of available water, above DUL, during the crop growing season. The parameter has been termed CMUL by Hensley *et al.* (1997). It has been employed effectively in the SWAMP model (Bennie *et al.*, 1998). The concept is based on the assumption that drainage below the root zone occurs only as long as the drainage rate is faster than the rate of evapotranspiration. Water moving through the root zone at a rate slower than the rate of ET will therefore be available to the plant, and should therefore be added to DUL to give CMUL. In his study Hattingh (1993) showed that 45 mm of water was available above DUL for mature maize on the Glen/Hutton-Ventersdorp ecotope. This is an indication that DUL is an underestimation of the soil water available to crops.

Bennie *et al.* (1998) gave estimates of the coefficients for the equation for calculating CMUL:

$$\text{CMUL} = b - a \ln (a/\text{ETr}) \quad \text{(mm)} \tag{2.7}$$

where b = a constant value (which can be approximated by the field saturation (fSat) value of the soil profile under consideration) (mm)

a = regression coefficient of the equation (slope of the drainage curve)

ETr = evapotranspiration rate (mm day^{-1})

The estimation formulas are:

$$a = 32.61 - 0.5099\,(Si + Cl)\mathrm{mean} \qquad (r^2 = 0.81) \tag{2.8}$$

$$b' = 176.9 + 6.255\,(Si + Cl)\mathrm{mean} - 0.0324\,(Si + Cl)^2\mathrm{mean} \qquad (r^2 = 0.86) \tag{2.9}$$

$$b = b'\,PD/1000 \tag{2.10}$$

where PD = potential rooting depth (mm)
(Si + Cl)mean = weighted mean content of particles finer than 0.05 mm (%) over the whole root zone
= $\Sigma((Si + Cl)_i\, z_i / \Sigma z_i)$ (%) (2.11)
z_i = thickness of soil layer i (mm)
$(Si + Cl)_i$ = content of particles finer that 0.05 mm in layer i (%)

Crop modified upper limit estimates, using the above equation, together with the values obtained using measurements during the same study, are given in Appendix A. In the calculations a mean ET value of 4.5 mm day^{-1} was used. This is a common ET rate for a mature maize crop at Glen (Hensley *et al.*, 1993). The potential rooting depth of maize and sorghum was taken at 2 m (Bennie *et al.*, 1994). For soils shallower than 2 m, the actual soil depth was taken as the potential rooting depth. The estimated CMUL values were considerably higher than those calculated from *in situ* determined drainage curves for all of the soils except for soils 7 & 8. For soil 8 the estimated CMUL value was considerably lower. The equation also failed to estimate the CMUL value for the clayey soil (7), a clear indication that the equation is not suitable for such soils.

The importance of CMUL is accentuated under irrigated farming conditions since it makes larger applications of water possible without fear of losses by deep drainage. In dryland crop production systems the CMUL concept is valuable for determining losses through drainage during periods of heavy rain. The procedure is demonstrated in Section 2.4.5.

2.4.2.2 Lower limit of plant available water (LL)

The lower limit of plant available water (LL) has been defined as: “The lowest field-measured water content of a soil, after plants have stopped extracting water and are at or near premature death or became dormant as a result of water stress” (Ratliff *et al.*, 1983). In dryland crop production, where one cannot “refill” the profile at will, this definition of the lower limit is appropriate. LL depends on the atmospheric evaporative demand, depth and density of root ramification, drought resistance of the crop and the unsaturated hydraulic conductivity and water retention properties of each soil horizon within the rooting zone (Hensley and De Jager, 1982). It is important to note that the soil, crop and climate all influence LL. Any attempt to define LL using soil properties alone can therefore not be expected to be fully successful.

For irrigation purposes, an important soil water content is that measured when the plant shows the first visible signs of stress at approximately 10:00 in the morning. This limit is called "first material stress (FMS)" (Hensley, 1980). This is the water content of the root zone at which irrigation needs to be applied to obtain maximum yield and it should not be confused with LL.

The soil water content at a matric suction of –1500 kPa has long been considered by many agricultural scientists to represent the lower limit of plant available water (e.g. SIRI, 1985). This assumption has provided the foundation for a number of equations for predicting LL. The following are some examples:

(a) Hutson (1983):

$$\theta_{-1500} = 0.0602 + 0.0032\ Cl + 0.0031\ Si - 0.026\ \rho_b \qquad (r^2 = 0.79) \qquad (2.12)$$

where θ_{-1500} = volumetric soil water content ($m^3\ m^{-3}$) at a soil water potential of –1500 kPa
ρ_b = bulk density ($Mg\ m^{-3}$)
Cl = clay content (%)
Si = silt content (%)

(b) Bennie *et al.*, 1998:

$$LL = \Sigma(0.00385\ (Si + Cl)_i + 0.013)\ z_i \qquad (2.13)$$

where LL = lower limit of plant available water (mm)
$(Si + Cl)_i$ = silt plus clay content of layer i (%)
zi = thickness of layer i (mm)

(c) Ritchie *et al.*, 1999:

Here LL is estimated as the difference between θ (Equation 2.5) and PAW, where PAW is defined as follows:

$$\text{PAW} = 0.132 - 2.5 * 10^{-6} \exp(0.105\ \text{Sa}) \tag{2.14}$$

where PAW = plant extractable water ($m^3\ m^{-3}$)
Sa = sand content (%)

The estimated and measured values of LL are given in Appendix A. The crops used for LL measurements were maize (soils 1, 2, 3, 5, 6 & 10), sorghum (soils 8 & 9), and sunflower (soils 4 & 7). Values estimated using the equation of Bennie *et al.* (1998) were: considerably higher for soils 3, 4, 5, 6 & 7; considerably lower for soils 2, 8, 9, & 10; and similar to the measured values for soil 1. Values from Ritchie *et al.* (1999) were: considerably higher than the measured values for soils 1, 2, 3 & 9; considerably lower for soils 4, 5, 6, 7 & 10; and similar for soil 8. Results using Hutson (1983) were: considerably higher than the measured values for soils 4 & 7; considerably lower for soils 2, 3, 8, 9 & 10; and in agreement for soils 1, 5 & 6. Here it is worth noting that all three procedures overestimated the LL in the surface layers (except for soils 8, 9 & 10, where measured data is missing). This may be explained by the fact that evaporation, which was neglected by the procedures, is in fact considerable. The above results are a good indication that soil properties alone cannot be used to estimate LL.

The resultant profile available water values using the different estimation equations of the upper and lower limits as well as the measured values are given Appendix A. Table 2.3 summarizes the deviations of the estimations from the measured values. From the results it appears that all the equations tend to severely overestimate the PAW for the sandy soils (1, 2, 3 & 9) and underestimate it for the high clay and high CEC soil No. 7. For medium textured soils estimations are closer to measured values.

From the above it can be concluded that regression equations for estimation of plant available soil water limits, based on selected soil properties alone, have limited application to conditions different from those on which they were developed. Field measurements of these limits are therefore preferable.

Table 2.3 Deviations of the different PAW estimation procedures from the field measured values, expressed as percentages of the measured values. Positive values indicate higher, and negative values indicate lower estimations.

	Soil No.[1]									
Equations	**1**	**2**	**3**	**4**	**5**	**6**	7	**8**	**9**	**10**
Bennie *et al.*, 1994/1998	191	65	42	-10	5	0	-29	8	34	7
Ritchie *et al.*, 1999	163	71	55	1	16	11	-19	0	23	12
Hutson, 1983	142	58	55	10	10	10	-14	-10	9	7

[1] Numbers refer to the soils shown in Appendix A.

2.4.3 Evaporation

2.4.3.1 Evaporation from the soil surface

Evaporation (E) is the process whereby liquid water is converted to water vapour and removed from the evaporating surface (Allen *et al.*, 1998). In dryland crop production evaporation is the most important factor responsible for water loss in semi-arid areas. It may account for water loss of up to 70% of the annual rainfall (Jalota and Prihar, 1988; Hoffman, 1997; Bennie and Hensley, 2001). Evaporation does not contribute to crop production; it is rather a net loss. Reducing water available for transpiration should therefore be eliminated as much as possible to maximize rainfall use efficiency.

Evaporation from the soil's surface takes place in two stages (Ritchie, 1972):

a) *Constant-rate stage*. Evaporation occurs while the soil is sufficiently wet for the water to move to the evaporation front at least at a rate equal to the rate of evaporation. The evaporation rate is therefore controlled by the evaporative demand of the atmosphere. It follows that evaporation at this stage (E_1) can be approximated by the reference evapotranspiration, ETo (see Equation 2.17).

b) *Falling-rate stage*. During this stage, the water transmitting properties of the soil control the rate of water supply to the surface, which in turn controls evaporation. The cumulative evaporation water loss since the beginning of this stage (ΣE_2) can be calculated as follows:

$$\Sigma E_2 = \alpha\, t^{1/2} \qquad \text{(mm)} \qquad (2.15)$$

where α = slope of the curve for ΣE vs $t^{1/2}$ for stage 2 (mm $\text{day}^{-1/2}$)
t = time since the start of stage 2 (days)

Similarly, the daily evaporation rate for each subsequent day is calculated as:

$$E = \alpha\, t^{1/2} - \alpha\,(t-1)^{1/2} \qquad (\text{mm day}^{-1}) \qquad (2.16)$$

Ritchie (1972) indicated that α, as defined above, is dependent on the hydraulic properties of the soil and seems to be closely related to the unsaturated hydraulic conductivity of the surface soil at matric potential of –10 kPa. He reported α values for different soils viz. 5.08, 4.04, 3.50, & 3.34 mm $\text{day}^{-1/2}$ for a Adelanto clay loam, a Yolo loam, a Houston black clay, and a Plainfield sand respectively. Hensley *et al.* (2000) reported comparable α values of 6.57 and 2.75 mm $\text{day}^{-1/2}$ for a Swartland Rouxville and a Bonheim Onrus soil (soils No. 5 & 6 in Appendix A).

Hoffman (1997), studying evaporation from different soils contained in microlysimeters, reported that stage 1 evaporation lasted only a few hours. He also found that evaporation during the first week after wetting took place mainly from the top 100 mm and afterwards, simultaneously from a depth up to 300 mm. Hoffman (1997) tested a number of evaporation equations and found that Ritchie (1972) gave the best predictions.

2.4.3.2 Evapotranspiration (ET)

Evapotranspiration consists of soil evaporation (E) and evaporation from plants or transpiration (T). When crops are small with little vegetative cover, ET consists mainly of evaporation. As the plant cover increases, however, soil evaporation decreases and transpiration increases.

Determination of ET follows a series of steps. Allen *et al.* (1998) have developed a standard set of procedures mainly for irrigation agriculture. The principles involved are, however, relevant to any soil-plant-atmosphere system, and therefore they are briefly discussed below.

2.4.3.2.1 Reference evapotranspiration (ETo)

Reference evapotranspiration (ETo) is defined as that which occurs from a hypothetical extensive surface of green, well-watered, actively growing grass of 0.12 m height, a fixed surface resistance of 70 s m^{-1}, and albedo of 0.23 (Allen *et al.*, 1998). ETo is calculated from meteorological data using the FAO Penman-Monteith equation as follows:

$$\mathrm{ETo} = \frac{0.408\,\Delta(Rn - G)}{\Delta + \gamma(1 + 0.34u_2)} + \frac{\gamma u_2(e_s - e_a)(900/(\mathrm{T} + 273))}{\Delta + \gamma(1 + 0.34u_2)} \qquad (2.17)$$

where Δ = slope of vapour pressure curve at mean air temperature (kPa $^{o}C^{-1}$)
Rn = net radiation at the crop surface (MJ m^{-2} day^{-1})
G = soil heat flux density (MJ m^{-2} day^{-1})
γ = psychrometric constant (kPa $^{o}C^{-1}$)
T = mean daily air temperature at 2 m height (^{o}C)
u_2 = wind speed at 2 m height (m s^{-1})
e_s = saturation vapour pressure (kPa)
e_a = actual vapour pressure (kPa)
e_a - e_s = saturation vapour pressure deficit(kPa)

Alternatively, but less reliably, ETo can be calculated from A-Pan evaporation and an empirical coefficient that depends on the crop and the growing stage of the crop (Allen *et al.*, 1998).

2.4.3.2.2 Crop evapotranspiration under standard conditions (ETc)

Crop evapotranspiration under standard conditions is evapotranspiration from crops grown in large fields under excellent agronomic and soil water conditions. It is calculated as follows:

$$\mathrm{ETc} = \mathrm{Kc\,ETo} \qquad (\mathrm{mm\ day^{-1}}) \qquad (2.18)$$

where Kc = crop coefficient (dimensionless)

The crop coefficient integrates the difference in evapotranspiration between field crops and the reference grass defined above. It includes the effects of evaporation from soil surfaces and transpiration from plants. The crop coefficient is affected by the crop type, climatic conditions, soil evaporation, and crop growth stages. Consequently Kc will differ for different crops, over the growing season, and differences in climatic conditions. The growing season is normally divided into four growth stages namely the initial stage, crop development stage, mid-season stage, and late season stage. A crop coefficient curve can be constructed based on the above factors. Finally, the Kc factor can be derived from the crop coefficient curve for each day within the growing season.

2.4.3.2.3 ETc under soil water stress conditions

Under water stress conditions, crop evapotranspiration is corrected for the water stress effects (ETc adj.) as follows:

$$\text{ETc adj.} = \text{Ks Kc ETo} \qquad (\text{mm day}^{-1}) \qquad (2.19)$$

where Ks = water stress coefficient (dimensionless)

When there is no soil water stress Ks is equal to 1. When the soil water level drops below first material stress (FMS, see Section 2.4.2.2), Ks becomes less than one. The idea is that while the water content (θ) is between DUL and FMS, ETc adj. = KcETo; below FMS ETc adj. decreases progressively as θ approaches the lower limit of plant available water. The Ks values between FMS and LL can be estimated from Figure 2.7. The straight line connecting FMS and LL is a first approximation. The shape of this line is in fact crop-ecotope specific because, in addition to soil properties, it is influenced by the crop and the climate – as is the case in FMS (Hensley and De Jager, 1982).

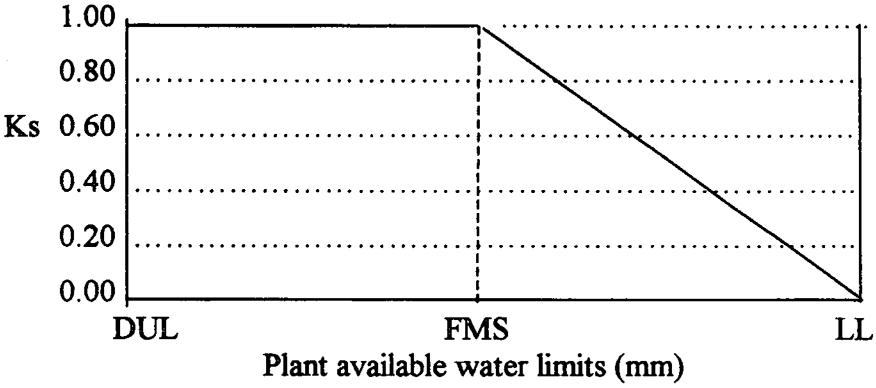


Figure 2.7 Ks at varying soil water contents (modified from Allen *et al.* (1998)).

An estimated value for the readily available water (RAW) for maize can be obtained using regression equations developed by Boedt and Laker (1985):

(a) For soils with less than 20% fine silt plus clay:

$$Y_i = z_i/100\,(6.1 + 0.26\,X_1 - 0.02\,X_2 - 0.002\,X_3) \qquad (2.20)$$

(b) For soils with more than 20% fine silt plus clay:

$$Y_i = z_i/100\,(13.91 - 0.009X_3) \qquad (2.21)$$

where Y_i = readily available water in the ith soil layer, or part thereof, within the rooting depth

z_i = thickness of the specified soil layer (mm)

X_1 = fine silt + clay content (particles < 0.02 mm) of the specified soil layer (%)

X_2 = structure index (%)

$$= \frac{\text{exchangeable }(Na^{+} + Mg^{2+}) * 100}{\text{total exchangeable cations}} \text{ of the specified soil}$$

layer

X_3 = depth index (the depth from the surface to the middle of the specified soil layer (mm)

RAW for the root zone is then calculated as $Y_1 + Y_2 + \ldots + Y_n$, where n is the number of layers within the root zone. To use this information to obtain a Ks value, DUL and LL first need to be determined in the field. FMS can then be calculated as the difference between DUL and RAW, and together with the measured DUL and LL values, used to draw up a diagram like Figure 2.7, relevant for the particular soil-plant-atmosphere continuum under consideration.

2.4.4 Surface runoff

Runoff is another process of water loss from the soil and therefore reduces the water available to plants. In a study on a red sandy loam soil with a 5% slope at Glen (MAR = 545 mm), Du Plessis and Mostert (1965) measured runoff and soil loss for 18 years on runoff plots. They reported mean annual runoff losses of 4.4%, 8.5%, 10.3% and 31.9% of the mean annual rainfall for natural veld, continuous maize, bare tilled plots and bare ground respectively. In a study under similar soil conditions for 27 years at Pretoria (MAR 730 mm) Haylett (1960) reported runoff losses as a percentage of MAR ranging from 4.2% from natural veld to 49.4% from bare soil.

Runoff is affected by several factors. Allen *et al.* (1998) indicated that the amount of water lost by runoff depends on rainfall intensity, slope of the land, hydraulic conductivity of the soil, initial water content of the soil, as well as land use and land cover. Morin and Benyamini (1977) reported that crust formation is a major factor controlling the reduction of infiltration rate (and hence increasing runoff) in dry areas. Bennie *et al.* (1998) indicated that if surface storage is neglected, surface runoff during a rain storm normally starts to take place when the rainfall intensity exceeds the infiltration rate of the soil. Reliable estimation of runoff therefore requires rainfall intensity data and a reliable estimate of the infiltration rate.

Two commonly accepted infiltration equations shown below are those of Green and Ampt (1911) and Philip (1957).

Green and Ampt (1911):

$$i = i_f + s/I \tag{2.22}$$

Philip (1957):

$$i = i_f + s/2t^{1/2} \tag{2.23}$$

$$I = i_f t + st^{1/2} \tag{2.24}$$

where
i = infiltration rate at any time t (mm h^{-1})
i_f = final infiltration rate (mm h^{-1})
s = sorptivity (mm)
I = cumulative infiltration (mm)
t = time of infiltration (h)

Bennie *et al.* (1998) determined the coefficients of the above equations using measurements of runoff and infiltration on a variety of soils by means of a rainfall simulator. They also developed a procedure to calculate runoff based on the above infiltration equations. They tested the equations against measured values and reported that the Philip (1957) equation performed better. However, they also concluded that the procedure did not estimate runoff in a reliable way.

Based on the infiltration equation of Morin and Benyamini (1977) for bare, crusting soils, Morin and Cluff (1980) proposed Equation 2.25 to calculate the total infiltration during any one time segment of a storm with a specified rain intensity.

$$F_{\Delta ti} = i_f \Delta t_i + \{(i_i - i_f)/ -\gamma P_i\}\{\exp(-\gamma d_i) - \exp(-\gamma d_{i-1})\} \qquad (2.25)$$

where $F_{\Delta ti}$ = total infiltration during any time segment Δt_i (mm)
P_i = rainfall intensity during time segment Δt_i (mm h^{-1})
d_i = $\sum P_i t_i$,the cumulative rainfall up to the time t_i (mm)
i_i = initial infiltration rate of the soil (mm h^{-1})
i_f = final infiltration rate of the soil (mm h^{-1})
Δt = $t_i - t_{i-1}$ (a given time segment, h)
γ = soil coefficient related to aggregate stability during crust formation (mm^{-1})

Equation 2.25 makes it possible to compute the runoff for any storm for which rainfall intensity is available, segment by segment, using Equation 2.26 (Morin and Cluff, 1980).

$$R_i = P_i\Delta t_i - F_{\Delta ti} - (SD_m - SD_{i-1}) \qquad (2.26)$$

where R_i = surface runoff during segment $_i$ of the storm (mm)
SD_i = surface storage and detention for the time segment Δt_i (mm)
SD_m = maximum surface storage and detention for the soil (mm)
Pi = rainfall intensity during time segment Δt_i (mm h^{-1})
$F_{\Delta ti}$ = total infiltration during time segment Δt_i (mm) (equation 2.25)

Hensley *et al.* (1997) tested the above equation and the DSSAT3 and PUTU models using rainfall intensity values at 1 minute intervals for 57 storms on 7 ecotopes. They reported that the Morin and Cluff (1980) equation predicted runoff "fairly well but slightly highly", with r^2 values of 0.61. The DSSAT3 and PUTU models that do not have subroutines that use rainfall intensity gave far less reliable results.

The fact that crust formation greatly increases runoff may be valuable in the case of water harvesting for dryland crop production. Runoff farming techniques can be implemented to collect water from uncropped plots within a farm or within the crop. Hensley *et al.* (2000), planting alternate wide and narrow rows with water harvesting into basins, reported maize yield increases of at least 37% compared to conventionally tilled plots without water harvesting. Runoff in this sense can therefore be very advantageous.

2.4.5 Deep drainage

On an uncropped land, when the root zone water content exceeds DUL, following a heavy rainstorm for example, soil water starts to drain below the root zone. This is referred to as deep drainage or deep percolation. In dryland crop production deep drainage may cause a considerable water loss, especially on coarse textured soils and when heavy rain storms occur. Hensley *et al.* (1997), for example, reported drainage water loss of up to 41% of the seasonal rainfall in sandy soils during seasons of high rainfall. The magnitude of deep drainage depends on initial soil water contents, the amount of rain or irrigation water added, and the water holding capacity of the soil, *i.e.* the drained upper limit (Bennie and Hensley, 2001).

Field measurement of deep drainage while the plant is growing is difficult. However, if the drainage curve of the soil has been determined, the drainage rate can be estimated from it. A slightly modified form of Equation 2.7 (Bennie *et al.*, 1998) is given below to explain this.

$$\theta = b - a \ln (a/Dr) \qquad (2.27)$$

where θ = volumetric soil water content at the time drainage is being determined (mm)
Dr = drainage rate (mm day^{-1})

Rearranging Equation 2.27 yields:

$$Dr = a/\exp\left(\frac{b-\theta}{a}\right) \qquad (\text{mm day}^{-1}) \qquad (2.28)$$

From the above equation, one can see that for a given profile, the drainage rate decreases exponentially with decreasing water content. Bennie *et al.* (1998) developed equations for determining the coefficients of the curve (a & b) from the average silt plus clay content of the soil profile (Equations 2.8, 2.9 & 2.10). They also indicated that the presence of a "restrictive" (slowly permeable) layer in the profile controls the drainage rate. It seems reasonable therefore that in such cases the drainage rate should be determined from the characteristics of the slowest draining layer.

In the presence of a crop, drainage does not necessarily start when the water content of the root zone exceeds DUL. As indicated in Section 2.4.2.1, drainage occurring above DUL will be offset to some extent by evaporation and root water uptake. Deep drainage in such cases will only start when the root zone water content exceeds CMUL. This can perhaps be explained as follows. Referring to Equation 2.27, in a soil having a saturation root zone water content (b) of 500 mm and a drainage curve with a slope (a) of 10.0, the drainage rates, using Equation 2.28, would be 10.0, 3.7, and 1.4 mm day^{-1} for a soil with a water contents (θ) of 500, 490, and 480 mm respectively. In a field planted with a crop with an evapotranspiration rate of say 8.0 mm day^{-1}, only 2.0 mm will be lost through deep drainage during the first day. In such cases the potential drainage rate has to exceed the evapotranspiration rate in order for deep drainage to occur. Determination of the CMUL is therefore important for drainage estimation in the presence of a crop.

2.5 Conclusions

In this chapter an example of a natural resource inventory and the factors that affect agricultural productivity has been briefly discussed. The major factors that affect agricultural productivity can be grouped into the climate, soil and topography of the area considered. An ecotope seems to be a useful unit to describe these factors, because there is no management or productivity difference within an ecotope.

The applicability of computer models in yield prediction has been briefly discussed. The strength of this technology lies in the fact that it is possible to generate long-term yield data from climate data. This can be used to construct CPF's. These CPF's can be used to make quantitative assessments of the productivity and the risks associated with each target yield. It is appreciated that adaptation of these models to the crop ecotope is imperative before using them for this purpose.

Sound management of the soil water balance is required to make maximum use of the scarce water resource, specifically in arid and semi-arid regions. Different approaches to estimate the components of the soil water balance have been discussed. Quantification of the plant available soil water is best done through field determination of the soil water drainage curve and the lower limit of available water. Attempts to estimate it from selected soil properties do not seem to be successful.

CHAPTER 3
ECOTOPE CHARACTERIZATION

3.1 Introduction

Effective quantification of crop production potential requires detailed characterization of the major factors affecting productivity. This is best done at an ecotope level as all of these factors are, for practical purposes, homogenous within an ecotope (MacVicar *et al.*, 1974). This also has the added advantage of the possibility of extrapolating findings from one ecotope to any other similar ecotope anywhere in the world (Hensley 1995a). Effective characterization at this level can therefore be highly advantageous for the efficient extrapolation of the results of expensive agricultural research.

3.2 Procedure

Two similar maize ecotopes were considered for productivity evaluation in this study, the Glen/Oakleaf and the Glen/Hutton ecotopes. Both ecotopes, as their name implies, are located at the Glen Agricultural Research Station in the Free State Province of South Africa. The climate of the area is semi-arid with a mean annual rainfall of 545 mm and mean annual class A pan evaporation of 2 317 mm (Table 3.1). The major crops grown in this area are dryland maize, wheat, sunflower and sorghum. The Glen/Oakleaf ecotope was studied in detail during the course of this study. For the Glen/Hutton, on the other hand, a detailed profile description and analytical data as well as soil water extraction and drainage data was obtained from previous studies (Hattingh, 1993; Hensley *et al.*, 1993; Hensley, personal communication, 2002).

3.2.1 Profile description and analytical data

To fully utilize the research of De Bruyn (1974), a profile pit was dug approximately in the centre of the experimental area that he had used (Figure 3.1). A detailed profile description was made using the system of the Institute for Soil, Climate and Water (Turner, 1991) at the site and samples were taken for analysis. This profile is considered to represent the Glen/Oakleaf ecotope. The drainage curve was also located at this site.

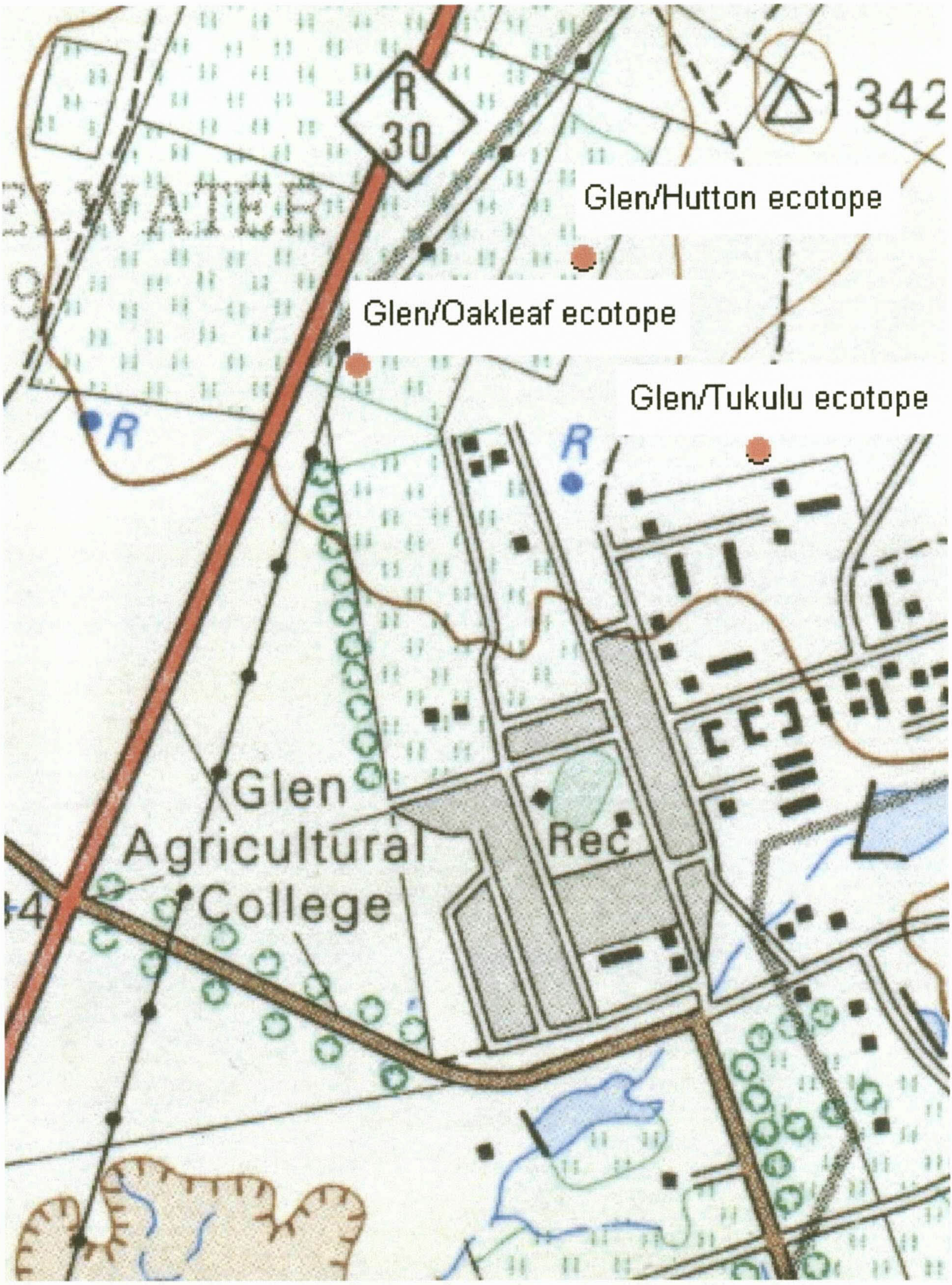


Figure 3.1 Location of the Glen/Hutton, Glen/Oakleaf and Glen/Tukulu ecotopes at the Glen experimental station (Chief Director of Surveys and Mapping, 1993).

3.2.2 Sampling and sample preparation

For the Glen/Oakleaf ecotope, soil sampling for particle size distribution and chemical analysis was done for the 0-200, 200-300, 300-450, and 450-700 mm depth intervals (Appendices B and C). Samples were taken from the sides of the pit dug for the profile description. The samples were placed in labelled plastic bags, sealed with masking tape and taken to the laboratory. The samples were air dried by spreading out on labelled flat plastic sheets. Air dry samples were ground with pestle and mortar to pass through a 2 mm sieve. The coarse fragments that remained on the sieve were weighed to determine their fraction in the soil. The particles that passed through the 2 mm sieve were analysed chemically as well as for particle size distribution. Bulk density samples were taken from 5 depths, namely, 0-200, 200-300, 300-450, 450-600, and 600-900 mm. The samples from the first 4 layers, from the soil surface, were taken using the core method with cores 104 mm diameter and 76 mm height. For the 0-200 mm layer, which was more difficult to sample due to its loose and dry condition, four replicates were taken. Water was sprinkled on the soil to avoid shattering of the samples while hammering in the cores. For the three deeper layers three samples were taken of each. For the saprolite layer from 600 to 900 mm, it was not possible to take core samples. The sand-fill method was used for this layer. Saprolite was carefully excavated out of cylindrical holes. The holes were then filled with sand of known bulk density. Three replicate determinations were made for this layer.

Gravimetric soil water content (θ_m) samples were taken throughout for NWM calibration purposes. Three to six samples, depending on the suspected spatial variation were taken for each 300 mm layer of the root zone. The samples were placed in labelled bottles with tightly sealing lids and taken to the laboratory for oven-drying for θ_m determinations.

3.2.3 Soil water measurements and soil analytical methods

For the drainage curve determination of the Glen/Oakleaf soil, the soil water content was monitored with a neutron water meter. The procedure followed for standardization and calibration of the NWM is presented in Section 4.3.1. Field layout for the construction of the drainage curve was as follows: A 3 x 3 m earthen dam was made at a representative site in the middle of the crop field. Three NWM access tubes (each 1.2 m long) were inserted, spaced roughly 500 mm apart from each other, around the centre of the dam. Soil water measurements, both gravimetric and NWM readings, were taken for the 0-300, 300-600 and 600-900 mm layers. These depths were chosen to coincide with the approximate size of the sphere of measurement of the NWM. The earthen dam was then repeatedly filled with water until water measurements showed that the soil water content of the bottom layer stayed constant, *i.e.*, an indication that the profile was fully saturated with water. The excess water in the earthen dam was then discarded and the first soil water content measurements were taken. The dam was thoroughly covered with a plastic sheet and the openings around the access tubes were carefully sealed to prevent evaporation. The water content of each 300 mm layer to a depth of 900 mm was then measured with the NWM until the rate of water loss due to deep drainage was negligible.

Drainage curves were drawn for each 300 mm layer as well as for the root zone as a whole. DUL, CMUL and equations for predicting drainage rate at any water content were determined from these curves. LL was estimated as follows: By the time the field work started, the surface layer had already been dried out by the maize crops which were close to maturity. The deeper layers, however, had been recharged by fairly recent rains. Estimates of LL for the deeper layers were therefore taken from a similar soil nearby (Hattingh, 1993).

Particle size distribution and chemical analyses were conducted according to the procedures described in the "Handbook of Standard Soil Testing Methods for Advisory Purposes" (The Non-Affiliated Soil Analysis Work Committee, 1990). A brief description of each procedure used in this study follows.

Particle size distribution: Determined by the sieve and pipette method. A soil suspension containing 10% calgon solution as dispersing agent was stirred at high speed with a mechanical shaker for 10 minutes and after the appropriate settling time the supernatant containing the silt and clay fractions was decanted through a 0.05 mm sieve into a 1000 ml measuring cylinder. The sand which remained on the sieve was separated into coarse (2-0.5 mm), medium (0.5–0.25 mm), fine (0.25-0.05 mm), and very fine (0.05-0.106 mm) sand fractions using appropriate sieve sizes. The pipette method was used to separate the coarse silt (0.05-0.02 mm), fine silt (0.02-0.002 mm) and clay (< 0.002 mm) fractions.

pH: A pH meter with combined glass electrode was used to determine pH in 1:2.5 soil to H_2O, and in 1:2.5 soil to 1 N KCl suspensions.

Organic carbon: Determined by the Walkley-Black method in which 0.5 N K_2Cr2O_7 solution, followed by concentrated H_2SO_4, is added to soil for oxidizing the organic C therein to CO_2. The excess dichromate was then back titrated with a 0.2 N $Fe(NH_4)_2(SO_4)_2.6H_2O$ solution.

Exchangeable cations and CEC: A soil sample was leached with 1 N NH_4OAc adjusted to pH 7. The filtrate was used for the determination of the exchangeable cations Ca^{++}, Mg^{++}, K^+, and Na^+ using an atomic absorption spectrophotometer. The NH_4^+ saturated soil sample was leached with 1 N NaOAc adjusted to pH 8.2 followed by a series of washings with alcohol. The sample was then leached with 1 N NH_4OAc adjusted to pH 7 and the filtrate used to determine the CEC via Na^+ by an atomic absorption spectrophotometer.

Total dissolved salts: Determined by the electrical resistance method. Electrical resistance readings at a specified temperature were taken from saturation pastes prepared in the laboratory. An appropriate correction factor was used to account for the effect of temperature.

3.2.4 NWM standardization and calibration procedure

3.2.4.1 NWM standardization

Soil water content in the Glen/Oakleaf ecotope was measured using a CPN neutron water meter (serial No. H34055438) throughout the time of construction of the drainage curve. The instrument was first standardized and calibrated. To make sure that it was functioning properly, the instrument was placed on top of its casing and 10 standard readings (S), along with their goodness-of-fit (χ^2) values, were taken. To be able to use another instrument in case the present one went out of order, 10 standard readings were taken with two CPN NWM's (serial No. H34055438 and H34055437) in specially constructed high density PVC cylinders of different diameters, one termed "medium" and the other termed "thin" (Reginato and Nakayama, 1987). Results are presented in Appendix D. This was done by inserting the neutron source into each of the tubes and taking the necessary readings. The medium and thin PVC readings roughly correspond to the dry and wet readings of the soil, respectively.

3.2.4.2 NWM calibration procedure for the Glen/Oakleaf soil

A detailed procedure for NWM calibration has been given by Hensley *et al.* (2000). A similar procedure was followed in this study for calibrating the neutron water meter for the Glen/Oakleaf soil. Two equations, one for the dry end and one for the wet end of the soil water spectrum, were developed for each 300 mm layer of the soil. This is because the relationship between count ratios (CR) and soil water content is not linear throughout the whole soil water regime. The curve is linear up to a certain point and, thereafter, it curves upwards towards a point defined by the maximum CR (CR_{max}) for the particular instrument, and θ at field saturation (fSat) for the particular layer (Hensley *et al.*, 2000). For each of the wet and the dry end cases, as many pairs as possible of neutron water meter readings and gravimetric samples were taken from each layer. The gravimetric water content (θ_m) values were multiplied by the bulk densities of the respective layers to obtain θ values. The data used for the calibration equations are presented in Appendix E. Fewer appropriate data pairs were obtainable for the deeper layers, especially for the 600 – 900 mm saprolitic layer.

A data pair of the θ value at fSat, as defined by the porosity of the layer, and CR_{max} was added to the wet end data for each layer. This value was determined in the following manner. The total porosity (Po) for the particular layer was first calculated from the bulk density. Previous research works have shown that at saturation the percentage of porosity filled with water falls in the range of 0.7 for sandy soils to 0.95 to clay soils (Hensley, personal communication, 2002). Accordingly, fSat values of 0.75, 0.80 and 0.90 of porosity were found to be appropriate values for the three soil layers, from top to bottom respectively.

An example of the calculation procedure, say for the top layer which has a bulk density of 1.56 Mg m^{-3} would be: $\theta = (1-1.56/2.65)*0.75*100$. This gives a θ value of 30.8% for that particular layer. This value, along with CR_{max}, is added to the wet end data set of the first layer. The same procedure is repeated for each layer. This data pair is very useful, because, in practice it is very difficult to get gravimetric samples immediately after saturation has been reached. It should be remembered that the drainage rate at this stage is relatively high, especially in sandy soils. The above data pair fills this data gap.

3.3 Results and discussion

3.3.1 NWM calibration results for the Glen/Oakleaf soil

Two calibration curves for each of the three soil layers are presented in Figure 3.1. The results clearly indicate the need for a separate equation for very wet soil, since extrapolation of the lower curve does not provide a reliable count rate value near to saturation. The need for this is also described in the handbook which accompanies the CPN neutron water meter. Applying only one equation for this profile may lead to unreliable results at the wet end. The regression equations shown in Figures 3.2 to 3.4 can be used to convert neutron water meter count rates taken at any time from the Glen/Oakleaf ecotope to θ values.

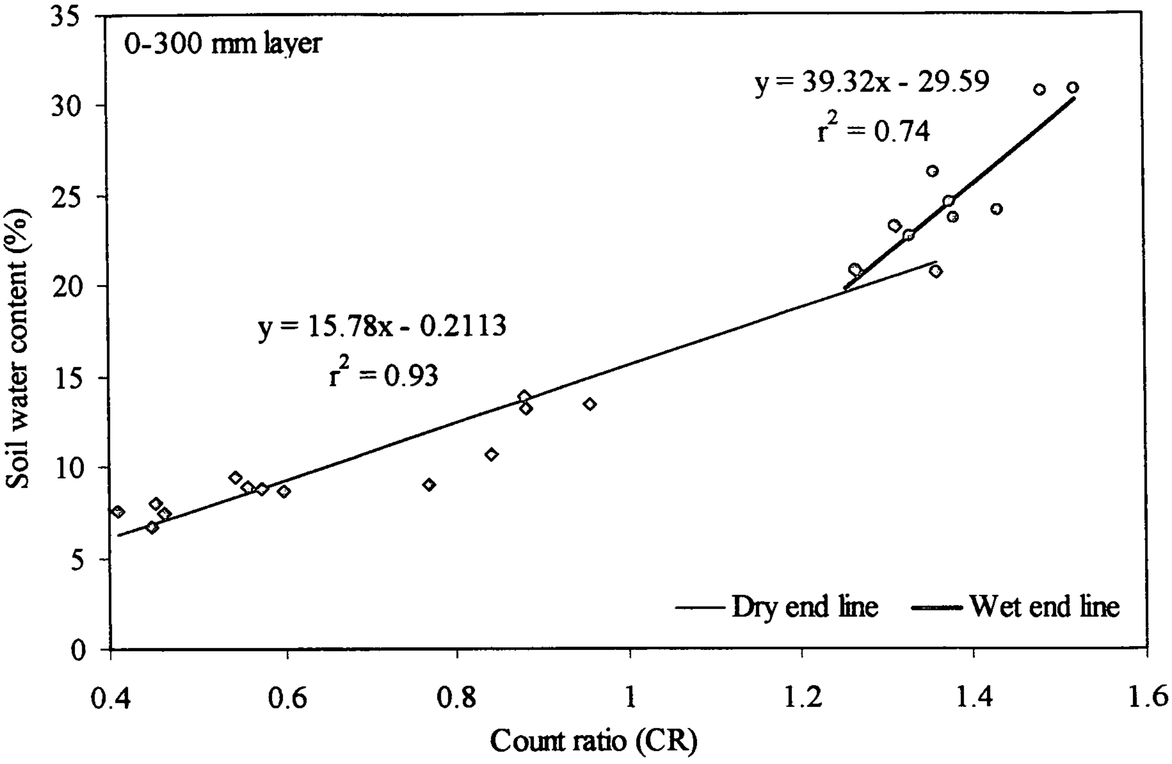


Figure 3.2 The wet end and dry end neutron water meter calibration curves for the 0-300 mm layer of the Glen/Oakleaf soil.

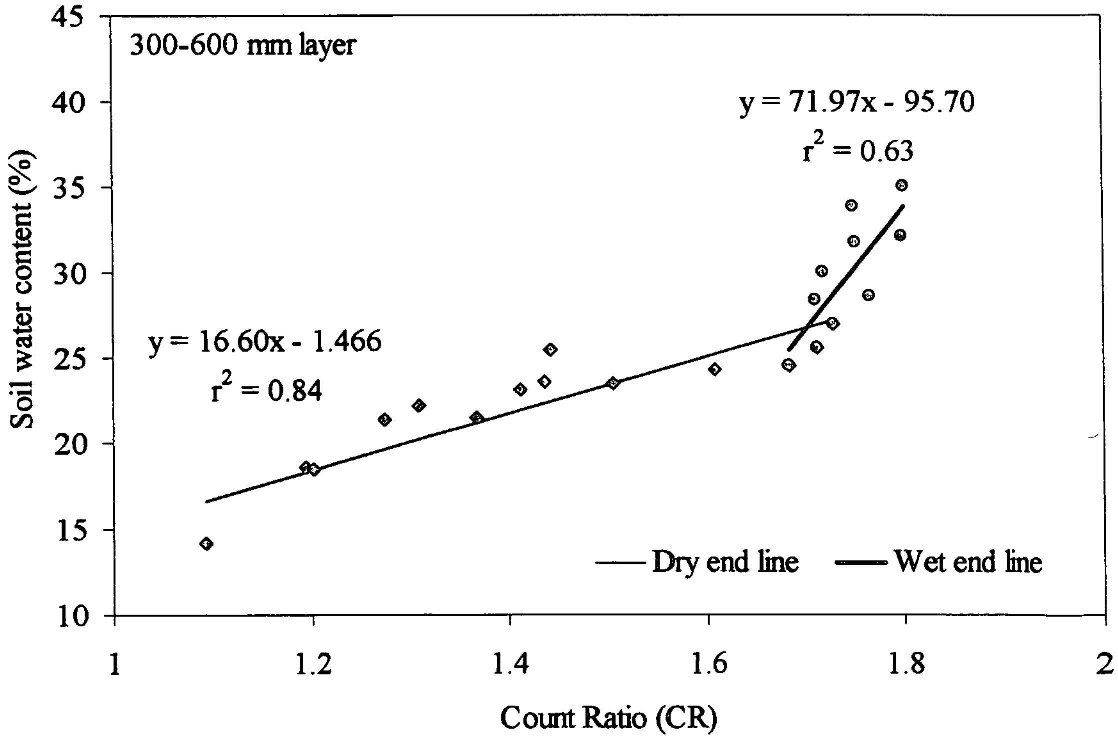


Figure 3.3 The wet end and dry end neutron water meter calibration curves for the 300-600 mm layer of the Glen/Oakleaf soil.

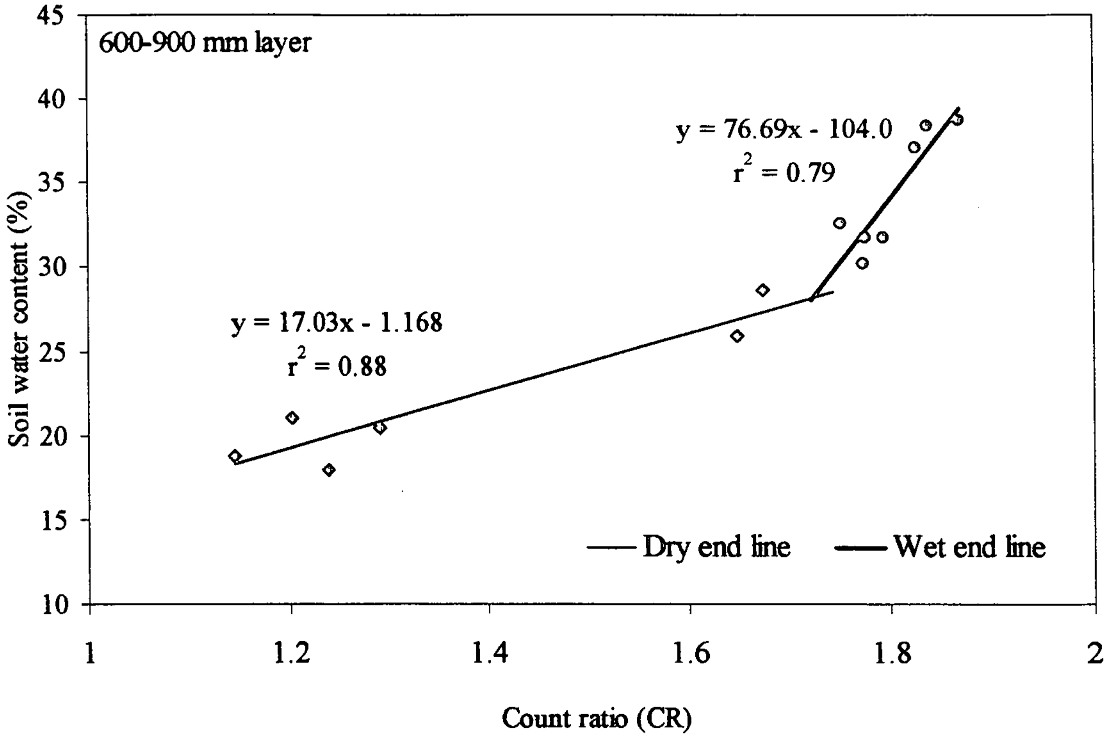


Figure 3.4 The wet end and dry end neutron water meter calibration curves for the 600-900 mm layer of the Glen/Oakleaf soil.

3.3.2 Glen/Oakleaf ecotope

3.3.2.1 Climate

Hensley *et al.* (2000) made a comprehensive summary, based on long-term climatic data from the ISCW climate data bank, of the monthly averages for the major climatic characteristics of Glen. Results are presented in Table 3.1. The high evaporative demand and relatively low rainfall make this a semi-arid climate, with the worst conditions for crop production generally occurring during December, January and February. Hensley *et al.* (2000) also observed that rainfall during these months is generally very erratic and much of it occurs in the form of high intensity rainfall events. Low temperatures and very little rain characterize the winter months. The most ideal month for crop production, with the highest rainfall and lowest evaporative demand, is March. This fact can be taken advantage of by planting short growing season crops, such as the new early maturing maize cultivars, early in January. The most stress sensitive stage of growth (*i.e.* flowering) then occurs during March, thereby rendering crop production much more reliable. Radiation is generally ample in this area during this time (Hensley *et al.*, 2000).

Table 3.1 Monthly and annual means of major climatic elements for Glen (28°57'S, 26°20'E, 1304 m a.m.s.l.) (Hensley *et al.*, 2000).

Item	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Mean/ Total
Rain (mm)	8	12	19	48	67	67	82	79	84	51	19	9	545
Evap (mm)[1]	96	143	219	248	264	301	313	216	186	129	118	84	2317
T max (°C)[2]	17.8	20.6	24.5	26.8	28.4	30.3	30.9	29.4	27.2	23.8	20.6	17.6	24.8
T min (°C)	-1.6	0.9	5.2	9.2	11.7	13.9	15.2	14.6	12.3	7.7	2.6	-1.2	7.5
T ave. (°C)	8.1	10.7	14.9	18.0	20.2	22.1	23.0	22.0	19.7	15.7	11.6	8.2	16.2
AI[3]	0.08	0.08	0.09	0.19	0.25	0.22	0.26	0.37	0.45	0.40	0.16	0.11	0.24

[1] Class A pan evaporation

[2] Mean temperature values for the month

[3] Aridity index = Rain/Evap.

3.3.2.2 Topography

This ecotope is located on a footslope terrain unit with a concave, 1% slope in a southwesterly direction (Figure 3.1).

3.3.2.3 Soil

3.3.2.3.1 Pedological characteristics

A detailed profile description is presented in Appendix B and soil analysis data for selected properties is presented in Appendix C. The soil is classified as belonging to the Oakleaf form, Dipene family (Soil Classification Working Group, 1991). It consists of a reddish brown fine sandy loam A horizon, and reddish brown fine sandy clay loam B horizon. The parent material of the soil is binary, consisting of aeolian material overlying weathered dolerite colluvium. A layer of ferruginised dolerite colluvial gravel occurs at a depth of 450 mm. The latter, in turn, overlies a layer of saprolitic feldspathic sandstone at a depth of 700 mm. The saprolite layer shows, near its upper boundary, a considerable amount of soil illuviation into the cracks. $CaCO_3$ coatings also occur in localized patches in this layer. This layer is weakly weathered to a depth of 1000 mm, a depth at which the hard rock starts. The surface layer has a low to medium CEC of 5.0 to 6.0 $cmol_c\ kg^{-1}$ increasing in the subsoil to 12.2 $cmol_c\ kg^{-1}$. The soil has an intermediate pH value and, generally low contents of organic matter, Na, K, Mg, and Ca. The bulk density varies from 1.48 Mg m^{-3} in the plough layer to 1.51 Mg m^{-3} in the gravel layer, except for the relatively high value (1.72 Mg m^{-3}) observed at the 200-300 mm depth. The latter value suggests incipient plough pan development, and hence a need for ripping.

3.3.2.3.2 Drainage characteristics

The θ values taken at different dates after saturation are presented in Appendix F. The drainage curves for each 300 mm layer are presented in Figure 3.5, and the one for the root zone is presented in Figure 3.6. The equations for the drainage curves, and the drainage rates, for the three layers and the whole root zone, along with the soil water limits, are summarized in Table 3.2.

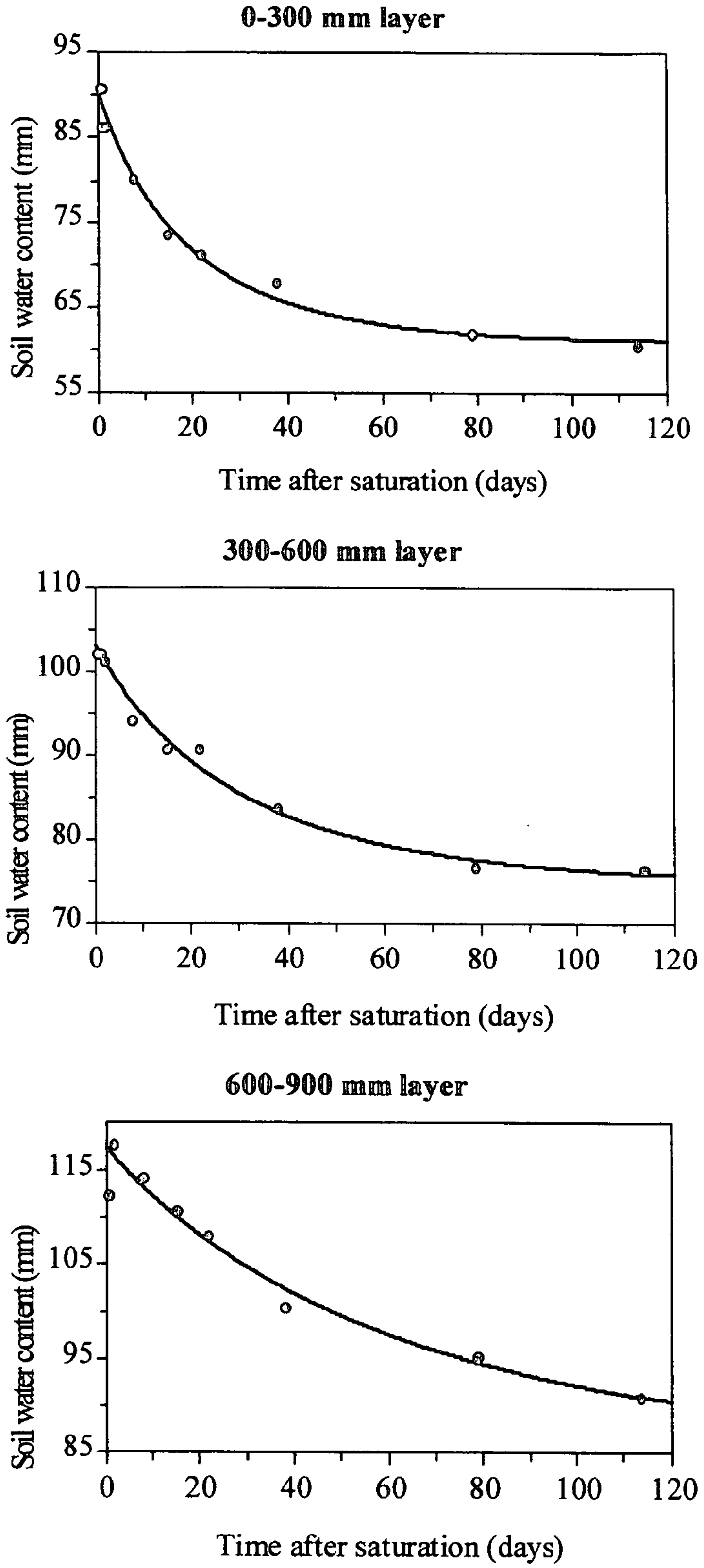


Figure 3.5 Drainage curves for the 0-300 mm, 300-600 mm, and 600-900 mm layers of the Glen/Oakleaf soil.

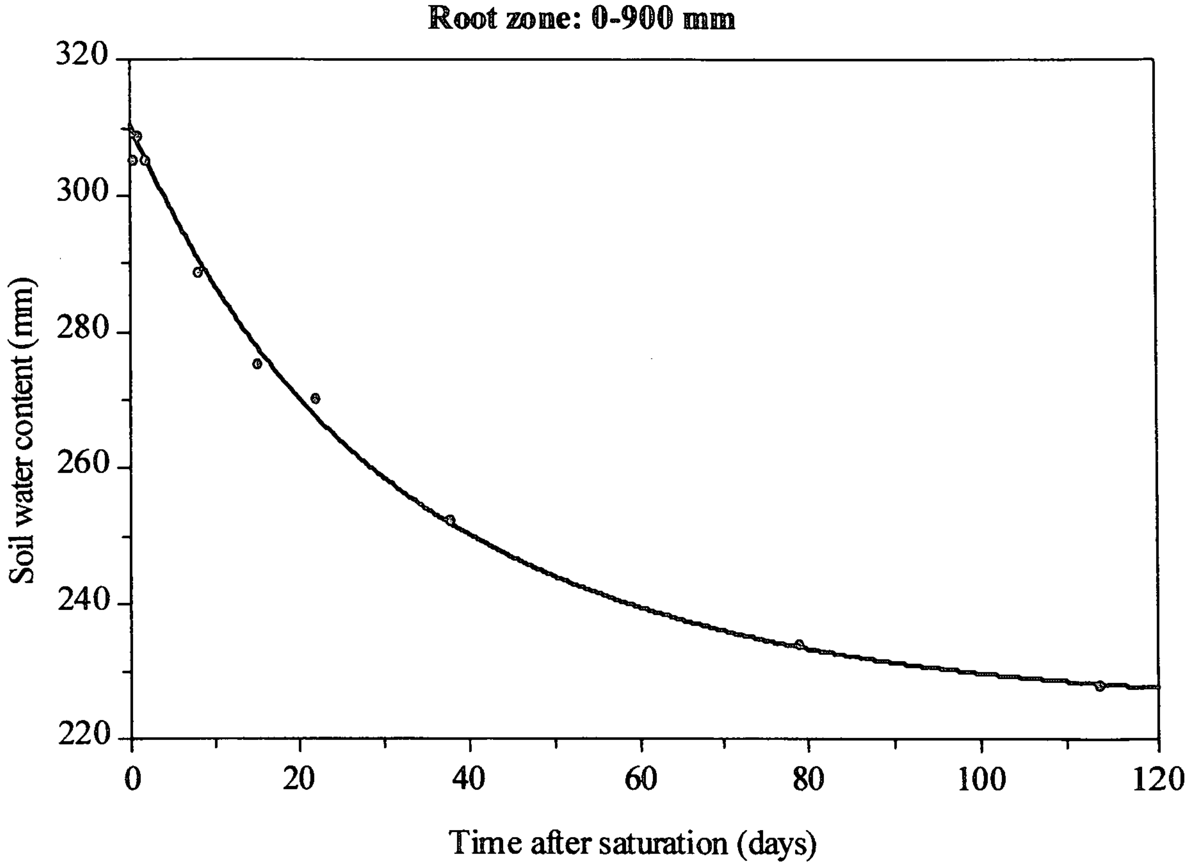


Figure 3.6 Drainage curve for the root zone of the Glen/Oakleaf soil.

The effective root zone was considered to be 900 mm deep due to the observation of some roots in the saprolite layer. The DUL for the root zone is 228 mm. Drainage took nearly 4 months to reach DUL, indicating a very slow drainage rate, probably due to the influence of the slowly permeable underlying material. Based on the DUL value and an estimate of LL (108 mm) the plant available soil water was estimated to be 120 mm for the root zone. This value is just below the value reported for the twice as deep Glen/Hutton soil (see Table 3.3). Another important observation is the relatively high CMUL value for this soil of the 0-300 mm layer, considering a mature maize crop growing in summer on this ecotope. An ET value of 4.5 mm day^{-1} was considered for making an estimate of CMUL (Hensley *et al.*, 1993). It was estimated from the drainage curve equation for the root zone that CMUL would be attained 94 hours (nearly 4 days) after saturation. The fSat value for the root zone is 314 mm.

Table 3.2 Drainage curve equations, drainage rate equations, and soil water limits for the Glen/Oakleaf maize ecotope.

Layer	ρ_b	Drainage curve				DUL	LL[4]	PAW[5]	CMUL[6]
(mm)	(Mg m^{-3})	Curve equation[1]	Drainage rate equation[2]	Coefficients[3]	r^2	(mm)	(mm)	(mm)	(mm)
0-300	1.56	$\theta r = \frac{a}{(1+be^{-ct})}$	$\frac{d\theta r}{dt} = \frac{abce^{-ct}}{(1+be^{-ct})^2}$	61.09 -0.3237 0.0385	0.98	61	27	34	85
300-600	1.49	$\theta r = \frac{a}{(1+be^{-ct})}$	$\frac{d\theta r}{dt} = \frac{abce^{-ct}}{(1+be^{-ct})^2}$	75.11 -0.2737 0.0269	0.98	76	38	38	100
600-900	1.51	$\theta r = \frac{a}{(1+be^{-ct})}$	$\frac{d\theta r}{dt} = \frac{abce^{-ct}}{(1+be^{-ct})^2}$	85.54 -0.2719 0.0133	0.95	91	43	48	115
Root zone		$\theta r = \frac{a}{(1+be^{-ct})}$	$\frac{d\theta r}{dt} = \frac{abce^{-ct}}{(1+be^{-ct})^2}$	224.74 -0.2770 0.0252	0.99	228	108	120	300

[1] From regression curves fitted to the drainage data (Figures 3.5 & 3.6).

$d\theta r$ = deep drainage loss from the specified soil layer or from the root zone starting from saturation (mm)

$d\theta r/dt$ = the drainage rate at any point on the drainage curve (mm day^{-1})(Figures 3.5 & 3.6).

[2] Derivatives of the drainage equations.

[3] Coefficients in each cell represent a, b, and c in the equations, respectively.

[4] The LL for the layers from 300 to 900 mm was estimated from research done on a nearby similar soil (Hattingh, 1993).

[5] PAW=DUL-LL.

[6] CMUL computed from the drainage curve equations (3rd column) at t = 94 hours after saturation, assuming a mature maize crop with ET = 4.5 mm day^{-1} (Hensley *et al.* 1993).

The above values indicate that with a mature maize crop, a maximum of only 14 mm of water could be lost as deep drainage, as compared to about 50 mm from the Glen/Hutton soil. Based on the CMUL and the LL values the plant available water for a mature maize crop growing on this ecotope (CMUL – LL) would be 192 mm. The comparable value for the Glen/Hutton is only 183 mm. These observations accentuate the importance of field determined soil water limits wherever possible, in preference to values obtained from matric suction curves, or from regressions.

3.3.3 Glen/Hutton ecotope

3.3.3.1 Climate

Since the ecotope is situated a few hundred meters upslope from the Glen/Oakleaf ecotope (see Fig. 3.1), the climate is the same as described under 3.3.3.1.

3.3.3.2 Topography

This ecotope is located on a midslope terrain unit with a straight, 3% slope in a westerly direction (Figure 3.1).

3.3.3.3 Soil

3.3.3.3.1 Pedological characteristics

A detailed profile description is presented in Appendix G and soil analysis data is presented in Appendix H. The profile description and the soil analysis data were obtained from previous research (Hensley, personal communication, 2000). During present research, a profile pit was dug close to the site of the original profile. The soil is classified as belonging to the Hutton form, Ventersdorp family (Soil Classification Working Group, 1991). It consists of a deep soil with a reddish brown fine sandy loam A horizon. A series of B horizons extend to a depth of 1200 mm. It consists of reddish brown fine sandy clay loam B1 and B2 horizons and a reddish brown fine sandy loam B3 horizon. The material below 1200 mm is transitional to the C horizon. It contains a considerable amount of relatively unweathered dolerite colluvium. The soil analytical data show that the surface layer has a low CEC of

5.0 $\text{cmol}_c\,\text{kg}^{-1}$, slowly increasing in the subsoil to 7.1 $\text{cmol}_c\,\text{kg}^{-1}$. The soil has an intermediate pH value and generally low organic matter, Na, K, Mg, and Ca contents. The bulk density varies from 1.54 Mg m^{-3} in the plough layer to 1.73 Mg m^{-3} in three deeper layers.

3.3.3.3.2 Drainage characteristics

A drainage curve for the root zone was obtained from Hensley *et al.* (1993). Detailed measurements of the soil water limits were obtained from Hattingh (1993). The drainage curve for the root zone is presented in Figure 3.7. The important drainage and water extraction features are summarized in Table 3.3. The fast decay of the drainage curve indicates the high drainage loss that might take place following heavy rainstorms. The drained upper limit for this ecotope is 360 mm. The drainage equation is given below (Hensley *et al.*, 1993).

$$\theta r = 460.82 - 12.11(\ln t) \qquad (r^2 = 0.94) \qquad (3.1)$$

where θr = root zone water content (mm)
t = time after saturation (days).

Differentiation of Equation 3.1 gives Equation 3.2 which can be used to determine the drainage rate at any point on the drainage curve, as follows:

$$\frac{d\theta r}{dt} = -12.11(1/t) \qquad (3.2)$$

where $\frac{d\theta r}{dt}$ = the drainage rate at any point on the drainage curve (mm day^{-1}).

The CMUL value for a mature crop growing on this soil is 410 mm. The LL value for maize for the root zone is 227 mm, resulting in PAW of 133 mm. The measured root zone soil water content at the onset of serious stress in mature maize (SS) around 260 mm (Hensley, personal communication, 2000). As indicated in Section 3.3.3.3.2, despite the higher water holding capacity of the Glen/Hutton soil due to its much greater soil depth, the two ecotopes have similar amounts of plant available water for mature maize. Taking the differences between CMUL and DUL for these two soils, for example, the Glen/Oakleaf soil has a higher value (72 mm) than the Glen/Hutton soil (50 mm).

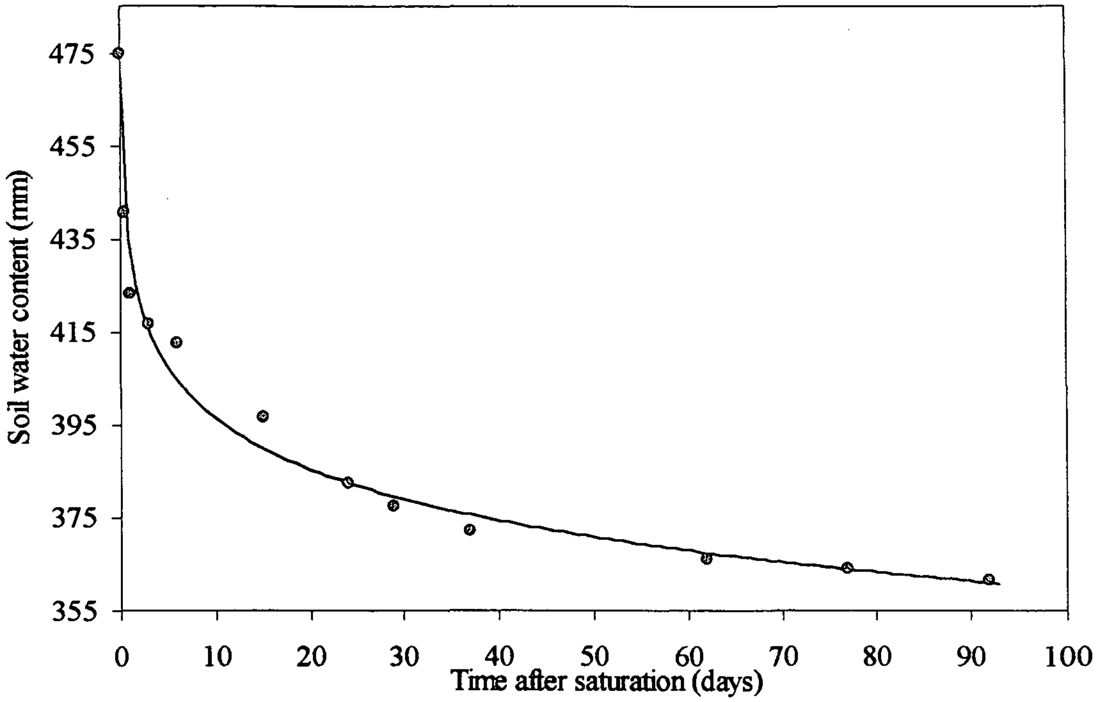


Figure 3.7 Drainage curve for the 0-1800 mm root zone of the Glen/Hutton ecotope (Hensley *et al.*, 1993).

As shown by the slopes of their respective drainage curves, the Glen/Oakleaf has a slow drainage rate (without signs of hydromorphy), whereas the Glen/Hutton drains fairly fast, resulting in fairly similar soil water availability for a mature maize crop on these two ecotopes. For this study, the mean water limits for the two ecotopes have been approximated by using the measured values for the Glen/Hutton soil, *i.e.* DUL = 360 mm, SS = 260 mm, and LL = 227 mm.

Table 3.3 Drainage characteristics of the Glen/Hutton maize ecotope (Hattingh, 1993; Hensley *et al.*, 1993).

Profile detail[1]					Maize soil water extraction properties		
Depth[2] (mm)	Diagnostic Horizon[3]	Clay (%)	ρ_b ($Mg\ m^{-3}$)	DUL (mm)	LL (mm)	PAW (mm)	CMUL (mm)
300	ot	14	1.54	45	19	26	
600	re	22	1.70	66	38	29	
900	re	23	1.73	62	44	19	
1200	re	19	1.73	68	45	23	
1500	-	-	1.73	61	41	20	
1800	-	-	1.73	58	41	17	
Root zone		-	1.73	360	227	133	410

[1] Soil profile description and some analytical data was available only to a depth of 1200 mm.
[2] Lower depth of the horizon.
[3] ot = orthic A, re = red apedal B (SIRI, 1985).

3.4 Conclusions

The procedure described in this chapter has made it possible to produce a detailed characterization of the main natural agricultural resource factors which influence maize productivity. The need for separate neutron water meter calibration equations for the dry and the wet ends of the soil water spectrum for each soil layer was clearly demonstrated by the resulting graphs.

The ecotopes are located in a semi-arid climate area with high evaporative demand and low rainfall. The Glen/Hutton ecotope has 3% slope, as compared to the 1% for the Glen/Oakleaf. Their pedological characteristics are fairly similar. The soils on both ecotopes have low to medium CEC, intermediate pH, as well as low contents of organic carbon, Na, K, Mg, and Ca. The clay content in both soils is in the range 14 - 24%. The Glen/Hutton soil is twice as deep as that of the Glen/Oakleaf soil. However, due to the presence of the slowly permeable material at a depth of about 1000 mm in the Glen/Oakleaf soil, the drainage rate on this soil is considerably slower than that on the Glen/Hutton soil. Comparisons of the plant available soil water contents in both these ecotopes indicated that they have fairly similar water holding capacities.

CHAPTER 4
ESTIMATION OF RUNOFF FROM MAIZE ECOTOPES AT GLEN

4.1 Introduction

Runoff is an important component of the soil water balance. In arid and semiarid areas, where crust formation is a common occurrence and where occasional heavy rainstorms occur, runoff may constitute a considerable proportion of the annual rainfall. In order to improve water availability for crops in these water scarce areas, long-term modelling of the system is imperative. This requires making reliable estimates of the components of the soil water balance. However, it is often difficult to reliably estimate runoff. This fact often creates difficulties in modelling and other activities involving water balance determinations. The problem is accentuated in situations where the necessary data for estimating runoff, such as rainfall intensity and infiltration rate, are not available. Availability of this information, or a reliable means of estimating runoff, is therefore crucial for reliable soil water balance modelling.

Hensley *et al.* (2000) developed a linear regression equation to predict runoff on the Glen/Swartland and Glen/Bonheim ecotopes, both planted to maize under conventional tillage, based on measured runoff values for 3 years. Using this equation, the researchers estimated runoff values for each rainfall event greater than 8 mm during the period 1937 to 1955, added the values for each year, and correlated the results with the measured annual runoff values for these years measured by Du Plessis and Mostert (1965) on the Glen/ Tukulu ecotope. They reported an r^2 value of 0.51 and D-index of 0.82. The RMSEs was also less than 65% of the RMSE.

The objective of this chapter is to describe the development of an expert system for predicting runoff from daily rainfall data on selected Glen ecotopes that are conventionally tilled and planted to maize. The expert system developed will help in making daily soil water balance estimations, as described in subsequent chapters.

4.2 Procedure

4.2.1 Site description and data obtained

A detailed profile description and particle size analysis was done for the soil at the Du Plessis and Mostert (1965) runoff site. Soil samples for particle size analyses were taken at 0-300, 300-500, 500-650, and 650-850 mm depth intervals. Analysis was done as discussed in Chapter 3 for the Oakleaf soil. Profile description and particle size distribution results are presented in Appendix I and Appendix J respectively. The site is located at Glen (Figure 3.1), a few hundred meters away from the Glen/Hutton and Glen/Oakleaf ecotopes on which the present study focuses. The climate at all these ecotopes is therefore the same. It is described in section 4.3.4.1. The experimental site is located on a midslope terrain unit with a straight, 5% slope in a south-easterly direction. The soil component consists of a soil belonging to the Dikeni family of the Tukulu Form (Soil Classification Working Group, 1991). The topsoil, which is of major importance for runoff characteristics, consists of reddish brown fine loamy sand.

Du Plessis and Mostert (1965) conducted long-term runoff measurements under different plant cover and cultivation practices on the Glen/Tukulu ecotope for 18 years (1937/38-1954/55). The runoff plots used were 9 ft x 100 ft (2.7 m x 30.5 m). The study included bare plots, maize plots subjected to various cultivation practices (grown in monoculture and rotation), and perennial vegetation (both established pasture for grazing and veld plots which were protected, grazed and burnt). The results from their study are available in the form of cumulative annual runoff graphs (Du Plessis and Mostert, 1965). Using modernised units for the y-axis, their runoff curves for conventionally tilled annual maize, and bare plots, are presented in Figure 4.1. Unfortunately, the measured runoff data from this research for each storm could not be found – not even from one of the authors! Only the published cumulative runoff curves are available. They give one total runoff value for each year. This section therefore describes an attempt to model these missing runoff values for each rainfall event for the 18 years. Another data set was obtained from previous research work (Hensley personal communication, 2002). This includes measured runoff data for 4 seasons (1985/86 to 1989/90) from the Glen/Hutton ecotope.

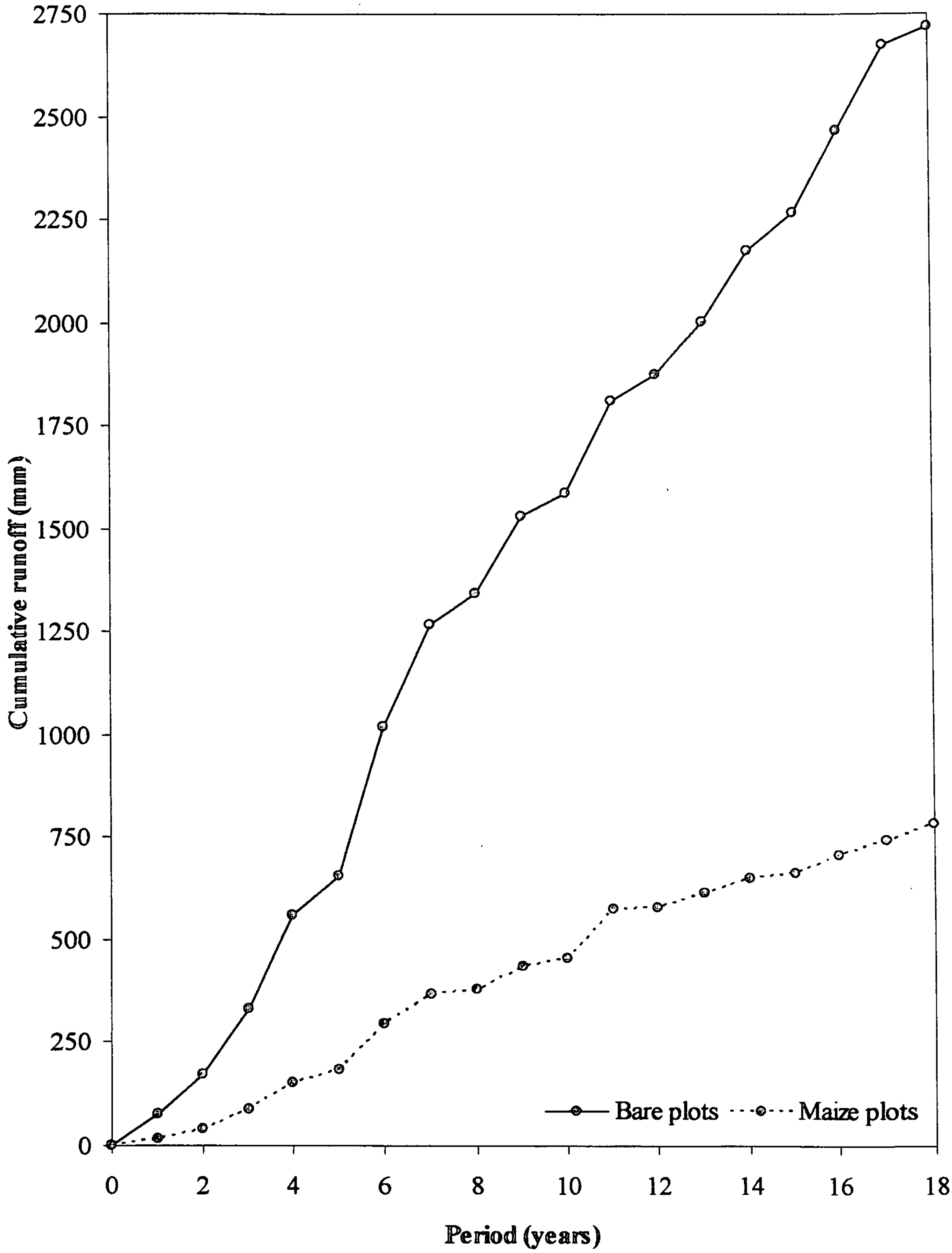


Figure 4.1 Long-term (1937/38-1954/55 seasons) cumulative runoff graphs for bare, and conventionally tilled, annual maize plots (Du Plessis and Mostert, 1965; y-axis units modernised.)

4.2.2 Development procedure

Annual runoff losses from the maize plots under conventional tillage were read from the graphs of Du Plessis and Mostert (1965) presented in Figure 4.1. These results, along with the seasonal runoff data (Hensley, personal communication, 2002) are presented in Table 4.1. Runoff data for each significant rainfall (≥8 mm) during the 18 years were estimated using an iterative process. The runoff values, as percentages of rainfall, as well as the total annual runoff values were used as guiding constraints. That is, the annual percentages served as departure points, and the annual runoff values served as controlling points. Hensley *et al.* (2000) observed that rainfall events smaller than 8 mm generally do not produce significant runoff on certain Glen ecotopes. All rainfall events below this value were therefore omitted from the data generation process. This left a lesser number of rainfall events for each year, simplifying the iterative process. The iterative process was carried out under the following conditions:

All significant rainfall events during a specific year (≥8 mm in wet conditions or ≥10 mm in dry conditions) received a certain portion of the total annual runoff.

For a given year, rainfall events that occurred under wet conditions received higher runoff values than comparable rainfall events occurring in dry conditions. Hence a rainfall event following a wet period (total of ≥8 mm in the previous 3 days) was assumed to have taken place under a wet condition, and received a larger share than a comparable rainfall event occurring on a dry soil.

Progressively larger rainfall events received proportionally higher runoff values than smaller events, *i.e.*, a non-linear relationship between rainfall and runoff was assumed. This was done in order to accommodate the effect of possible higher rainfall intensities and extended wetter soil conditions during larger storms.

The runoff values assigned to each rainfall event in a particular year, both for wet and dry conditions, had to add up to the annual runoff (*i.e.* it was used as a controlling point).

Table 4.1 Measured annual runoff for the Glen/Tukulu ecotope (Du Plessis and Mostert, 1965) and real-time measured runoff data (last four rows) from the Glen/Hutton ecotope (Hensley, personal communication, 2002).

Season	Rainfall [1] (mm)	Runoff (mm)	Runoff ÷ Rainfall (%)
1937/38	324.9	15.5	4.8
38/39	463.7	23.3	5.0
39/40	579.3	49.4	8.5
40/41	641.9	65.3	10.2
41/42	421.1	31.4	7.5
42/43	914.5	110.0	12.0
43/44	730.2	73.2	10.0
44/45	409.0	12.2	3.0
45/46	538.8	53.7	10.0
46/47	348.9	20.0	5.7
47/48	705.5	121.4	17.2
48/49	212.8	6.0	2.8
49/50	530.7	33.6	6.3
50/51	549.5	34.6	6.3
51/52	336.2	15.4	4.6
52/53	495.6	40.9	8.3
53/54	581.9	36.0	6.2
54/55	510.3	42.5	8.3
85/86 [2]	377.0	63.0	16.7
86/87	420.5	9.9	2.4
88/89	242.0	31.1	12.9
89/90	279.2	44.6	16.0
Mean	**482.4**	**42.4**	**8.4**

[1] Measured rainfall obtained from the ISCW climate data bank.

[2] Rainfall and runoff for only the crop growing seasons.

Every significant rainfall event from 1937/38 to 1954/55 was assigned a certain runoff value in this manner. Runoff values thus generated, and the four seasons real-time runoff measurements, were plotted against the corresponding rainfall amounts obtained from the ISCW climate data bank. Regression equations were finally fitted to the two data sets and the equations with the highest r^2 values were selected.

4.3 Results and discussion

The two best-fitting curves, one for dry conditions and one for wet conditions are presented in Figures 4.2 and 4.3 respectively. The following are the corresponding equations:

(i) **For dry soil ($10 \text{ mm} \leq P \leq 70 \text{ mm}$):**

$$R_i = 0.005\,P_i^2 - 0.134\,P_i + 2.032 \qquad (r^2 = 0.84) \qquad (4.1)$$

(ii) **For wet soil ($8 \leq P \leq 70 \text{ mm}$):**

$$R_i = 0.042\,P_i^{1.386} \qquad (r^2 = 0.82) \qquad (4.2)$$

where R_i = runoff (mm) for each rainfall event P_i (mm).

Despite the variation in estimated runoff values between comparable rainfall events, which is most probably due to differences in rainfall intensities, the results showed fairly high r^2 values viz. 0.84 and 0.82 for dry and for wet conditions, respectively. It is noticeable that variations are particularly large for rainfall events greater than about 40 mm. However, in any particular growing season there are generally a few storms of this magnitude. These equations can therefore be used, as an expert system, for estimating runoff from rainfall. One has to observe the soil wetness conditions in order to decide which equation to use for estimating runoff for a specific storm. The good agreement between the data ensures that the expert system can be used with reasonable confidence for runoff estimation.

It was decided to use the expert system to make long-term runoff estimations for the two Glen crop ecotopes under consideration (Glen/Hutton and Glen/Oakleaf). This made it possible to calculate a daily water balance, and hence yield estimations for the 80 years for these two ecotopes. It is believed that these ecotopes have similar runoff patterns to that of the Glen/Tukulu ecotope as they have the same climate as well as similar topographic and topsoil characteristics. An important limitation of the equations, as for all regression equations, is that they cannot be used for estimating runoff from rainfall events that lie outside of the range of the data used for developing the equations (i.e. $8 \leq P_i \leq 70$ mm). Extrapolation of data outside this range might lead to erroneous results. Validation of the equations against measured values, if available, could also add reliability to these equations.

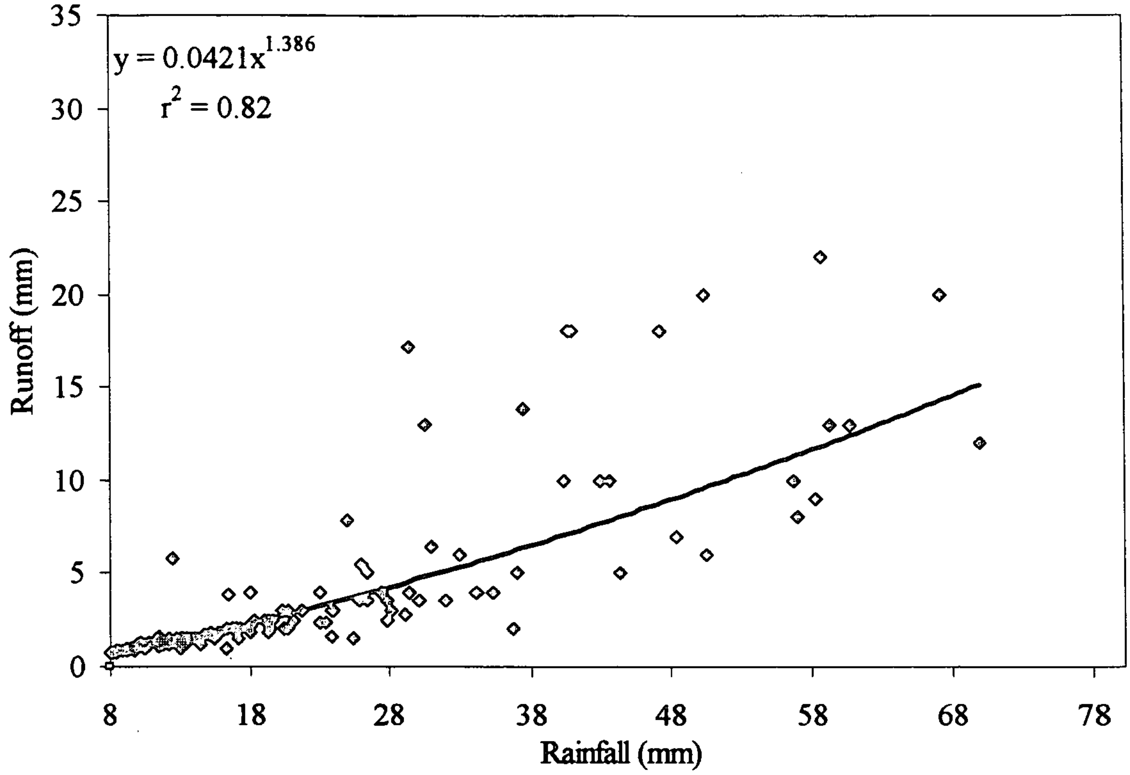


Figure 4.2 Runoff vs. rainfall curve for a dry soil on the Glen/Tukulu ecotope.

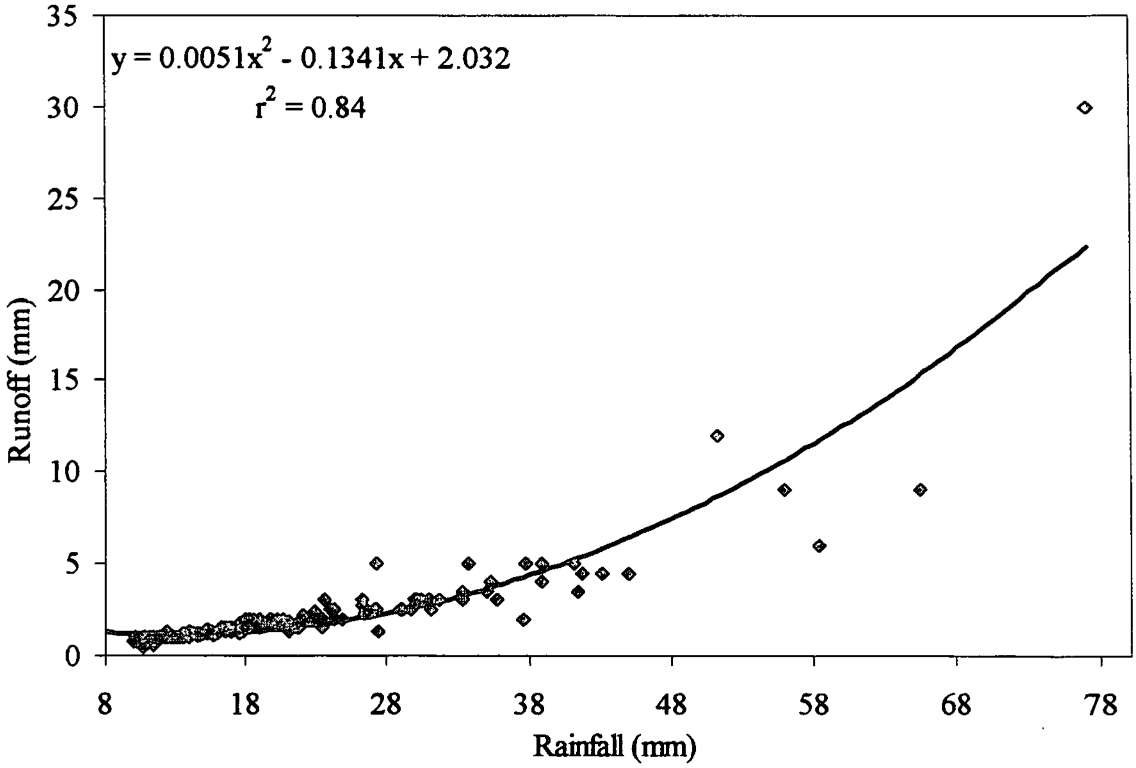


Figure 4.3 Runoff vs. rainfall curve for a wet soil on the Glen/Tukulu ecotope.

4.4 Conclusions

Two regression equations were developed, one for dry and one for wet soil conditions, for estimating runoff from rainfall. The equations developed are: $R_i = 0.005\ P_i^2 - 0.134\ P_i + 2.032$ for dry soil, and $R_i = 0.042\ P_i^{1.386}$ for wet soil, where R_i (mm) refers to the runoff generated from a certain rainfall amount (P_i, mm). The r^2 values are 0.84 for the dry equation and 0.82 for the wet equation. The r^2 values indicate a good agreement between the data. The equations can therefore be applied with reasonable confidence to predict runoff from rainfall data on Glen ecotopes with similar runoff patterns to the above ecotope and that are planted to maize with conventional tillage. This is very helpful in modelling the long-term soil water balance and, therefore, long-term yield prediction for the relevant ecotopes.

CHAPTER 5
DEVELOPMENT OF A YIELD PREDICTION PROCEDURE

5.1 Introduction

The main objective of this study was to evaluate the maize production potential of the semi-arid Glen/Hutton and Glen/Oakleaf ecotopes. Effective productivity evaluation is achieved through long-term yield prediction using historical climatic data and a crop growth simulation model. In such cases, the inputs for the model need to be carefully chosen to include the factors that limit productivity. The major factors affecting the productivity of an agricultural system include the climatic, soil and topographic characteristics of the ecotope, as well as the production techniques applied. Since the ecotopes considered are located in a semi-arid climate, plant available water is the main factor limiting their productivity. It is therefore imperative that plant available water be modelled in a reliable way to achieve meaningful productivity evaluation. This requires estimation of each component of the soil water balance. The water available for crops is then converted to total biomass production and then to grain yield through appropriate relationships. What follows is a description of the development of a simple stress model for long-term yield prediction for these ecotopes.

With reference to Equation 2.1, the water available for yield (T) at any time is estimated from the water gains and water losses to the soil-plant-atmosphere system. In dryland agriculture the water gains are rainfall plus the seasonal change in soil root zone water content during the growing season, if any. The losses include soil evaporation (E), runoff (R) and deep drainage (D). Since there was no efficient means of separating soil evaporation and transpiration, the generic crop evapotranspiration (ET) was considered to be directly related to yield. Moreover, it is reasonable in semi-arid areas to assume that deep drainage, especially under maize, is generally negligible. The eutrophic nature of the B horizons in the Glen/Oakleaf and Glen/Hutton soils (Appendices B and C), and the presence of lime in the subsoil in the Glen/Oakleaf soil, provide further support for this assumption. As rainfall was available in the form of long-term climate data, only the estimation of R and ΔS were necessary to estimate ET for each growing season. A runoff estimation procedure has been discussed in Chapter 4. The following is a description of the procedure used for the estimation of the soil water content at planting (θp), essential for obtaining ΔS.

5.2 Estimation of soil water content at planting

In dry areas soil water content at planting (θp) has a marked influence on yield. It is therefore important that this value be estimated as reliably as possible for each growing season. Measured θp values for the Glen/Hutton soil for five seasons were obtained from previous research (De Jager and Hensley, 1988; Hattingh, 1993). The data are presented in Table 5.1. These values were used to develop regression equations based on the rainfall pattern during the preceding fallow period. Several possible procedures were tested for this purpose and are described below.

It is obvious that soil water content at harvesting (θh) will be influenced by the yield obtained and by the rainfall pattern. Based on previous observations (Hattingh, 1993) some guidelines were established regarding θp. Higher yields are assumed to consume more water and so promote low θh values. Accordingly, a certain estimate of the water left for the next season was done based on the yield obtained in the previous season, as well as the crop evapotranspiration (ET) and potential evaporation (Eo) during the maturity stage (period C, Section 5.4) of that season.

The soil water balance model SWAMP (Bennie *et al.*, 1998) was used to generate θp for each of the 5 seasons for which measured values were obtained. The model requires an input of soil water content at the beginning of each simulation. This water content is normally taken as the soil water content at harvest (θh) for the previous growing season. However, measured values of θh were not available for these seasons. Therefore, three different initial soil water contents were assumed for running SWAMP to estimate θp for each of the 5 seasons, as follows:

A The effective rainfall (rainfall less runoff) for March and April during the preceding growing season was reduced by a mean value of maize water extraction during the same period, i.e. 120mm for March and 50 mm for April (Hensley, *et al.* 2000). The resulting value was added to the mean LL (227 mm for Glen/Hutton ecotope) and was used as input into SWAMP to generate θp for the fallow period. The θp values generated in this way were plotted against the measured θp values.

B The effective rainfall for only the month of April was reduced by the mean maize water extraction in the same month (50 mm). The resulting value was used in the same way as in A.

C For each season, the soil water content at harvest was taken to be at LL, *i.e.* assuming no plant available soil water was left from the previous growing season. Accordingly, SWAMP was run for the fallow periods with θh inputs at LL to generate values, which were plotted against the measured θp values.

Another approach was to simply plot the total effective rainfall during a specified period prior to planting to the measured θp values. Three such options were tested:

D The effective rainfall for the whole fallow period was added and plotted against the measured θp values. The fallow period, if no recorded dates were available, was assumed to extend from 01 May to planting.

E The total effective rainfall of the period starting from 01 October until planting was plotted against θp values.

F The total effective rainfall for the period starting from 15 October until planting was plotted against θp values.

Table 5.1 Comparing measured soil water contents at planting (θp) against estimated θp values (A-C) and different estimated effective rainfall (Ep) values (D-F) over 5 seasons on the Glen/Hutton ecotope. r^2 values compare estimated and measured values for the 5 seasons.

Growing	**Measured [1]θp**	**Estimated θp(mm) [2]**			**Effective rainfall (Pe, mm)**		
season	**(mm)**	**A**	**B**	**C**	**D**	**E**	**F**
84/85	282.0	273.0	273.0	273.0	209.1	110.7	59.8
85/86	360.0	306.0	306.0	306.0	255.6	194.6	175.8
86/87	319.0	319.0	320.0	312.0	309.7	197.6	190.1
88/89	335.0	376.0	353.0	368.0	397.7	224.2	167.5
89/90	317.8	283.0	257.0	283.0	256.2	163.4	152.1
r^2	-	**0.25**	**0.24**	**0.28**	**0.18**	**0.63**	**0.63**

[1] Obtained from De Jager and Hensley (1988), Hattingh (1993).

[2] (i) A, B and C are SWAMP generated θp as already described.
(ii) D, E and F according to the total effective rainfall procedure as already described.

The resulting correlations between the estimated values and the measured θp values are presented in Table 5.1. The coefficients of determination (r^2 values) for the different procedures mentioned above show that the estimated values were all related to some extent to the measured soil water contents. Estimates using SWAMP are poorly correlated to the measured values. The probable reason being that the current version of SWAMP generally overestimates E from these soils. The prediction of E during the fallow period appears to be difficult. The PUTU and CERES crop models also generally give poor predictions (Hensley, personal communication, 2002). The highest correlations were found to be for procedures E and F; these results are presented in Figure 5.1. Of these, procedure E has been selected for the estimation of θp. The relationship is given in Equation 5.1.

$$\theta p = 0.5227\,Pe + 229.7 \qquad \text{(mm)} \qquad (r^2 = 0.63) \qquad (5.1)$$

where Pe = effective rainfall for the period from 1 October to planting (mm).

It is interesting to note that the constant in Equation 5.1, 229.7 mm, is close to the LL value for maize on this soil. The worst scenario (zero effective rainfall) will result in a θp value close to LL. This is a reasonable assumption, as, under normal planting conditions, the profile does not dry out to below LL.

The initial soil water content for each growing season during the 80 years could now be estimated using Equation 5.1. However, as it can be deduced from the relatively low r^2 value, this is still not a very reliable procedure. For one thing the measured θp data are rather few to establish such an important relationship in a reliable way. It was therefore decided to add an augmenting procedure to improve the estimation of θp. This is described in the following paragraph.

The evapotranspiration for period C was reduced by a certain proportion (f, Table 5.2) of the Eo for the same period. The resulting value, if any, was then added to the θp value estimated from Equation 5.1. For instance, assuming that Yg for a growing season was 3000 kg ha^{-1}, and that for the maturity stage ET = 150 mm and Eo = 350 mm, the θp estimated using Equation 5.1 for the following growing season would be increased by 150-(350*0.33) = 35 mm. This procedure was possible for each season after yield and soil water balance estimation was done for the preceding seasons.

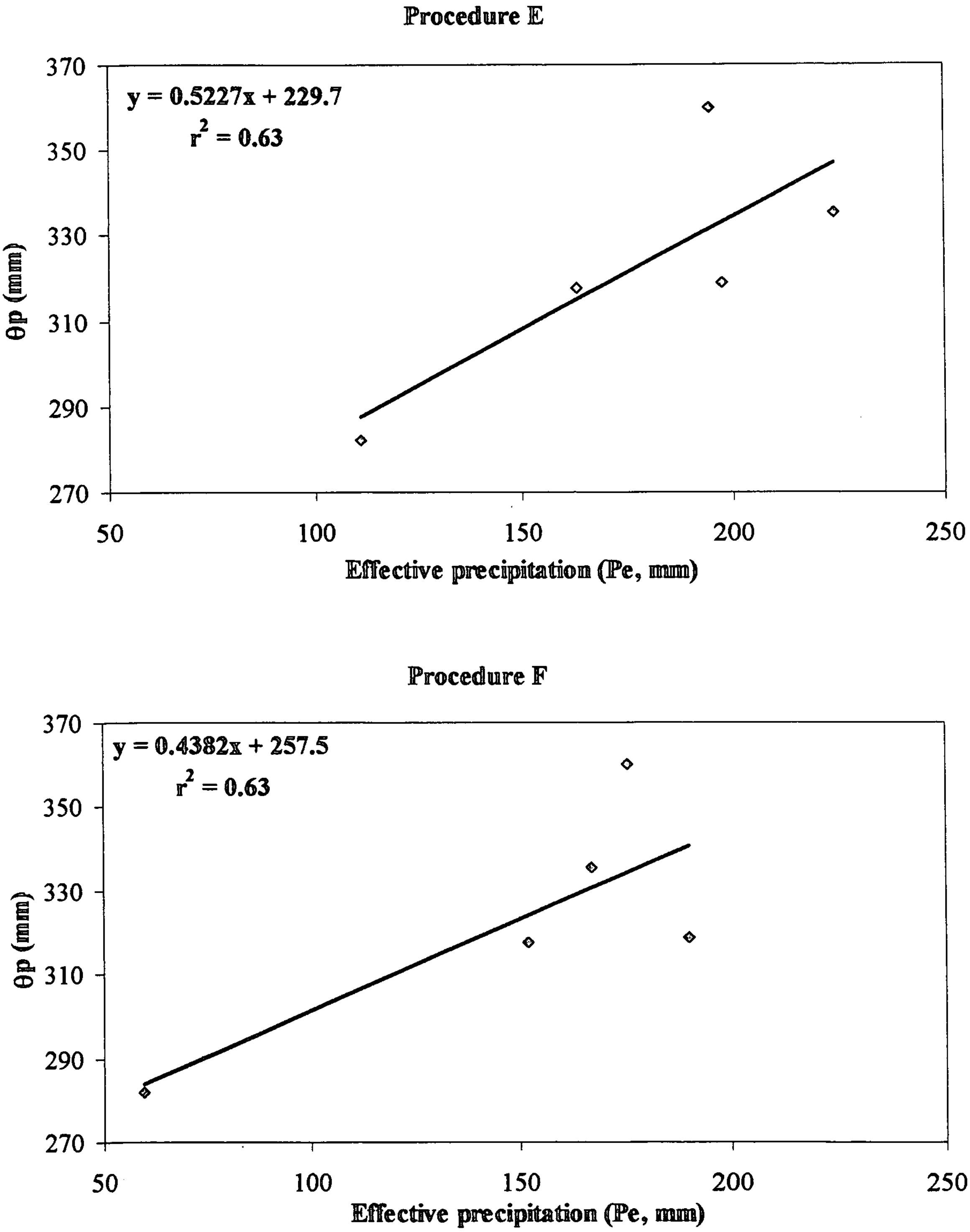


Figure 5.1 Soil water content at planting (θp) as a function of the effective precipitation (Pe) from 1 October to planting (Procedure E); and from 15 October to planting (Procedure F).

Table 5.2 Yield-dependent correction factor (f) for improving the estimation of θp for the Glen/Hutton and Glen/Oakleaf soils.

Yg (kg/ha)	**f**
>2500	0.33
$2000 < Yg \leq 2500$	0.30
$1500 < Yg \leq 2000$	0.27
$1000 < Yg \leq 1500$	0.24
$500 < Yg \leq 1000$	0.21
≤ 500	0.18

5.3 Measured maize yields at Glen

The prediction of long-term maize productivity on the Glen/Hutton and Glen/Oakleaf ecotopes was facilitated by the availability of long-term climate data and many measured yields over a long period (Table 5.3). Maize yields for a total of 22 seasons were obtained from past research work. These include six yields from De Wet and Engelbrecht (1962), ten from De Bruyn (1974), and six recent yields obtained from two other publications (De Jager and Hensley; 1988; Hattingh 1993). During the period under consideration (1955-1990) maize production techniques have improved a great deal, resulting in large yield increases independent of the natural resources under discussion. The breeding of better cultivars have probably made the greatest contribution to these yield increases. Quantifying the extent of these increases is difficult. An estimate is nevertheless necessary in order to use earlier measured yields in a meaningful way to evaluate the ecotope in terms of maize productivity using modern production techniques. Du Toit (1994) stated, "Genetic progress in terms of yield over the past 10 years seems to be approximately 1% per year..." Du Toit (1994) also stated that Kühn and Gevers reported in 1980 that the first hybrids (evidently introduced ± 1960) yielded 25-30% more than open pollinated varieties. In view of these results, it seems reasonable to estimate that the yields measured by De Wet and Engelbrecht (1962), using the old variety Boesman/Cincinnati, over the period 1955-1961 would have been 30% higher if they had used modern cultivars and tillage methods (e.g. deep ripping), and that the yield measured by De Bruyn (1974) would have been about 25% higher using modern production techniques. Support for estimates of this order has been obtained from an expert in this field (J. Du Plessis, personal communication, 2002). The necessary adjustments are presented in Table 5.3.

Table 5.3 Measured and adapted maize grain yields (Yg) from Glen/Hutton and Glen/Oakleaf ecotopes.

Ecotope	**Season**	**Measured Yg (kg/ha)**	**Increment factor**	**Adapted (kg/ha)**	**Source of data**
Glen/Hutton	55/56	1340	1.3	1820	De Wet and Engelbrecht (1962)
Glen/Hutton	56/57	2420	1.3	3146	De Wet and Engelbrecht (1962)
Glen/Hutton	57/58	2224	1.3	2892	De Wet and Engelbrecht (1962)
Glen/Hutton	58/59	684	1.3	889	De Wet and Engelbrecht (1962)
Glen/Hutton	59/60	1497	1.3	1947	De Wet and Engelbrecht (1962)
Glen/Hutton	60/61	944	1.3	1227	De Wet and Engelbrecht (1962)
Glen/Oakleaf	61/62	1558	1.25	1948	De Bruyn (1974)
Glen/Oakleaf	62/63	2210	1.25	2763	De Bruyn (1974)
Glen/Oakleaf	63/64	1115	1.25	1394	De Bruyn (1974)
Glen/Oakleaf	64/65	2127	1.25	2659	De Bruyn (1974)
Glen/Oakleaf	65/66	2200	1.25	2750	De Bruyn (1974)
Glen/Oakleaf	66/67	2857	1.25	3571	De Bruyn (1974)
Glen/Oakleaf	67/68	2419	1.25	3024	De Bruyn (1974)
Glen/Oakleaf	69/70	1665	1.25	2081	De Bruyn (1974)
Glen/Oakleaf	70/71	1794	1.25	2243	De Bruyn (1974)
Glen/Oakleaf	73/74	4744	1.25	5930	De Bruyn (1974)
Glen/Hutton	83/84	460	N/A[1]	460	De Jager and Hensley (1988)
Glen/Hutton	84/85	3000	N/A	3000	De Jager and Hensley (1988)
Glen/Hutton	85/86	2000	N/A	2000	De Jager and Hensley (1988)
Glen/Hutton	86/87	3000	N/A	3000	De Jager and Hensley (1988)
Glen/Hutton	88/89	2753	N/A	2753	Hattingh (1993)
Glen/Hutton	89/90	3580	N/A	3580	Hattingh (1993)

[1] N/A = Not applicable; recent yields were obtained with modern production techniques.

The relationship between plant water stress and crop production has long been appreciated by researchers (e.g. Briggs and Shantz (1913) cited by Rasmussen and Hanks (1978), and De Wit (1958)). Total biomass yield is closely related to plant water use, especially in dry areas, rendering estimation of the soil water balance very important for yield prediction. Several yield prediction models have been developed, based on plant water stress, and have been applied for many purposes with a considerable degree of success (e.g. Hanks and Rasmussen, 1982). For this study, total above ground biomass (Yb) and grain yields (Yg) were available for the 1961/62 to 1973-74 seasons (De Bruyn, 1974) and for the 1988/89 and 1989/90 seasons (Hattingh, 1993). For the rest of the 22 seasons, Yb was estimated from the grain yields (Yg) as follows: A total of 38 pairs of Yb-Yg values, produced under different production techniques from various ecotopes at Glen, were obtained from De Bruyn (1974), Hattingh (1993), Schmidt (1993), Hensley *et al.* (2000), and Botha *et al.* (2002). These values were plotted against each other to obtain the regression equation of Yb against Yg (Figure 5.2). The relationship is presented in Equation 5.2.

$$Yb = 1.95\,Yg + 780.7 \qquad (r^2 = 0.90) \qquad (5.2)$$

where Yb = total above ground biomass yield (kg ha^{-1})
Yg = grain yield (kg ha^{-1})

This is a linear relationship where Yg is about 45% of Yb. This is in good agreement with the values reported by Sinclair *et al.* (1990). The relationship was used to estimate Yb from Yg for all seasons on which measured Yb values were not available. The same relationship was also used to estimate Yg from Yb to complete the yield prediction procedure (see following sections and Chapter 6).

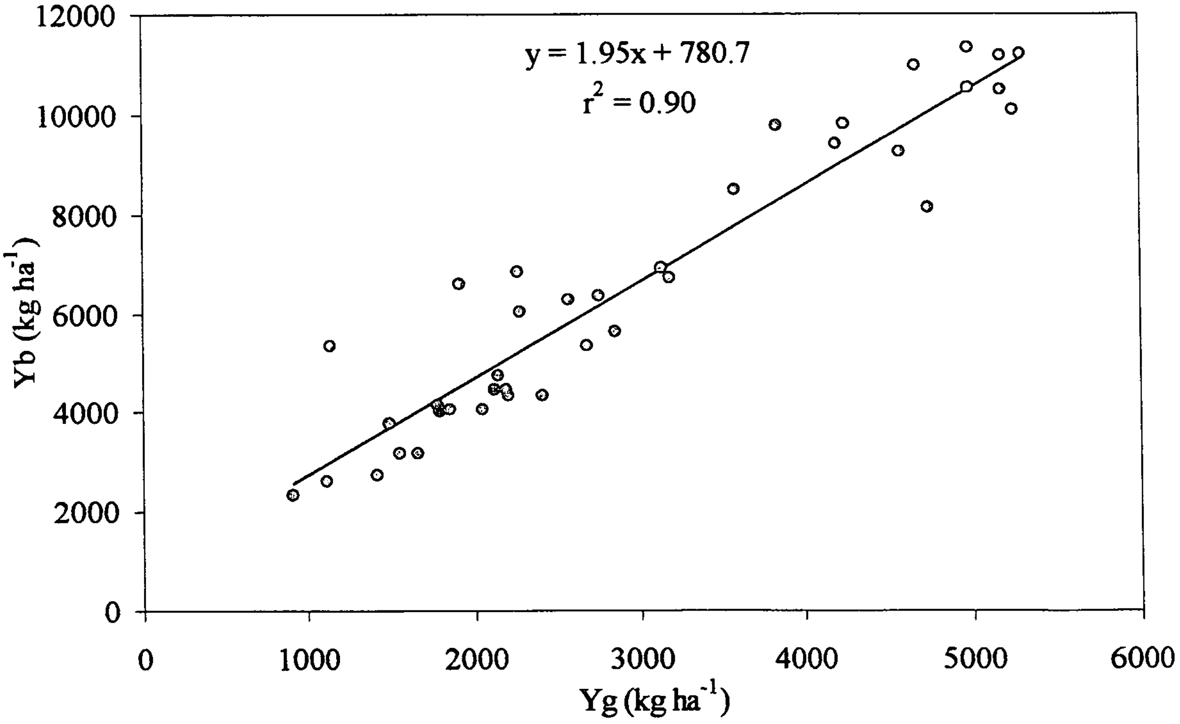


Figure 5.2 Measured maize grain yield (Yg) vs. total biomass yields (Yb) at Glen. Data from: De Bruyn (1974), Hattingh (1993), Schmidt (1993), Hensley *et al.* (2000) and Botha *et al.* (2002).

Based on the above yields an attempt was made to calibrate SWAMP, to be able to use it for yield prediction for the whole 80 year period for which climate is available for these ecotopes. The current version of SWAMP, however, was found to be unsatisfactory for yield prediction on these ecotopes. The model is in the process of being updated. The complete updated version was, however, not available during this study.

5.4 Developing an integrated stress index for yield prediction

It was decided to develop a maize stress index (SI) yield prediction procedure similar to that originally developed by Rasmussen and Hanks (1978) and used with reasonable success for wheat by Korentajer and Berliner (1988) and for wheat at Glen by Hensley and Snyman (1991). The procedure is based on the hypothesis that in a dry area, where the crop is generally under some degree of water stress during entire growing season, the yield will be inversely proportional to the degree of stress experienced. It is appropriate to express this degree of stress as an integrated value, formulated from individual SI values representing selected portions of the season and weighted according to the sensitivity of the crop to drought stress during that particular part of the growing season. The weighting can be achieved in two ways, firstly by the choice of the location and length of the subdivisions of the season, and secondly by the formula used to integrate the indices for each of the subdivisions into an integrated stress index (ISI).

The planting date and the length of the growing season for seasons on which there were no yields were determined in accordance with available records. Based on a mean value for 10 growing seasons (De Bruyn, 1974), a mean growing season length of 153 days was chosen for all seasons previous to De Bruyn's. For seasons following De Bruyn's, a mean growing season length, recorded for seven seasons (De Jager and Hensley, 1988; Hattingh, 1993) of 145 days was used. The planting dates, for each season for which there were no yields, were chosen to be the date following the first effective rainfall event (about 15 mm) in November.

The symbol Eo will be used for potential evaporation considered to be equivalent to A-pan evaporation. It was decided that the ratio ET/Eo for a particular period was a suitable stress index (Rasmussen and Hanks, 1978; Korentajer and Berliner, 1988; Hensley and Snyman, 1991), and that ET for a particular period could be reasonably estimated as rainfall during the period minus runoff. For the first period of each growing season the plant available water, based on the predicted θp was added to the rainfall.

Potential evaporation (Eo) for Glen during the 80 years was estimated in the following manner. Measured daily A-pan evaporation data from 1958 to date for Glen was obtained from the ISCW climate data bank. For the period 1922-1958 only temperature and rainfall data is available. The A-pan data has many missing values. It is therefore not reliable in its present state. Reference evapotranspiration (ETo) data generated by the PUTU crop growth model, for the whole 80 years, was also obtained (Anderson, personal communication, 2002). For the period 1958-2002, the available A-pan data was correlated with the PUTU generated ETo data. The resultant r^2 value was about 0.7, indicating only an approximate relationship between the two sets of data. A probable cause for the unsatisfactory relationship is the unreliable nature of the A-Pan data. An alternative procedure was therefore followed for the generation of daily Eo data for the 80 years. Conversion factors between ETo and Eo for each month for Glen were obtained (Crosby, personal communication, 2002). The following are the factors: 0.703, 0.753, 0.709, 0.724, 0.676, 0.747, 0.735, 0.737, 0.630, 0.659, 0.716, and 0.699 for January through December, respectively. Using these conversion factors, daily Eo data for the 80 years (1922-2002) were generated from the PUTU generated ETo data.

It was decided to divide each growing season into three distinct growth periods, namely:

- First period (A) extends from planting to the end of the vegetative phase (60-65 days).
- Second period (B) extends from the end of A to the end of reproductive phase *i.e.* the flowering and most drought sensitive phase (25 days).
- Third period (C) extends from the end of flowering to harvesting *i.e.* the stage considered to be least sensitive to drought.

An SI value was calculated for each of these periods as ET/Eo. The range of values is therefore between 0 and 1.0. In order to identify the best formula for integrating the individual SI values to get an integrated stress index (ISI) for the growing season with a range from 0 to 1.0, the following eight logical alternatives were formulated:

$$ISI_1 = A^{0.3} . B^{0.2} . C^{0.5} \tag{5.3}$$

$$ISI_2 = A^{0.33} . B^{0.33} . C^{0.33} \tag{5.4}$$

$$ISI_3 = (2A + 4B + C)/7 \tag{5.5}$$

$$ISI_4 = (A + 5B + C)/7 \tag{5.6}$$

$$ISI_5 = (A + B + C)/3 \tag{5.7}$$

$$ISI_6 = ETt/Eot \tag{5.8}$$

$$ISI_7 = (2A + 3B + C)/6 \tag{5.9}$$

$$ISI_8 = (2A + 3B + 2C)/7 \tag{5.10}$$

where A = SI for the first period
B = SI for the second period
C = SI for the third period
ETt = total crop evapotranspiration (mm) for the whole growing season
Eot = total potential evaporation (mm) for the whole growing season.

The ET for period A of each season was calculated by adding the effective rainfall for the period plus an estimate of plant available soil water at planting. The latter was estimated as θp minus the value at serious stress (SS) for the Glen/Hutton ecotope (260 mm). θp was estimated as discussed in Section 5.2 for seasons on which measured values were not available. ET for periods B and C was estimated as the effective rainfall (rainfall minus runoff). Occasionally the estimated ET was found to be higher than the corresponding Eo for a given period. This would give a SI value greater than unity, which is impossible. In such cases, the excess value was considered to be deep percolation loss. Each of the ISI calculation procedures were then carried out for each of the 22 seasons and the resultant values regressed against the measured or estimated biomass yields.

5.5 Results and discussion

The eight possible ISI's computed for each of the 22 seasons and their component values for each growth stage are presented in Table 5.4. The regression equations between each of the alternative ISI's and the biomass yields, together with their respective r^2 values, are presented in Table 5.5. Looking at the r^2 values of the different curves, it can be concluded that ISI_8 vs. Yb is the best relationship of all the alternatives. The relationship is presented in Equation 5.11.

$$Yb = 15238\ ISI_8 + 1067 \qquad (r^2 = 0.69) \qquad (5.11)$$

where Yb = Total biomass (kg ha^{-1})
ISI_8 = Integrated stress index, as calculated from Equation 5.10.

As it can be deduced from the linear regression equation, the minimum biomass yield predicted using this equation will be 1 067 kg ha^{-1}. From Equation 5.2, the corresponding minimum grain yield value will be 427.3 kg ha^{-1}. This value is just below the minimum observed Yg (1983/84 season) from the Glen/Hutton ecotope, which is 460 kg ha^{-1} (De Jager and Hensley, 1988). This fact lends credence to the prediction procedure. The slightly low r^2

value is most probably due to slight discrepancies between planting dates and growth stages experienced during the planting seasons and those selected for the prediction procedures. This relationship was used for estimating Yb for all seasons during the 80 years (from 1922 to 2002). The Yg values were then estimated from Yb using Equation 5.2.

Table 5.4 Integrated stress indices (ISI's) developed for predicting maize yield on the Glen/Hutton and Glen/Oakleaf ecotopes.

Growing	Plants	Period A			Period B			Period C			Full season			Possible indices[3]								Yb[4]
season	per ha	ET[1] (mm)	Eo[2] (mm)	ET/Eo	ET[1] (mm)	Eo[2] (mm)	ET/Eo	ET[1] (mm)	Eo[2] (mm)	ET/Eo	ET[1] (mm)	Eo[2] (mm)	ET/Eo	ISI_1	ISI_2	ISI_3	ISI_4	ISI_5	ISI_6	ISI_7	ISI_8	(kg ha^{-1})
1955/56	17940	140	611	0.23	6	261	0.02	314	439	0.71	460	1311	0.35	0.25	0.15	0.18	0.15	0.32	0.35	0.21	0.28	4329
56/57	17940	178	615	0.29	56	239	0.24	90	451	0.20	324	1304	0.25	0.23	0.24	0.25	0.24	0.24	0.25	0.25	0.24	6914
57/58	17940	206	607	0.34	40	237	0.17	105	459	0.23	351	1302	0.27	0.24	0.24	0.23	0.20	0.25	0.27	0.24	0.23	6419
58/59	17940	139	676	0.21	59	222	0.27	93	487	0.19	291	1385	0.21	0.21	0.22	0.24	0.25	0.22	0.21	0.23	0.23	2513
59/60	17940	233	649	0.36	53	248	0.21	125	473	0.26	411	1369	0.30	0.28	0.27	0.26	0.24	0.28	0.30	0.27	0.27	4576
60/61	17940	116	630	0.18	59	230	0.26	129	468	0.27	304	1329	0.23	0.24	0.24	0.24	0.25	0.24	0.23	0.24	0.24	3173
61/62	17900	77	693	0.11	86	200	0.43	145	448	0.32	308	1341	0.23	0.25	0.25	0.32	0.37	0.29	0.23	0.31	0.31	4578
62/63	17900	188	609	0.31	88	221	0.40	209	429	0.49	485	1259	0.39	0.41	0.39	0.39	0.40	0.40	0.39	0.38	0.40	6167
63/64	17900	178	640	0.28	50	256	0.20	106	502	0.21	334	1397	0.24	0.23	0.23	0.22	0.21	0.23	0.24	0.23	0.22	3498
64/65	17900	156	611	0.26	119	242	0.49	18	539	0.03	292	1392	0.21	0.10	0.16	0.36	0.39	0.26	0.21	0.34	0.29	5964
65/66	17900	140	676	0.21	112	184	0.61	24	458	0.05	275	1318	0.21	0.13	0.19	0.41	0.47	0.29	0.21	0.38	0.33	6142
66/67	17900	231	598	0.39	48	192	0.25	175	283	0.62	453	1073	0.42	0.45	0.39	0.34	0.32	0.42	0.42	0.36	0.39	7744
67/68	17900	72	669	0.11	24	256	0.09	204	398	0.51	300	1322	0.23	0.23	0.17	0.16	0.15	0.24	0.23	0.17	0.22	6676
69/70	17900	226	657	0.34	26	244	0.11	43	379	0.11	296	1280	0.23	0.16	0.16	0.18	0.14	0.19	0.23	0.19	0.18	4839
70/71	17900	185	588	0.31	28	208	0.13	111	384	0.29	324	1180	0.27	0.25	0.23	0.21	0.18	0.25	0.27	0.22	0.23	5153
73/74[5]	17900	243	579	0.42	229	174	1.00	215	355	0.61	632	1108	0.57	0.60	0.63	0.78	0.86	0.67	0.57	0.74	0.72	12342
83/84	17500	166	614	0.27	22	255	0.09	60	400	0.15	248	1269	0.20	0.16	0.15	0.15	0.12	0.17	0.20	0.16	0.16	1678
84/85	15000	127	604	0.21	75	195	0.39	114	407	0.28	316	1206	0.26	0.27	0.28	0.32	0.35	0.29	0.26	0.31	0.31	6630
85/86	18000	149	592	0.25	28	238	0.12	140	394	0.35	316	1224	0.26	0.26	0.22	0.19	0.17	0.24	0.26	0.20	0.22	4680
86/87	15000	71	662	0.11	107	200	0.53	114	400	0.28	291	1262	0.23	0.24	0.25	0.38	0.44	0.31	0.23	0.35	0.34	6630
88/89	13333	101	477	0.21	117	193	0.61	123	328	0.38	341	998	0.34	0.35	0.36	0.46	0.52	0.40	0.34	0.44	0.43	6333[6]
89/90	13333	167	561	0.30	107	182	0.59	104	265	0.39	378	1008	0.38	0.39	0.41	0.48	0.52	0.43	0.38	0.46	0.45	8453[6]

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[1] Evapotranspiration (ET) for period A was calculated as rainfall minus runoff, added to the plant available soil water content at planting, as described in Section 5.4. For the other periods, ET was simply calculated as rainfall minus runoff.

[2] Potential evapotranspiration (Eo) as calculated from Eo-ETo relationships developed by Crosby (see text).

[3] Different combinations of the stress indices for the three growth stages (A-C) as presented in Equations 5.3 to 5.10.

[4] Estimated "actual" total biomass yields (Yb) using Equation 5.2 with the measured and adapted Yg yields presented in Table 5.3.

[5] ET in period B of this season is in excess of Eo. The difference was considered as deep drainage.

[6] Measured Yb values (Hattingh, 1993).

Table 5.5 Relationships between different integrated stress indices (ISI's) and maize biomass yields (Yb) for 22 seasons on the Glen/Oakleaf and Glen/Hutton ecotopes.

Relationship	Regression equation obtained	r^2
Yb vs. ISI_1	$Yb = 14065\ ISI_1 + 1915$	0.50
Yb vs. ISI_2	$Yb = 15201\ ISI_2 + 1666$	0.59
Yb vs. ISI_3	$Yb = 12366\ ISI_3 + 1922$	0.63
Yb vs. ISI_4	$Yb = 9826\ ISI_4 + 2603$	0.58
Yb vs. ISI_5	$Yb = 16891\ ISI_5 + 628$	0.68
Yb vs. ISI_6	$Yb = 18339\ ISI_6 + 477$	0.55
Yb vs. ISI_7	$Yb = 13988\ ISI_7 + 1475$	0.66
Yb vs. ISI_8	$Yb = 15238\ ISI_8 + 1067$	0.69

5.6 Conclusions

A reliable θp estimation procedure was developed based on the pattern of effective rainfall during a preceding fallow period and the yield level for the preceding season. The effective precipitation for the period from 1 October to planting (Pe) was found to be well correlated to the soil water content at planting (θp)((*i.e*, $\theta p = 0.5227\ Pe + 229.7$, $r^2 = 0.63$). This correlation, augmented by a procedure that depends on the yield obtained in the previous season as well as the ET and Eo values during the maturity stage of that season, was used to estimate θp. This procedure, together with the runoff estimation procedure discussed in Chapter 4, enables the estimation of ET on a daily basis from the Glen/Hutton and Glen/Oakleaf ecotopes.

Based on the estimated ET and Eo values, as well as 22 seasons of measured maize yields, it was possible to develop a reliable relationship between the integrated stress index (ISI, dimensionless) and total above ground maize biomass yield (Yb, kg ha^{-1}) for the Glen/Hutton and Glen/Oakleaf ecotopes. The following relationship was developed: $Yb = 15\ 238\ ISI + 1067$, $r^2 = 0.69$. The ISI was weighted from the individual SI values for each growth stages (A, B, and C) as $ISI = (2A+3B+2C)/7$. Grain yield (Yg, kg ha^{-1})) was estimated from Yb using the relationship developed ($r^2 = 0.90$) as $Yb = 1.95\ Yg + 780.7$.

This yield prediction procedure is valuable for making long-term yield predictions on these ecotopes from historical climate data, thereby making it possible to conduct a useful maize productivity evaluation for these ecotopes.

CHAPTER 6

LONG-TERM YIELD PREDICTION TO EVALUATE MAIZE PRODUCTION POTENTIAL

6.1 Introduction

Long-term yield prediction has enormous advantages over short-term yield observations. This is particularly true in arid and semi-arid areas, where rainfall is marginal and erratic in terms of amount, intensity and distribution. Long-term yield data can demonstrate the effect of these climatic variations on crop yield. Using long-term yield data it is possible to evaluate the productivity of crop ecotopes, using different production techniques, with known probability, and therefore with known risk of crop failure. This is possible because, having enough number of observations, it is possible to produce CPF's for each crop ecotope under specified production techniques. Cumulative probability functions enable one to make a quantitative assessment of the risk attached to each target yield. This is not possible from short-term yield measurements obtained from field experiments.

This chapter describes the application of the stress model developed in this study to predict maize yields for 80 years for the Glen/Oakleaf and Glen/Hutton ecotopes. The four different production techniques considered have first been briefly described and then compared based on the yield CPF's drawn for each of them.

6.2 Procedure

Long-term yield prediction was carried out for the Glen/Hutton and Glen/Oakleaf ecotopes using four different production techniques for 80 seasons (1922/23 - 2001/02). This was carried out using the yield prediction model developed during the course of this study (Chapter 6), along with historical daily rainfall and reference evaporation data. A CPF graph of grain yields was drawn for each of four production techniques. The performance of the ecotopes under these production techniques was then analysed from the CPF's using statistical tests. The following four different production techniques were evaluated.

- November planting with conventional tillage

- November planting with in-field water harvesting and basin tillage
- January planting with conventional tillage
- January planting with in-field water harvesting and basin tillage

The procedures followed for each production technique are briefly discussed below.

6.2.1 November planting with conventional tillage (CTN)

The CTN technique comprises early planting of long growing season maize varieties. In this technique, it was attempted to mimic, as much as possible, the most common production technique practiced in this area. For each growing season the planting date was chosen to be the day following the first effective rain (about 15 mm) in November. The length of the growing season and the different growth stages during the season were determined in a manner discussed in Section 5.4. ET for each period of the growing season was calculated as described in Chapter 6. The soil water content at planting (θp) was estimated from the effective rainfall using Equation 6.1 and the augmenting procedure described. The ISI was then calculated for the growing season using Equation 6.10. Yb was estimated from ISI using Equation 6.11 and, finally, Yg was estimated from Yb using Equation 6.2. This was repeated for all growing seasons from 1922/23 to 2001/02, except for the 22 seasons for which measured (or adapted) yields were available.

6.2.2 January planting with conventional tillage (CTJ)

The value of this cropping technique is based on the fact that March is the month with the highest and most reliable rainfall, and by far the most favourable aridity index (Table 3.1). Short season maize planted early in January would flower in March. Maize is most sensitive to drought during the flowering period. The advantage of January planting was originally suggested by De Bruyn (1974) after 10 years of maize experimentation at Glen. This production technique is similar to the CTN in that both are practised under conventional production techniques. In this case, however, short growing season maize cultivars were considered. The planting date was chosen as the day following the first significant rainfall (about 15 mm) rainfall in the first half of January. If there was no significant rainfall in this period, then the day following the last significant rainfall (about 15) mm in the second half of

December was chosen as the planting date. In seasons where none of these was possible, a suitable planting time, just out of the chosen periods, or days following smaller rainfall events was chosen. The length of the growing season was set to 120 days. This was divided into 60, 20, and 40 days for the first, second, and third growth stages.

6.2.3 November planting with in-field water harvesting and basin tillage (WHBN)

This production technique is similar to the CTN technique with regard to planting date and length of growing season. In the WHBN technique in-field water harvesting (WH) was applied. Runoff water was collected from the unplanted 2 m wide area between crop rows into basins within the 1 m wide area where the plant roots can reach. This is illustrated in Figure 6.1. Crop Evapotranspiration (ET) was therefore estimated as the total rainfall plus twice the total runoff for each period of the season. Conventional tillage was assumed on the runoff area. If the runoff areas remained untilled (*i.e.* adding no-till to WHB), they would produce higher runoff (See Figure 4.1). It should therefore be noted that in the WHBN technique described here runoff is minimal compared to an equivalent no-till procecure.

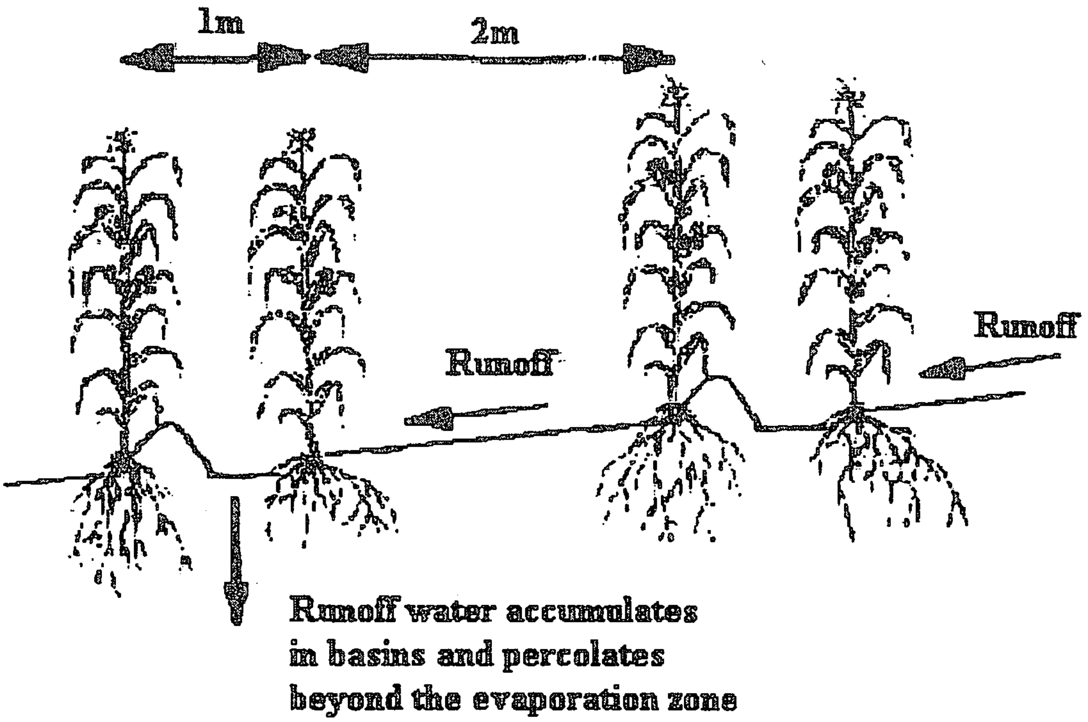

Figure 6.1 A diagrammatic description of the WHB production technique (Hensley *et al.*, 2000).

6.2.4 January planting with in-field water harvesting and basin tillage (WHBJ)

This technique is the same as CTJ regarding the planting date and growth periods, and it is similar to the WHBN in that in-field water harvesting is applied. This is expected to be the best production technique because it has the advantages of both water harvesting and the fact that flowering occurs in March, thereby benefitting from the generally higher rainfall and lower evapotranspiration conditions. A possible disadvantage in this and the CPJ techniques is that, if high rainfall occurs in the months October to December, deep drainage water loss might take place, thereby reducing the water available to crops.

6.2.5 Statistical analyses

Cumulative probability functions of maize yields were constructed for each of the production techniques discussed above. In each case, yields of the 80 years were arranged in ascending order and ranked. The cumulative probability of each yield was then calculated as the probability of the particular yield plus the sum of the probabilities of the yields ranked below it. The CPF's were finally drawn as the cumulative probabilities against the corresponding yields. To analyse the CPF's, two stochastic dominance criteria, as described by Anderson (1977) and Boehlje and Eidman (1984), were applied, namely the first-degree and second-degree stochastic dominance criteria. First-degree stochastic dominance (FSD) assumes that more yield is preferred during the decision making process. This implies that, if the cumulative probability of a production technique is greater than the cumulative probability of another for all levels of outcome, then the production technique with the lower cumulative probability dominates the other one. Graphically, this means that the CPF of the dominant technique, in terms of FSD, always lies below and to the right of the dominated technique. FSD cannot be applied if the CPF's of the alternatives considered cross or touch each other. In such cases, the second-degree stochastic dominance (SSD) can be used. In addition to preferring more to less, the SSD assumes that the decision maker is risk averse. Graphically, using SSD, the production technique with a smaller area below its CPF is preferred to the one with a larger area.

To test the degree to which the cumulative distributions are statistically different, the Kolmogorov-Smirnov (K-S) two sample test was applied (Steel *et al.*, 1997; Langyintuo *et al.*, 2002). According to the K-S test, two distributions are significantly different if the maximum vertical deviation between them (D-statistic) exceeds the critical value at the specified significance level (α). In other words, the hypothesis that the CPF's are similar (Ho) is tested, using the K-S test. This test serves to identify the validity of stochastic dominance comparisons. If the K-S test is not significant, stochastic dominance comparisons can only be considered indicative (Langyintuo *et al.*, 2002).

6.3 Results and discussion

Predicted grain yields for 80 years for the four production techniques are presented in Appendix K. The corresponding CPF graphs are presented in Figure 6.2.

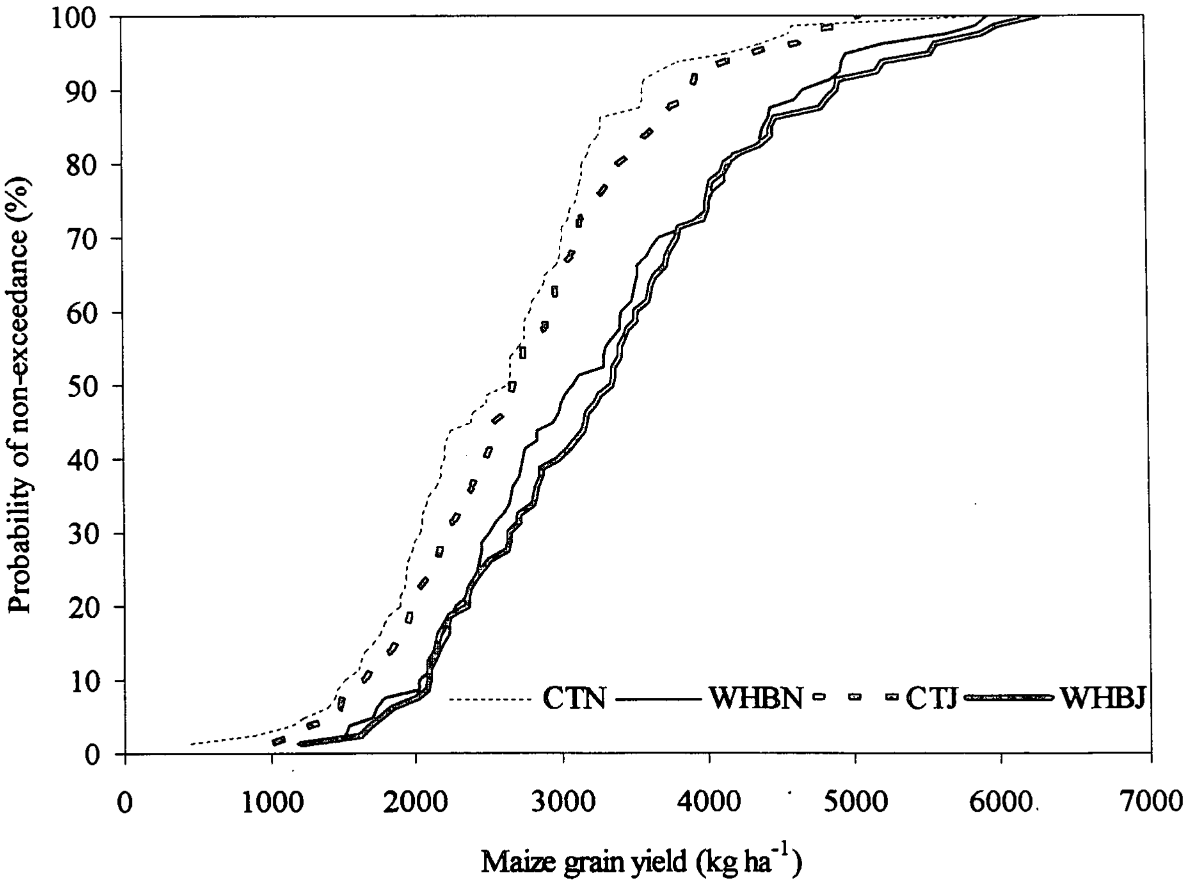

Figure 6.2 CPF graphs for predicted maize yields four different production techniques on the Glen/Oakleaf and Glen/Hutton ecotopes.

In general the CPF's for the water harvesting techniques (WHBN and WHBJ) were located to the right of the conventional tillage techniques (CTN and CTJ), indicating better results from the former. The WHBJ technique is shown to exhibit well defined first degree dominance over both the CTN and CTJ, and second degree dominance over the WHBN technique. This is consistent with the expected benefits of water harvesting and January planting, because the flowering period occurs in the relatively cooler and wetter month of March. The results also confirm the observation by Hensley *et al.* (2000) on the Glen/Swartland and Glen/Bonheim ecotopes that WHB treatments showed significant increases of yield over conventional production techniques. The WHBN treatment dominated the CTN and CTJ with first degree stochastic dominance. Among the conventional tillage treatments, the CTJ dominated the CTN in terms of second degree stochastic dominance; the two treatments did not differ in terms of first degree stochastic dominance.

The long-term mean yields at three levels of probability, namely at 25%, 50% and 75% probability of exceeding the given yields, are presented in Table 6.1. As shown in the table, the CPF's predict that the long term mean yields (50% probability) were 2 653, 2 685, 3 108 and 3 355 kg ha^{-1} for the CTN, CTJ, WHBN and WHBJ techniques respectively. De Bruyn's (1974) measured mean Yg for 10 seasons at the Glen/Oakleaf ecotope, after the necessary adaptations (see Section 6.3), was 2 836 kg ha^{-1}. This mean Yg value is fairly close to the long-term means from the two conventional tillage techniques (CTN and CTJ), giving confirmation of the results predicted. The CPF graphs, at the above three levels of probability, also predict that the water harvesting techniques show greater differences from the conventional production techniques than within themselves.

Table 6.1 Simulated long-term maize grain yields (kg ha^{-1}) the Glen/Hutton and Glen/Oakleaf ecotopes for four different production techniques. Results are expressed in terms of three probabilities.

Probability of a specified yield being exceeded	**Production techniques**			
	CTN	CTJ	WHBN	WHBJ
75%	1954	2127	2434	2482
50%	2653	2685	3108	3355
25%	3123	3266	4031	4019

The K-S test results for the CPF's are presented Table 6.2. The CPF for the WHBJ technique was highly significantly different ($\alpha \leq 0.01$) to those of the conventional techniques (CTN and CTJ). Similarly, the WHBN technique was found to be significantly different to the CTN ($\alpha \leq 0.01$) and CTJ ($\alpha \leq 0.05$) techniques. No statistical significant difference was observed within the WHB as well as within the CT techniques. As with the stochastic dominance, the K-S results reveal that the water harvesting technique was very effective. However, not enough evidence was obtained to show that the short growing season varieties produced significantly higher yields than the long growing season varieties. As it is mentioned above, this might be due to large deep drainage water losses estimated by the model for the considerably wet pre-planting periods.

Table 6.2 Statistical significance test results for comparing the CPF's of the four different production techniques, using the Kolmogorov-Smirnov test (Steel *et al.*, 1997).

Pairs of CPF's	**D-statistic**	**Significance level (α)**
WHBJ - CTN	0.3750 [1]	0.0000
WHBJ - CTJ	0.3000 [1]	0.0010
WHBJ - WHBN	0.0875 [ns]	0.9070
WHBN - CTN	0.3500 [1]	0.0000
WHBN - CTJ	0.2375 [1]	0.0180
CTJ - CTN	0.1375 [ns]	0.4090

[1] CPF's significantly different at $\alpha = 0.05$.
[ns] CPF's not significantly different at $\alpha = 0.05$.

6.4 Conclusions

The simple stress model made it possible to make fairly reliable long-term maize yield predictions for the Glen/Hutton and Glen/Oakleaf ecotopes.

With the help of cumulative probability functions, it was possible to quantitatively describe the maize production potential of the above ecotopes and to compare the different production techniques at known probability levels. The cumulative probability functions predicted that the long term mean yields for these ecotopes (at 50% probability) were 2 653 kg ha^{-1} for conventional tillage November planting, 2 685 kg ha^{-1} for conventional tillage January planting, 3 108 kg ha^{-1} for water harvesting and basin tillage November planting, and 3 355 kg ha^{-1} for water harvesting and basin tillage January planting techniques.

The model predicted that the water harvesting and basin tillage treatments were considerably better than the conventional tillage treatments, demonstrating the benefits of water harvesting and basin tillage techniques. There was no evidence that the January planting was better than the November planting.

CHAPTER 7
GENERAL CONCLUSIONS AND RECOMMENDATIONS

7.1 General conclusions

The objective of characterization of the natural agricultural resources that affect the maize production potential of the Glen/Hutton and Glen/Oakleaf ecotopes was effectively achieved. Results of detailed characterization together with measured maize yields indicated that the two ecotopes have similar production potentials. Although the Glen/Oakleaf soil is only half the depth of the Glen/Hutton, its much slower drainage rate enables it to contribute nearly as much plant available water as the Glen/Hutton. The maize production potentials of the two ecotopes were therefore considered similar.

Plant available water is a major factor limiting crop production in arid and semi-arid rainfed areas, and therefore requires special attention for effective ecotope characterization. An important contribution towards quantifying plant available soil water is through field determination of the drainage curve. The value of the drainage curve determined for the Glen/Oakleaf soil, and the way in which the results could be compared with the equivalent data for the far deeper Glen/Hutton soil, has demonstrated this clearly. Without a drainage curve the plant water availability of these two ecotopes would be estimated incorrectly. In spite of its time consuming nature this parameter has been shown to be of paramount importance for the reliable determination of the DUL, CMUL and deep drainage. Estimation procedures for the parameters based on selected soil properties such as texture have been shown to be only marginally successful.

It was necessary to calibrate the neutron water meter at the wet and dry ends for each different soil layer. The importance of doing this, as opposed to a single equation for all water contents, has been clearly demonstrated by the different regression equations obtained for wet and dry ends. Having reliable determinations of the soil water contents at the wet end are of particular importance for reliable estimation of water losses by deep drainage, because soils are very wet when this is occurring.

An expert system was developed for estimating runoff as follows: $R_i = 0.005\ P_i^2 - 0.134\ P_i + 2.032$ for dry soil, and $R_i = 0.042\ P_i^{1.386}$ for wet soil, where R_i (mm) refers to the runoff generated from a certain rainfall amount (P_i, mm). This was used to predict runoff from rainfall data for 80 years. This, together with another equation developed for estimating the soil water content at planting (θp) from the effective precipitation (Pe) for the period of 1 October to planting (*i.e.*, $\theta p = 0.5227\ Pe + 229.7$, $r^2 = 0.63$), made it possible to make reliable long-term determination of the soil water balance.

The concept of plant stress-biomass relationships proved to be a good approach for developing a yield estimation procedure, given enough yield and climate data, as well as appropriate soil water balance estimation procedures. It is therefore considered that the second objective was achieved to a satisfactory extent. Additional measured maize yield data with recorded planting and harvesting dates as well as growth stages could improve the stress-yield relationship.

The procedure developed for yield prediction on the Glen/Hutton and Glen/Oakleaf ecotopes made it possible to make long-term yield predictions for four different production techniques, namely, November planting with conventional tillage, January planting with conventional tillage, November planting with water harvesting and basin tillage, and January planting with water harvesting and basin tillage. Results indicated that the water harvesting and basin tillage treatments were significantly better than the conventional tillage treatments, indicating the advantages of in-field water harvesting and basin tillage in improving the maize productivity of these ecotopes. There was no statistically significant yield increase (using the K-S test) due to the late planting (in both the conventional and water harvesting and basin tillage techniques) compared to their early planting counterparts. This could be due to the high drainage losses of soil water estimated by the model at the beginning of most seasons during late planting. Generally, it is considered that the use of a yield prediction model to generate cumulative probability functions for comparing the different production techniques was satisfactorily achieved.

7.2 Recommendations

Detailed characterization of the factors affecting productivity is imperative for making a quantitative assessment of the production potential of an ecotope. Future studies attempting to make quantitative productivity evaluations of any ecotope worldwide, should give more consideration to this aspect

Characterization of the water holding capacity of the soil is shown to be most effectively done by the determination of the drainage curve in the field. Regression procedures based on selected soil properties should be considered with reservation.

The use of a simple yield prediction procedure for making quantitative productivity evaluations of ecotopes in arid and semi-arid areas could be adopted in future where no better, tested models are available.

More reliable procedures for predicting yields from long and short growing season maize cultivars should be developed to identify the benefits of late planting.

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APPENDICES

Appendix A Measured and estimated crop modified upper limit (CMUL), drained upper limit (DUL), lower limit (LL), and the resultant plant available water (PAW) values for 10 soils in South Africa. Data from: Hensley (1991), Bennie *et al.* (1994), Hensley *et al.* (1997), and Hensley *et al.* (2000).

		Soil type[1]																				
		Clovelly-Setlagole (1)				**Hutton-Ventersdorp (2)**					**Hutton-Hayfield (3)**						**Swartland -Amandel (4)**					
	Layers	**1**	**2**	**3**	**Total**	**1**	**2**	**3**	**4**	**Total**	**1**	**2**	**3**	**4**	**5**	**Total**	**1**	**2**	**3**	**4**	**5**	**Total**
Analytical Data	Layer thickness (mm)	460	340	1200	**2000**	280	320	500	700	**1800**	250	100	500	550	400	**1800**	300	100	150	150	500	**1200**
	Bulk density (Mg m^{-3})	1.61	1.64	1.60		1.54	1.70	1.73	1.73		1.30	1.45	1.60	1.60	1.60		1.50	1.43	1.43	1.42	1.49	
	Sand (%)	89.1	86.2	83.8		79.9	71.0	69.7	73.7		67.6	63.5	58.0	52.0	49.7		61.6	35.4	26.4	29.9	31.9	
	Silt (%)	4.0	4.9	5.5		5.2	6.1	7.1	6.7		11.8	10.7	12.4	15.3	17.7		18.7	13.2	12.9	17.6	22.5	
	Clay (%)	6.3	8.7	10.4		13.8	22.1	22.9	18.9		18.2	23.3	27.7	31.3	30.9		17.5	48.7	58.5	50.1	42.8	
	CEC ($cmol_c$ kg^{-1})	1.90	2.11	2.02		5.00	6.90	7.10	6.30		4.73	4.79	4.08	4.42	6.34		8.01	14.66	16.92	16.48	19.00	
CMUL (mm)	Field estimated				**299**					**410**						**364**						**423**
	Bennie *et al.* (1998)				**475**					**546**						**680**						**521**
DUL (mm)	Measured	49	38	137	**224**	42	69	108	141	**360**	48	17	83	98	77	**323**	69	34	52	54	176	**385**
	Bennie *et al.* (1994)	81	64	237	**383**	59	78	125	164	**425**	63	26	144	171	128	**531**	82	37	60	58	190	**428**
	Ritchie *et al.* (1999)	95	75	266	**436**	63	86	138	186	**472**	50	23	134	152	111	**471**	70	28	45	43	144	**330**
	Hutson (1983)	69	56	208	**333**	51	71	116	150	**389**	57	24	137	167	126	**513**	81	35	58	57	192	**423**
LL(mm)	Measured	23	23	93	**139**	18	39	73	97	**227**	13	5	41	62	50	**171**	35	24	36	32	101	**228**
	Bennie *et al.* (1998)	24	22	89	**136**	24	39	64	78	**205**	32	14	84	106	80	**316**	46	25	43	41	132	**287**
	Ritchie *et al.* (1999)	47	37	128	**212**	29	45	73	98	**245**	18	10	69	80	59	**236**	31	15	25	23	78	**172**
	Hutson (1983)	23	21	83	**127**	23	34	55	68	**179**	30	13	73	91	69	**277**	41	22	38	36	114	**250**
PAW (mm)	Measured	26	15	44	**85**	24	30	35	44	**133**	35	12	42	36	27	**152**	34	10	16	22	75	**157**
	Bennie *et al.* (1994)	57	42	148	**248**	34	39	61	86	**220**	30	12	60	65	47	**215**	36	12	17	17	58	**141**
	Ritchie *et al.* (1999)	47	38	139	**224**	34	41	64	88	**227**	32	13	65	72	53	**236**	39	13	20	20	66	**158**
	Hutson (1983)	46	35	125	**206**	28	37	61	83	**210**	27	11	65	76	57	**236**	40	13	20	21	77	**173**

[1] Soil classification according to South African Soil Classification System (Soil Classification Working Group, 1991).

Appendix A Continued.

		Soil Type[1]															
		Swartland-Rouxville (5)							**Bonheim-Onrus (6)**					**Arcadia-Lonehill (7)**			
	Layers	**1**	**2**	**3**	**4**	**5**	**6**	**Total**	**1**	**2**	**3**	**4**	**Total**	**1**	**2**	**3**	**Total**
Analytical Data	Layer thickness (mm)	250	150	200	230	170	200	**1200**	400	150	250	400	**1200**	150	290	760	**1200**
	Bulk density (Mg m^{-3})	1.50	1.63	1.66	1.51	1.51	1.46		1.34	1.45	1.45	1.45		1.38	1.43	1.43	
	Sand (%)	52.1	49.7	49.1	46.6	42.0	53.5		44.4	44.3	44.2	40.9		44.1	30.8	27.5	
	Silt (%)	7.5	6.3	8.9	7.4	12.9	13.2		9.5	11.8	13.9	20.0		16.9	15.1	16.2	
	Clay (%)	38.2	42.8	39.2	44	42.6	31.2		43.5	43.0	39.6	37.7		37.0	52.4	54.1	
	CEC (cmol$_c$ kg^{-1})	23.15	23.57	27.02	26.12	26.45	21.53		24.30	23.12	24.04	26.21		21.77	27.50	34.77	
CMUL (mm)	Field estimated							**393**					**422**				**477**
	Bennie *et al.* (1998)							**482**					**507**				**-**[2]
DUL (mm)	Measured	68	46	64	74	50	56	**358**	105	53	87	140	**385**	57	107	292	**456**
	Bennie *et al.* (1994)	77	48	63	76	59	61	**383**	134	51	84	141	**411**	51	113	303	**467**
	Ritchie *et al.* (1999)	67	45	60	64	48	50	**333**	99	40	66	107	**313**	38	83	222	**343**
	Hutson (1983)	71	45	60	70	56	58	**360**	124	49	81	140	**393**	49	109	295	**453**
LL(mm)	Measured	28	27	45	48	34	40	**222**	64	37	61	81	**243**	19	53	189	**261**
	Bennie *et al.* (1998)	47	30	40	49	39	37	**241**	87	34	55	94	**269**	33	79	216	**328**
	Ritchie *et al.* (1999)	34	25	34	34	25	24	**176**	47	21	33	54	**155**	18	45	122	**185**
	Hutson (1983)	42	26	34	42	34	33	**210**	78	30	48	82	**237**	29	69	187	**285**
PAW (mm)	Measured	40	19	19	26	16	16	**136**	41	16	26	59	**142**	38	54	103	**195**
	Bennie *et al.* (1994)	30	18	24	27	20	24	**142**	47	18	29	47	**141** 0	18	34	88	**139**
	Ritchie *et al.* (1999)	33	20	26	30	22	26	**158**	53	20	33	53	**158**	20	38	100	**158**
	Hutson (1983)	29	19	26	28	23	25	**149**	46	19	33	58	**156**	20	40	108	**168**

[2] The equation failed to estimate CMUL.

Appendix A Continued.

		Soil Type[1]																				
		Bainsvlei-Amalia (8)								**Hutton-Ventersdorp (9)**								**Wesleigh-Mareetsane (10)**				
	Layers	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Total**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Total**	**1**	**2**	**3**	**4**	**Total**
Analytical Data	Layer thickness (mm)	300	300	300	300	300	300	300	**2100**	300	300	300	300	300	300	300	**2100**	300	300	300	300	**1200**
	Bulk density (Mg m^{-3})[3]	1.65	1.65	1.65	1.65	1.65	1.65	1.65		1.65	1.65	1.65	1.65	1.65	1.65	1.65		1.65	1.65	1.65	1.65	
	Sand (%)	92.5	84.5	83.9	83.1	82.4	83.2	71.2		88.9	85.8	84.2	84.5	82.6	82.9	82.1		85.1	74.7	40.4	18.5	
	Silt (%)	2.0	4.0	3.0	2.0	3.0	4.0	4.0		2.0	2.0	4.0	2.0	4.0	2.0	2.0		4.0	6.0	4.0	4.0	
	Clay (%)	8.0	14.0	14.0	14.0	14.0	14.0	24.0		6.0	14.0	12.0	12.0	14.0	14.0	14.0		12.0	20.0	54.0	75.0	
CMUL (mm)	Field estimated								**572**								**446**					**416**
	Bennie *et al.* (1998)								**519**								**483**					**463**
DUL (mm)	Measured								**508**								**404**					**374**
	Bennie *et al.* (1994)	53	62	61	59	61	62	73	**430**	51	59	59	57	62	59	59	**407**	59	71	106	129	**365**
	Ritchie *et al.* (1999)	65	71	72	72	72	72	79	**502**	63	71	70	70	72	72	72	**489**	70	76	96	112	**354**
	Hutson (1983)	44	54	52	51	52	54	65	**372**	42	51	52	48	54	51	51	**347**	52	64	98	122	**335**
LL(mm)	Measured								**268**								**210**					**240**
	Bennie *et al.* (1998)	15	25	24	22	24	25	36	**171**	13	22	22	20	25	22	22	**147**	22	34	71	95	**222**
	Ritchie *et al.* (1999)	38	37	37	37	36	37	41	**263**	32	38	36	36	36	37	36	**250**	36	39	56	73	**204**
	Hutson (1983)	15	22	21	20	21	22	32	**155**	13	20	20	19	22	20	20	**136**	20	30	61	81	**192**
PAW (mm)	Measured								**240**								**194**					**134**
	Bennie *et al.* (1994)	37	37	37	37	37	37	37	**259**	37	37	37	37	37	37	37	**260**	37	37	35	34	**143**
	Ritchie *et al.* (1999)	27	34	35	35	35	35	38	**240**	31	33	34	34	35	35	35	**239**	34	38	40	40	**151**
	Hutson (1983)	29	32	31	30	31	32	33	**217**	29	30	31	30	32	30	30	**212**	31	34	38	41	**143**

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[3] An average bulk density value assumed for all 3 soils, because a measured value was not available.

Appendix B Soil profile description for the Glen/Oakleaf soil.

Profile No :
Map/Photo : 2836 Winburg
Latitude & Longitude : 28° 55.903' S, 26° 19.391' E
Land type No : Ea39
Climate zone : 45S
Altitude :
Terrain unit : Footslope
Slope : 1%
Slope shape : Concave
Aspect : Southwest
Microrelief : None
Parent material of solum : Binary, aeolian, local colluvium
Underlying material : Sandstone feldspathic

Soil form : Oakleaf
Soil family : Dipene 1220
Surface rockiness : None
Surface stoniness : None
Occurrence of flooding : None
Wind erosion : None
Water erosion : Slight
Vegetation/Land use : Agronomic cash crops
Water table : None
Described by : T.B. Zere, M. Hensley
Date described : 2001-05
Weathering of underlying material : Weak physical, weak chemical
Alternation of underlying material : Ferruginised, calcified

Horizon	Depth (mm)	Description	Diagnostic horizons
Ap	0 - 200	Moist; dry dull reddish brown 5YR4/4; moist dark reddish brown 5YR3/3; fine sandy loam; apedal massive; friable; common fine and very fine normal pores; water absorption 1 second; many roots; gradual smooth transition.	Orthic
A12	200 - 300	Moist; dry dull reddish brown 5YR4/4; moist dark reddish brown 5YR3/3; fine sandy loam; apedal massive; friable; common fine and very fine normal pores; fine cracks; water absorption 1 second; many roots; gradual smooth transition.	Orthic
B	300 - 450	Dry; dry dull reddish brown 5YR4/4; moist dark reddish brown 5YR3/4; fine sandy clay loam; few medium prominent black geogenic mottles; moderate coarse subangular blocky structure; hard; few fine and very fine normal pores; fine cracks; very few, mixed shapes coarse gravel rock fragments; very few angular stones; few clay cutans; water absorption 2 seconds; common roots; clear smooth transition.	Neocutanic
C1	450 - 700	Dry; dry reddish brown 2.5YR4/6; moist dark reddish brown 2.5YR3/4; coarse sandy loam; common fine distinct black oxidized iron oxide mottles; common medium distinct many coloured geogenic mottles; moderate medium subangular blocky structure; hard; few fine and very fine normal pores; fine cracks; slightly cemented, continuous, unknown agent; many coarse round rock fragments; few coarse gravel, angular fragments; few fine sesquioxide concretions; common clay cutans; water absorption 3 seconds; few roots; clear smooth transition.	Unconsolidated material without signs of wetness
C2	700 - 900	Moist; saprolite; water absorption 1 second; few roots.	Saprolite

Remarks: (i) Structure of the B1 becomes noticeably stronger towards the bottom of the layer. Cutans increase in frequency.

(ii) The C1 horizon is a layer with much colluvial gravel, mainly dolerite but sandstone pieces also present. It has been ferruginised. In places, a thin incipient black iron pan (discontinuous) has formed at the transition B1/C1.

(iii) The C2 horizon shows, near its upper boundary, a considerable amount of soil illuviation into the cracks. CaCO3 coatings and concretions seem to occur in localised patches.

Appendix C Soil analytical data for the Glen/Oakleaf soil.

Horizon	Ap	A12	B	C1
Depth range (mm)	0-200	200-300	300-450	450-700
Bulk density (Mg m^{-3})	1.48	1.72	1.49	1.51
Particle size distribution (%)				
Coarser than 2 mm	0.4	0.8	2.2	31.9
Coarse sand 2-0.5 mm	3.7	4.6	4.0	26.0
Medium sand 0.5-0.25 mm	5.6	12.4	9.9	10.7
Fine sand 0.25-0.106 mm	37.5	37.7	32.5	13.5
Very fine sand 0.106-0.05 mm	21.7	22.2	21.3	11.6
Coarse silt 0.05-0.02 mm	8.0	3.0	4.5	10.5
Fine silt 0.02-0.002 mm	1.5	1.5	2.5	12.0
Clay < 0.002 mm	16.5	17.0	23.5	14.5
Total content of particles finer than 2 mm	100.0	98.4	98.2	98.7
Texture	fiSaLm	fiSaLm	fiSaClLm	coSaLm
Chemical analysis				
Organic carbon (%)	0.22	0.22	0.31	0.21
pH (H2O)	6.3	6.2	6.8	7.6
pH (KCl)	4.6	4.6	5.1	5.9
Electrical resistance (Ohm)	2929	2598	1821	925
Exchangeable cations and CEC (c mol$_c$/kg soil)				
Na	0.16	0.16	0.13	0.18
K	1.09	0.67	0.85	1.14
Mg	2.21	2.30	4.77	10.28
Ca	3.95	3.89	6.35	12.88
S value (soil)	7.41	7.03	12.10	24.47
CEC (soil)	5.18	6.18	12.22	ND
CEC (clay)	31.37	36.33	52.01	ND
S value (clay)	44.91	41.35	51.50	168.76

Appendix D Standardization of CPN NWM No. H34055438 against CPN NWM No. H34055437. Count ratios (CR) for both instruments calculated for the "thin" and "thick" plastic standards (PVC) were plotted as shown Figure D.1. The resultant regression equation serves to estimate NWM No. H34055438 (y-values) CR's from those of NWM No. H34055437 (x-values).

Reading	**NWM No. H34055438**		**NWM No. H34055437**	
	CR in Medium PVC	**CR in Thin PVC**	**CR in Medium PVC**	**CR in Thin PVC**
1	1.331	0.465	1.694	0.586
2	1.324	0.468	1.694	0.581
3	1.329	0.463	1.691	0.615
4	1.332	0.462	1.694	0.600
5	1.331	0.462	1.695	0.603
6	1.331	0.466	1.700	0.581
7	1.333	0.467	1.686	0.603
8	1.333	0.461	1.691	0.575
9	1.338	0.463	1.685	0.605
10	1.328	0.462	1.684	0.582
CV (%)	0.28	0.54	0.30	2.28

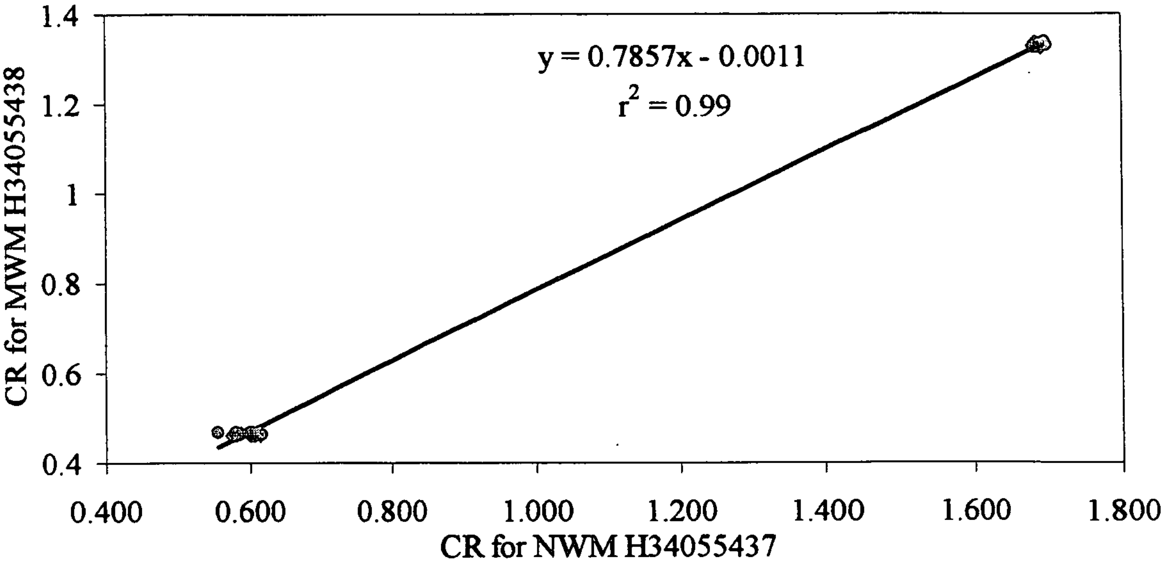

Figure D.1 Regression relationship between count ratios of CPN neutron water meters No. H43055437 and No. H43055438.

Appendix E Calibration data for NWM No. H34055438 on the Glen/Oakleaf soil. Count ratios (CR) and soil water content (θ) values taken for each layer on or near the drainage dam.

	0-300 mm layer		**300-600 mm layer**		**600-900 mm layer**	
	CR	**θ (%)**	**CR**	**θ (%)**	**CR**	**θ (%)**
Dry end data	0.769	9.1	1.610	24.3	1.675	28.6
	0.557	8.9	1.092	14.1	1.647	25.9
	0.572	8.8	1.092	14.2	1.202	21.1
	0.597	8.7	1.437	23.6	1.240	17.9
	0.842	10.7	1.309	22.2	1.145	18.8
	0.878	13.9	1.411	23.2	1.292	20.4
	0.955	13.5	1.505	23.5		
	0.882	13.2	1.194	18.6		
	0.409	7.6	1.201	18.5		
	0.461	7.5	1.367	21.5		
	0.446	6.7	1.443	25.5		
	0.450	8.1	1.276	21.4		
	0.542	9.5				
Wet end data [1]	1.482	30.7	1.799	32.1	1.838	38.4
	1.431	24.1	1.767	28.6	1.826	37.1
	1.377	24.6	1.751	31.8	1.793	31.7
	1.356	26.2	1.750	33.9	1.775	30.1
	1.328	22.7	1.718	30.0	1.777	31.7
	1.380	23.7	1.710	28.3	1.752	32.6
	1.360	20.7	1.713	25.6	1.870	38.7
	1.265	20.8	1.684	24.5		
	1.314	23.2	1.729	27.0		
	1.522	30.8	1.800	35.0		

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[1] The last row of the wet end θ (%) data in each layer represents fSat, a fraction of porosity considered appropriate for field saturation. The corresponding values on the CR columns represent the maximum observed count ratios (CRmax) for each layer.

Appendix F Volumetric soil water contents at different times after the saturation in the drainage dam –Glen/Oakleaf soil.

Time after wetting (days)	0.1	0.5	1	2	8	15	22	38	79	114
Soil water content (mm) for:										
0-300 mm layer	92.5[1]	90.7	86.2	86.1	80.1	73.6	71.2	67.9	62.0	60.5
300-600 mm layer	105.1[1]	102.1	102.1	101.3	94.3	90.9	90.8	83.8	76.7	76.4
600-900 mm layer	116.2[1]	112.3	120.6	117.7	114.2	110.6	107.9	100.4	95.2	90.9
Root zone	**313.8[1]**	**305.1**	**308.8**	**305.2**	**288.6**	**275.2**	**269.9**	**252.2**	**233.8**	**227.7**

[1] fSat value: the fraction of porosity considered appropriate for field saturation.

Appendix G Soil profile description for the Glen/Hutton soil (Hensley, personal communication, 2002).

Profile No	: MH95	Soil form	: Hutton
Map/photo	: 2826 Winburg	Soil family	: Ventersdorp 3200
Latitude & Longitude	: 28° 55.691' S, 26° 19.599' E	Surface rockiness	: None
Land type No	: Ea39	Surface stoniness	: None
Climate zone	: 45S	Occurrence of flooding	: None
Altitude	: 1320 m	Wind erosion	: None
Terrain unit	: 3	Water erosion	: None
Slope	: 3%	Vegetation/Land use	: Cash crops
Slope shape	: Straight	Water table	: None
Aspect	: West	Described by	: M. Hensley
Microrelief	: None	Date described	: 1984-10
Parent material of solum	: Dolerite	Weathering of underlying material	: Weak chemical, weak physical
Underlying material	: Not known	Alternation of underlying material	: Ferruginised

Horizon	Depth (mm)	Description	Diagnostic horizons
A1	0 - 300	Dry; dry reddish brown 5YR4/6; moist dull reddish brown 5YR4/4; fine sand loam; massive; slightly hard; few pores; water absorption 1 second; many roots; clear smooth transition.	Orthic
B1	300 - 600	Dry; dry reddish brown 2.5YR4/6; moist dark reddish brown 2.5YR3/6; fine sandy clay loam; weak coarse angular blocky structure; few pores; water absorption 1 second; many roots; gradual smooth transition.	Red apedal
B2	600 - 900	Dry; dry reddish brown 2.5YR4/6; moist dark reddish brown 2.5YR3/6; fine sandy clay loam; few medium red brown mottles; moderate coarse angular blocky structure; few pores; few clay cutans; water absorption 1 second; common roots; gradual smooth transition.	Red apedal
B3	900 - 1200	Dry; dry reddish brown 2.5YR4/78; moist reddish brown 2.5YR4/6; fine sandy loam; moderate coarse angular blocky structure; few pores; water absorption 1 second; few roots; gradual smooth transition.	Red apedal

Remarks: (i) The material below 1200 is transitional to the C horizon. It contains a considerable amount of relatively unweathered dolerite colluvium.

(ii) A tendency towards a coarse prismatic structure is visible in the B2, and it seems as though there is a greater concentration of roots in the vicinity of the cracks.

Appendix H Soil analytical data for the Glen/Hutton soil (Hensley, personal communication, 2002).

Horizon	A1	B1	B2	B3
Depth range (mm)	0-300	300-600	600-900	900-1200
Bulk density (Mg m^{-3})	1.54	1.70	1.73	1.73
Particle size distribution (%)				
Coarse sand 2-0.5 mm	1.0	0.0	0.0	1.0
Medium sand 0.5-0.25 mm	10.0	10.0	9.0	10.0
Fine sand 0.25-0.106 mm	48.0	43.0	42.0	45.0
Very fine sand 0.106-0.05 mm	22.0	18.0	18.0	18.0
Coarse silt 0.05-0.02 mm	3.0	4.0	5.0	4.0
Fine silt 0.02-0.002 mm	2.0	2.0	2.0	3.0
Clay < 0.002 mm	14.0	22.0	23.0	19.0
Total content of particles finer than 2 mm	100.0	99.0	99.0	100.0
Texture	fiSaLm	fiSaClLm	fiSaClLm	fiSaLm
Chemical analysis				
Organic carbon (%)	0.20	0.20	0.20	0.10
pH (H2O)	6.2	6.0	6.7	7.1
pH (KCl)	4.9	4.8	5.6	5.8
Electrical resistance (Ohm)	1620	1200	1400	1900
Exchangeable cations and CEC (c mol$_c$/kg soil)				
Na	0.10	0.30	0.30	0.20
K	0.30	0.20	0.20	0.30
Mg	1.80	2.80	3.70	3.80
Ca	3.30	4.80	4.90	5.10
S value (soil)	5.50	8.10	9.10	9.40
CEC (soil)	5.00	6.90	7.10	6.30
CEC (clay)	35.71	31.36	30.87	33.16
S value (clay)	39.29	36.82	39.57	49.47

Appendix I Soil profile description for the Glen/Tukulu soil.

Profile No	:	Soil form	: Tukulu
Map/photo	: 2836 Winburg	Soil family	: Dikeni 1220
Latitude & Longitude	: 28° 56.031' S, 26° 19.725' E	Surface rockiness	: None
Land type No.	: Ea39	Surface stoniness	: None
Climate zone	: 45S	Occurrence of flooding	: None
Altitude	:	Wind erosion	: None
Terrain unit	: Midslope	Water erosion	: None
Slope	: 5%	Vegetation/Land use	: Abandoned field
Slope shape	: Straight	Water table	: None
Aspect	: South east	Described by	: T.B. Zere, M. Hensley
Microrelief	: None	Date described	: 2002-06
Parent material of solum	: Binary, aeolian, local colluvium	Weathering of underlying material	: Moderate physical, moderate chemical
Underlying material	: Sandstone feldspathic	Alternation of underlying material	: Ferruginised

Horizon	Depth (mm)	Description	Diagnostic horizons
A	0 - 300	Dry; dry reddish brown 5YR4/6; moist dark reddish brown 5YR3/3; fine loamy sand; apedal massive; friable; few fine and very fine normal pores; water absorption 1 second; many roots; gradual smooth transition.	Orthic
B1	300 - 500	Dry; dry reddish brown 5YR4/6; moist dark reddish brown 5YR3/3; fine sandy loam; weak coarse subangular blocky structure; hard; few fine and very fine normal pores; common clay cutans; water absorption 1 second; many roots; gradual smooth transition.	Neocutanic
B2	500 - 650	Dry; dry bright reddish brown 5YR5/6; moist reddish brown 5YR4/6; fine sandy clay loam; many medium faint red and yellow, oxidized iron oxide mottles; few fine prominent black manganese mottles; moderate coarse subangular blocky structure; very hard; common fine and very fine normal pores; very few coarse gravel, angular fragments; very few fine sesquioxide concretions; common clay cutans; water absorption 3 seconds; common roots; abrupt smooth transition.	Neocutanic
B3	650 - 850+	Dry; mottled; fine sandy clay loam; many medium distinct yellow brown and red oxidized iron oxide mottles; common fine prominent black manganese mottles; strong coarse angular blocky structure; very hard; few fine and very fine normal pores; fine cracks; very few round coarse gravel rock fragments; very few fine sesquioxide concretions; many clay cutans; water absorption 10 seconds; few roots.	Unconsolidated material, with signs of wetness

Remark: Well-defined cutans have a grey colour in the B3.

Appendix J Particle size distribution for the different soil horizons – Glen/Tukulu soil.

Textural class	**Depth range (mm)**			
	0-300	*300-500*	*500-650*	*650-850*
Coarser than 2 mm	0.2	0.3	0.2	0.1
Coarse sand 2-0.5 mm	0.8	0.5	0.6	0.4
Medium sand 0.5-0.25 mm	4.0	3.7	3.4	2.8
Fine sand 0.25-0.106 mm	51.3	49.0	43.0	36.4
Very fine sand 0.106-0.05 mm	24.6	23.4	22.9	19.9
Coarse silt 0.05-0.02 mm	6.4	4.1	6.2	7.5
Fine silt 0.02-0.002 mm	2.0	3.6	2.0	4.1
Clay < 0.002 mm	11.2	15.3	21.9	29.3
Sum of < 2 mm	100.3	99.6	100.0	100.4
Texture	LmfiSa	fiSaLm	fiSaClLm	fiSaClLm

Appendix K Predicted yields for 80 years using four different production techniques (CTN, CTJ, WHBN, and WHBJ) for the Glen/Hutton and Glen/Oakleaf ecotopes. 22 years of the CTN technique are measured data (see Table 5.3).

Growing	**Yg (kg ha^{-1})**				**Growing**	**Yg (kg ha^{-1})**			
Season	**CTN**	**CTJ**	**WHBN**	**WHBJ**	**Season**	**CTN**	**CTJ**	**WHBN**	**WHBJ**
1922/23	2978	2689	4379	3466	**62/63**	2763	3673	4044	4369
23/24	3282	3087	4381	3736	**63/64**	1394	2022	2351	2357
24/25	3211	4644	4177	5996	**64/65**	2659	1874	3124	2096
25/26	3267	3945	4128	4799	**65/66**	2750	1026	3622	2450
26/27	3066	2760	3855	4130	**66/67**	3571	3563	4017	4478
27/28	2198	2403	2722	2868	**67/68**	3024	3901	2674	4834
28/29	1896	2175	2238	2645	**68/69**	2491	3239	3355	4038
29/30	2152	2488	2760	3240	**69/70**	2081	1288	2272	2101
30/31	2209	2537	2834	3354	**70/71**	2243	2185	2429	3767
31/32	2179	2675	2665	3102	**71/72**	4382	3294	5661	6282
32/33	1467	1743	1732	2084	**72/73**	2390	1959	2947	2358
33/34	3575	3647	4612	4003	**73/74**	5930	4934	5858	5540
34/35	2399	2902	3032	3514	**74/75**	3200	2973	4664	3183
35/36	2666	3111	3401	3590	**75/76**	4578	4165	5937	4902
36/37	3117	2727	4193	3357	**76/77**	2889	3592	4010	4450
37/38	1903	1878	2112	2141	**77/78**	2650	2637	3403	3174
38/39	2048	2162	2373	2408	**78/79**	2213	2362	2605	2649
39/40	2101	2972	2550	3719	**79/80**	1925	1970	2189	2092
40/41	3813	2422	4928	2838	**80/81**	4141	3336	5223	3657
41/42	1620	2788	1791	3408	**81/82**	2716	3096	3514	4104
42/43	2791	2960	3485	3433	**82/83**	1445	1667	1708	1850
43/44	2849	1990	3528	2153	**83/84**	460	1436	1519	1632
44/45	1961	2295	2454	2867	**84/85**	3000	2648	3296	3269
45/46	3056	3003	4140	3811	**85/86**	2000	2530	2644	3153
46/47	1611	1845	2019	2229	**86/87**	3000	2178	3502	2633
47/48	3278	3948	4435	4923	**87/88**	3130	5078	3293	5901
48/49	1511	2074	1538	2209	**88/89**	2753	3408	4392	3977
49/50	2052	3503	2460	4229	**89/90**	3580	3141	3921	3807
50/51	2182	2681	2742	3065	**90/91**	3151	4326	3595	5178
51/52	1985	1501	2398	1765	**91/92**	1142	1165	1188	1211
52/53	1761	1489	2231	2369	**92/93**	1797	2269	2135	2716
53/54	2814	3759	3674	4450	**93/94**	3676	3032	4860	3357
54/55	4600	4719	4980	5222	**94/95**	1656	2091	2160	2514
55/56	1820	3330	3093	3609	**95/96**	3024	3145	3418	4013
56/57	3146	2011	2839	2165	**96/97**	2488	2752	3525	3400
57/58	2892	2936	2240	3626	**97/98**	3151	2913	4946	4024
58/59	889	1705	2438	2018	**98/99**	1713	1565	2023	1699
59/60	1947	3913	3306	5587	**99/00**	2656	3229	3002	3514
60/61	1227	2528	2710	2714	**00/01**	2041	2355	2503	2806
61/62	1948	2433	2994	2985	**01/02**	3557	2534	4453	2822